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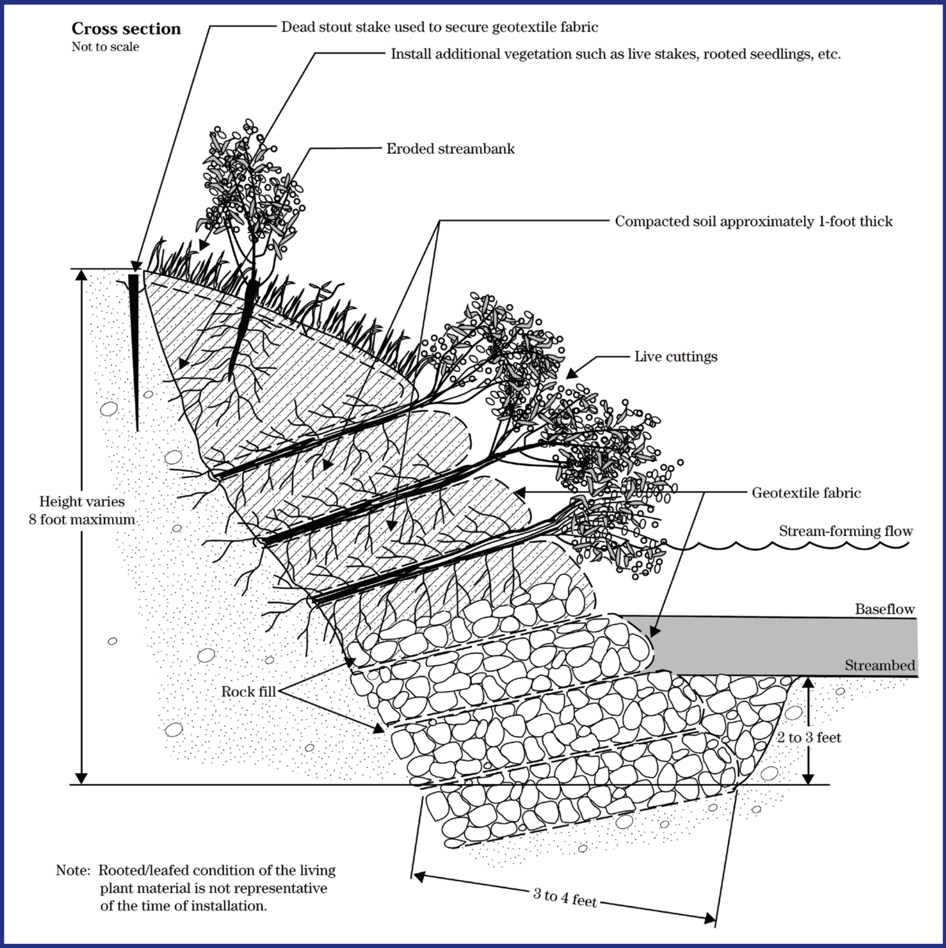
Approaches to the Design of Biotechnical Streambank Stabilization

Volume I—A Guide to the Literature



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16. Abstract

Streambank stabilization has traditionally been performed with riprap for which reliable design and installation procedures are available. Due to concerns about the environmental impact of riprap, there has been increasing interest in more natural biotechnical (or bioengineering) alternatives. A review of the litera-ture on biotechnical approaches to streambank stabilization has been per-formed, with a focus on those works that might be particularly useful in developing design guidelines or standards for the Indiana Department of Transportation. Works that synthesized the literature (up to about the year 2000) and so covered a broad range of topics, were examined, including monographs and manuals published by federal and state agencies. More recent publications were also found on narrower more specific topics, including the ecological effects of riprap and bio-technical approaches, advances in the geotechnical modeling of vegetation effects on bank stability, the effectiveness of biotechnical measures, and screening methods for selecting appropriate measures. Implications of the reviewed work for the development of design guidelines are discussed.

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EXECUTIVE SUMMARY

APPROACHES TO THE DESIGN OF BIOTECHNICAL STREAMBANK STABILIZATION: VOLUME I—A GUIDE TO THE LITERATURE

Introduction

Streambank stabilization has traditionally been performed with riprap or other hard-armor techniques for which reliable design and installation procedures are available. Due to concerns about the environmental impact of riprap and the consequent regulatory pressures, the Indiana Department of Transportation (INDOT) is interested in finding softer, more environmentally sensitive alternatives to the pure hard-armor approaches. This report examines the literature on biotechnical approaches, which emphasizes the use of vegetative elements, possibly in combination with hard-armor elements. Documents of particular interest would be those helpful in formulating detailed design guidelines for the application of biotechnical techniques to Indiana conditions, and, specifically, INDOT projects.

Findings

The review found a large body of literature related to biotechnical engineering of slopes and/or streambanks. These were divided into (i) works of synthesis, frequently monographs or federal and state agency reports and manuals, including those of state departments of transportation, that discussed a broad range of topics, often reviewing the previous literature (up to 2003), and (ii) works of narrower scope, frequently recent (2003 and after) articles in research journals but also sometimes federal agency publications with a very specific focus. For the present purposes, the works of synthesis were more useful as they usually presented a consensus view of the issues and had more immediate implications for design. In addition to providing detailed descriptions of various techniques, such as vegetated mechanically stabilized earth (also known as soil lifts) and live staking, they also discussed the selection of techniques for different conditions. A number of short works, mainly originating from the U.S. Army Corps of Engineers and devoted to a single technique, were also identified. From the review, several points might be highlighted:

- Prior to any design of a bank stabilization scheme, whether hard-armor or biotechnical, project goals should be clearly formulated, fluvial geomorphology aspects should be considered to assess the extent to which a local solution will be adequate, and the main mechanisms of bank movement should be identified.
- The toe zone often represents the region critical for the success of bank stabilization (whether by hard- or soft-armoring techniques) and merits special attention.
- A biotechnical strategy combining hard and soft elements will likely be the most widely applicable and more conservatively reliable approach.

Implementation

The results of this literature review will be implemented

- in developing draft design guidelines and standards for INDOT,
- as a reference for INDOT Engineering Services and Design Support, and by its broader dissemination through INDOT Environmental Services.

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1. INTRODUCTION

From an engineering point of view, the banks of an alluvial channel may be considered stable if, over a period of 20 to 50 years, the location of the banks does not change appreciably. The bank instability of most concern is due to erosion or the net removal of alluvial material from the bank region by the stream flow. Instabilities may be entirely natural in that it would occur even in the absence of human activities. Human activities such as land development or agricultural practices, may exacerbate the effects of instabilities. The region where banks are actively eroding may be localized, driven by specific topographic features such as channel bends, or may include the entire reach of a straight stream. Bank erosion that directly impacts valuable assets such as bridges or roadways may be limited in streamwise extent, thus allowing localized countermeasures to arrest the erosion and avoid or mitigate its adverse consequences.

The conventional approach to protecting streambanks from erosion is the application of riprap revetment, namely a layer of hard granular stone-like material, to act as a non-erodible armor for the erodible bank. Standard procedures for stone sizing and its installation have been developed (see the recent NCHRP report 568 by Lagasse, Clopper, Zevenbergen, and Ruff (2006)), and the engineering and construction community supports its use due to its effectiveness and reliability. Questions regarding the environmental/ecological effects of riprap installation have been raised. Fischenich (2003) reviewed these issues and concluded: "The evidence presented in the literature strongly suggests that the impacts from riprap are very site-specific." The reviewed impacts could be positive, negative or negligible.

Alternatives to riprap revetment have been sought in response to concerns regarding its environmental effects. These alternatives may be divided into two broad categories, in-stream structures, and direct bank treatment. In-stream structures include bendway weirs and stream barbs (Lagasse et al., 2009, also to be referred to as HEC-23; USDA National Resources Conservation Service, 2007, also to be referred to as NEH-654; see also appendix B), spurs or other vane-like structures extending from the streambank to be protected into the channel (HEC-23; NEH-654), and low-head cross weirs (NEH-654), and is intended to redirect flow away from the bank to reduce or minimize its erosive capability. In addition to their bank-protective feature, such structures are also believed to have environmental benefits when compared to riprap, especially with regards to riparian impact, but possibly also the resulting local scour patterns may enhance aquatic habitat (see however the comments regarding flow redirection techniques in Bennett et al. (2011)). While the in-stream structures attempt to protect the bank by acting on the flow, the second approach, termed bioengineering or biotechnical techniques, acts directly on the bank. The common characteristic of these techniques is the central role, played by vegetation. They range from those in which the main protective element is not vegetative, but which allows vegetation to become established, such as conventional rip rap, or articulated concrete mats, or perforated polymer mats, to fully vegetative solutions, relying solely on vegetation characteristics, such as roots, for protection (see appendix B for some examples currently applied in Indiana streams). The present study focuses on the bank-treatment alternatives to riprap, and so this literature review will be restricted mainly to bioengineering or biotechnical options, and will deal with in-stream structures only to the extent that the reviewed works also deal with such options.

1.1 Review Organization

The review is intended to provide a guide to the literature on biotechnical approaches, and specifically to the issues that should be addressed in choosing an appropriate technique, or of techniques, and the subsequent design (and construction) questions. Because the appropriate techniques may be strongly influenced by geographical considerations, the Indiana context is highlighted. The literature compiled in this review therefore emphasizes design choices and regional effects.

A brief overview of flow and erosion processes is given in Chapter 2. Chapter 3 covers synthesis reports, often performed by or on behalf of federal or state agencies, and reviewing work done on a broad range of topics. These were found the most useful for the development of design guidelines, as they present a consensus view of the problem or technique, often with clearer design implications. Chapter 4 covers articles with a much narrower focus, such as research articles in archival journals, but also includes review articles on a specific topic. Because the synthesis works have generally considered the literature up to about the year 2000, the review in Chapter 4 focuses on work published since that time, and organizes these in themes that have attracted the most recent research attention. These documents can be more controversial and their design implications less clear. Appendix A lists brief works, that describe a single biotechnical technique, and so could contribute directly to a design standard.

2. FLOW, SEDIMENT AND EROSION PROCESSES

The phenomenon of bank erosion results from a complex interaction of flow, sediment and bank characteristics, much of which remains poorly understood. The addition of the effects of vegetation on bank stability further complicates the problem, and makes any detailed quantitative prediction even more precarious. An understanding of the qualitative and quantitative aspects of the physical processes involved in bank erosion is necessary to provide the context to the literature.

2.1 Qualitative Aspects of Bank Erosion Processes

In general, flow over a surface will exert a frictional force (or shear stress, i.e., shear force per unit area) on the surface. If the surface is made up of erodible material, such as sand or other granular matter, then under certain conditions the resulting flow force on the surface will be sufficient to cause the material to become mobile. This process is termed surficial or particle or hydraulic erosion or entrainment. By itself, particle mobility does not imply net erosion. A dynamic equilibrium may become established in which material transported away from a specific location is replaced by material that is deposited at the same location, such that over a relevant time period a material balance is maintained, and there is no net erosion.

Because of the complicated geometry of natural erodible streams, flow characteristics at any given cross-section can be quite complex, with wide variation in values of relevant quantities. In particular, the boundary shear stress, i.e., the shear stress on the erodible boundary that is responsible for transporting boundary material, can vary substantially. The flow in a bend may be taken as an example. In a straight channel, the maximum velocities and hence boundary stresses are observed in or near the midstream region. In a channel bend, maximum velocities and boundary stresses at some sections may not only be increased but also may occur markedly closer to the outer bank region. As a result, the outer banks of sharp channel bends tend to be prone to bank erosion. Such large local variations in flow quantities limit the direct usefulness of the quantitative predictions of the common one-dimensional hydraulic models forming the basis of practical design of bank-protection schemes. The results of one-dimensional models must be supplemented by additional empirical relations or more sophisticated multi-dimensional computer models.

Because larger flow events are associated with larger flow depths and possibly with larger main-channel velocities and boundary stresses, it is tempting to think that the most serious bank erosion event would occur during the largest flow event. If there are out-of-bank flows, local changes in flow characteristics could however potentially lead to reduced boundary stresses near banks and/or increased local deposition, resulting in reduced net erosion (see also the discussion regarding the design discharge for bank protection in Chapter 203-6.06(03) of the Indiana Department of Transportation (2013) Hydraulics and Drainage Manual, to be referred to as INDOT2013-203-6). Further complications may arise due to duration or history effects. Large relatively rare events may be less effective in inducing long-term bank erosion than smaller more frequent events. This is related to the issue of identifying the dominant or channel-forming discharge, often discussed in connection with stable hydraulic geometry. Similarly, bank erosion might also be affected by time history features, e.g., the shape of the hydrograph, or the specific sequence of flow events. Bank erosion events are often observed to occur in an episodic manner, and may not necessarily be closely correlated with the flow characteristics prevailing at the same time instant as the erosion event, but rather may be better interpreted as being the summation of effects of all past and present events. For engineering design purposes, consideration of such process details might not be required provided a sufficiently conservative specification of load (be it near-bank velocity or shear stress or other quantity) can be given.

Sediment (or more generally, soil) characteristics in the near-bank region are relevant since they determine the permissible velocities or shear stresses. The condition for the beginning of sediment motion is, for practical purposes, well defined in terms of particle characteristics only for non-cohesive material, such as sand. Quantitative results are available, in order of increasing uncertainty, for such material on a horizontal bed in a uniform flow in a straight channel, on a bank at a specified angle in a uniform flow in a straight channel, and in a curved channel. The standard design equations for riprap are based on such results. Even for non-cohesive material, banks can still remain stable even when such permissible velocities are exceeded if the flow transports sediment that can be deposited, thus replenishing eroded material.

Streambanks in Indiana are not generally expected to behave in a completely non-cohesive manner. Dealing with cohesion effects in the context of scour or erosion still remains a significant research topic. Mehta and McAnally (2008) discusses various aspects of fine-grained or cohesive sediment transport, including erosion models. Arneson, Zevenbergen, Lagasse, and Clopper (2012; also known as HEC-18) describes engineering approaches within the narrow context of bridge scour, relying heavily on the work summarized in Briaud, Chen, Li, Nurtjahyo, and Wang (2004). Because of the complexities of characterizing cohesive sediment properties relevant to the erosion process, and determining their relation to flow variables, the latter argued for an approach based on materials testing of samples taken from the site, and subjected to a standard flow. Besides the need for specialized testing equipment (the Erosion Function Apparatus or EFA), the approach is based on a uniform flow over a horizontal plane bed, which may differ significantly from flow near a bank or in a bend, and assumes surficial erosion as the only mechanism for erosion.

Due to the bank slope, which is typically large compared to the bed slope, a particle on the bank is more easily mobilized than a particle on the bed in the sense that it requires a smaller boundary shear stress to cause particle motion. This effect is captured in Lane's (1955) result (also see the discussion in Chang, 1992 or Garcia, 2008), which is incorporated in the Brown and Clyde (1989, also known as HEC-11) riprap design equation, or is otherwise dealt with in a sideslope correction factor as in the U.S. Army Corps of Engineers (1991; hereafter, U.S. Army Corps of Engineers will be referred to as USACE) riprap equation. As the boundary shear stress varies over the cross-section (for a straight trapezoidal channel, see the discussion in Chang (1992) or Miller, Fischenich, and Thornton (2012)), it should not be assumed that, under any given flow condition, a particle on the bank will be caused to move before a particle on the bed. The particles higher on the bank slope depend on the particles lower on the slope for their stability. If lower particles are removed due to the action of the flow, then the effect may not be restricted to those removed particles, as the stability of the higher particles may be compromised if the lower particles had provided any support or protection to the higher particles.

In addition to surficial erosion, a second general process leading to bank recession is classified as mass movement (or mass wasting or mass failure or geotechnical failure). Mass movement is a "downward and outward movement of slope-forming materials ..." involving "sliding, toppling, falling or spreading of fairly large and sometimes relatively intact masses" (Gray & Sotir, 1996), rather than the motion of individual particles. Fischenich and Allen (2000) and Pizzuto et al. (2008) discuss various mass failure mechanisms specifically relevant to streambank erosion (see also INDOT2014). Simple geotechnical models of slope stability involve the shear strength of the bank material, dependent on parameters typically obtained through material testing, but as Fischenich and Allen (2000) notes "No algorithms or techniques exist that allow the prediction of precise location, time, or extent of future bank erosion."

The description of bank erosion in terms of surficial erosion and mass movement processes is characteristic of traditional hydraulic (or geotechnical) engineering approaches. A different approach is influenced by fluvial geomorphology, wherein a main topic is the description and classification of stream geometry, especially stream plan-form. The stream is viewed as an evolving system that is continuously adjusting its boundaries, including the location of its banks, towards an equilibrium (or to be in "regime"), usually assumed to be unique, provided that the external forcing remains the same. A strategy of identifying potential bank erosion problems during design and before construction rather than trying to fix the problem after the fact is recommended. A brief general introduction to fluvial geomorphology is given in Biedenharn, Watson, and Thorne (2008), while Pizzuto et al. (2008) and Fischenich and Allen (2000) discuss the geomorphic context of width adjustment and bank erosion. Lagasse, Zevenberen, Spitz, and Arneson (2012; also known as HEC-20) review many of the same topics, but focus on implications for highway structures and the relevant engineering analyses and responses. While the qualitative insights are valuable, quantitative results, if there any, are laden with a high level of uncertainty, and much reliance must be placed on experience and judgment.

2.2 Quantitative Aspects of Bank Erosion Processes

There are few quantitative results in bank erosion that have been widely adopted in practice; on the other hand, what is termed here as the riprap design equation has been the basis for the traditional approach to the selection of stone size. It is used here to illustrate various aspects of bank erosion/protection that may have implications for bioengineering/biotechnical bank protection approaches. Various forms of a riprap design equation have been developed, but only the USACE equation (USACE, 1991) will be considered. In a recent NCHRP report, Lagasse et al. (2006) compared the performance of several riprap design equations, including the FHWA HEC-11 equation, and concluded that the USACE equation was the most reliable. The USACE equation expresses d_{30}, i.e., the required riprap stone size for which 30% of the material is finer by weight, relative to the local depth of flow (not the flow depth) above the stone, y_{ss}, as

$$\frac{d_{30}}{y_{ss}} = C_{sf}\, C_s C_v C_t \left[\frac{v_{ss}}{\sqrt{K_{ss} g(s-1) y_{ss}}} \right]^{2.5} \tag{2.1}$$

where v_{ss} is the depth-averaged velocity at a point 20% upslope on the bank, g is the acceleration due to gravity, S, the ratio of specific weight of the riprap material to that of water, K_{ss} the sideslope correction factor, C_{sf} a safety factor, C_s and C_t are factors related to the riprap characteristics, and C_v is a velocity distribution coefficient.

Several features of Equation (2.1) may be highlighted. The basic form of Equation (2.1), i.e., without the various correction factors, can be derived from a critical flow-induced boundary shear stress, $\tau_{b,crit}$, that when exceeded will result in the motion of particles. This can be expressed in terms of the convenient local depth-averaged velocity, such as v_{ss}, provided a model relating the $\tau_{b,crit}$ to v_{ss} is available. The basic result is obtained for a straight channel for a particle on a bed of negligible slope, necessitating the various correction factors to account for more complicated situations. Also, both v_{ss} and C_v depend on the ratio of the radius of curvature, R_c, of the channel to the channel (top) width, W_c, increasing as the bend becomes sharper. The sharper the bend the greater the erosive forces on stones or the surface in general is expected, and hence the need for more durable protection. Further, v_{ss} is taken at a point that is 20% upslope on the bank. This is the approximate location of the maximum boundary shear stress on the bank, and hence where a stone might be most susceptible to being caused to move first. Any bank protection measure should be mindful of the toe region (extending up to and including and probably some distance above the 20% upslope point on the bank) as being critical. The sideslope correction factor, K_{ss}, takes into account the increased instability of an individual stone as the bank slope increases. The steeper the bank, the greater is the challenge in protecting it from erosion. As it applies only to riprap stone size determination, Equation (2.1) considers only surficial erosion, and does not attempt to deal with mass movement. As NCHRP-568 (and also INDOT2013-203-6) notes, revetment riprap failure mechanisms include translational slide and slump as well as loss of toe or end supports, all of which may be considered mass movement. Practical revetment riprap design involves other aspects, such as toe and edge treatments, bank slope, and filter design, all of which may contribute to mass failure.

It is also instructive to compare Equation (2.1) with the practice recommended in the INDOT design manual, which is considerably simpler. According to INDOT2013-203-6, riprap is divided into only three size classes, revetment (d_{100} = 18-in), Class I (d_{100} = 24-in), and Class 2 (d_{100} = 30-in); a fourth energy dissipater class is not considered here), and the sole criterion for selection is based on the average velocity, v ($\leq$ 6.5 ft/s, 6.5 ft/s to 10 ft/s, 10 ft/s to 13 ft/s). Figure 2.1 shows a plot of the "stability" boundaries for various safety factors, $C_{sf} > 1$, ranging from 1 to 1.2 (a standard value of C_{sf} is 1.1 according to NCHRP-568), determined from Equation (2.1) for revetment riprap. The region to the right of the respective curves represents unstable conditions. The INDOT (dashed) line is vertical since it depends only on the average velocity (v = 6.5 ft/s for revetment riprap). Two sets of curves are given, one assuming R_c / W_c = 8 (moderate bend) and the other assuming R_c / W_c = 4 (sharp bend). Except for shallow flows, which are not of practical interest and for which Equation (2.1) may itself be questionable, the INDOT2013-203-6 specification is generally consistent with Equation (2.1) for moderate bends, with the safety factor, $C_{sf} \geq 1$, for flow depths at the bank toe, $y > 4$ ft. For sharp bends, Figure 2.1 suggests that a riprap class larger than revetment riprap would be more suitable, as

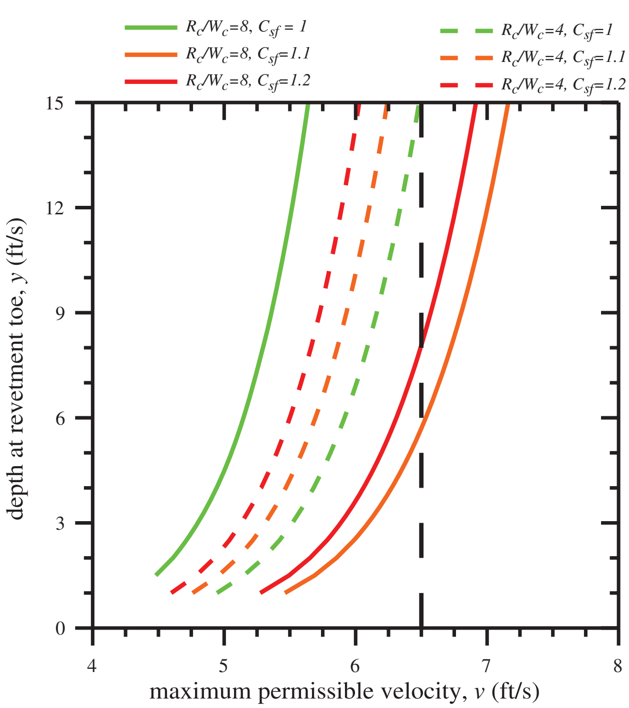

Figure 2.1 Comparison of USACE (1991) riprap design curves (full lines) of different safety factors with the simple INDOT revetment class riprap design specification (dashed lines).

values of C_{sf} are reduced below 1 for $v <$ 6.5 ft/s. The curves in Figure 2.1 assume specific values of various parameters, such as the bank slope (2H:1V). The INDOT riprap design standard is given as an example of what a practical biotechnical design standard might strive for, namely simplicity erring on the side of caution.

3. WORKS OF SYNTHESIS

This chapter discusses works that cover a broad range of topics related to streambank stabilization in general and biotechnical/bioengineering approaches in particular. The main sources are monographs (books) on the science and engineering associated with the general effects of vegetation on slope stability, and documents by various federal and state agencies specifically aimed at applications to streambank stability. References that might be especially useful in developing design guidelines and standards were of special interest.

3.1 Monographs (Books)

3.1.1 A Basic (Geotechnical) Reference

The monograph by Gray and Sotir (1996) provides a geotechnical basis for biotechnical and bioengineering approaches to slope stabilization. Its deals with earthen slopes in general, and discusses the streambank stabilization problem only in a limited manner. The distinction is made between the two erosion mechanisms: surficial (or hydraulic) erosion, typically due to the direct interaction with a flow (either of water or wind) with the slope surface, and mass movement or slope failure, associated with the movement of larger masses of material due to a failure along a critical sliding surface, located beneath the slope surface. This has the important practical implication that a measure used to counter one mechanism may not be effective for the other. Whereas grasses or herbaceous species with near-surface roots may be effective against surficial erosion, shrubs and trees with much deeper root systems would be needed against mass failure. For the problem of streambank erosion, both mechanisms may be important, and so the best solution may be more constrained.

Traditional slope stability analysis, formulated in terms of the intrinsic shear strength of the earthen material, is briefly reviewed. A model of the mainly positive effect of vegetation on slope stability is then examined in detail. Vegetation is viewed as increasing soil shear strength (and hence stability) through root (fiber) reinforcement, which might be parametrized by a root tensile strength and a root area ratio, i.e., the fraction of soil cross-section occupied by roots. For design, values of such parameters need to be known, and for natural species and soils, could be highly variable. Such information is not readily available (Gray and Sotir (1996) do provide some data for a very limited number of species), and design of streambank stabilization at the present time is typically not based on detailed geotechnical analysis of vegetation-enhanced slope stability. In their subsequent discussion of the various bioengineering techniques, no explicit use was made of geotechnical analysis results. The value of the theoretical model lies mainly in a conceptual framework for thinking about the effect of vegetation in terms of a standard geotechnical model.

The more traditional "hard" or structural-mechanical design approaches to slope stabilization are described, including i) retaining structures, ii) porous gravity retaining structures, and iii) revetments (including rock riprap and articulated blocks), but it is remarked that "many of these systems or products lend themselves to integrated or combined use with vegetation". A separate chapter deals at length with combined techniques, such as vegetated riprap, vegetated gabion or rock walls, toe wall with slope face plantings. It discusses in turn, the objectives, effectiveness, materials, and installation for each technique.

The important considerations in the preliminary "design" and implementation of vegetative approaches are discussed. These include site analysis, seeds and planting stock, selection and source of plant materials, site preparation, handling and installation of live cuttings. For example, for site preparation, they emphasize appropriate grading, protecting the slope toe against scour and undermining, interception and diversion of overland flow. During installation, inspection and quality control are required for any successful bioengineering solution. The most comprehensive chapter is devoted to eight common bioengineering techniques (live staking, live fascines, live fascines used in pole drains and with subsurface interceptor drains, brush layering, vegetated geogrids, branch packing, live gully repair, vegetated crib walls, live slope grating, see appendix B for sketches of some of these). Each technique is described, including their application and objectives, the materials involved, and their installation. Some guidance (e.g., their Tables 7.3 and 7.4, which apply to general slopes and not specifically streambanks) is also given regarding the choice of technique according to slope type, location, site, and soil conditions, and relative cost. Case studies are also presented, though only one case of riverbank stabilization is included.

Biotechnical ground cover solutions to counter the narrower problem of surficial erosion are addressed briefly, as traditional revetment techniques such as riprap or articulated concrete blocks were discussed in other chapters. One class of products of special interest for streambank stabilization consists of geosynthetic nets and meshes. These are often two-dimensional-like mats but some have a much thicker more three-dimensional profile. These are known as rolled erosion control mats or products (RECPs), which includes degradable erosion control blankets (ECBs) and a range of more permanent turf-reinforcement mats (TRMs). Narrowly focused on its revetment function, design of commercial products can be based quantitatively on manufacturer-specified permissible design velocities or shear stresses. As discussed later, these products may also be subjected to loads other than flow shear stress (Miller et al., 2012), and so may suffer damage or even fail due to other loads rather than those due to pure surficial erosion.

Two appendices may also be useful. The first lists plant species used in bioengineering applications with qualitative characteristics, such as habitat value, root type, and rooting ability from cuttings. The second provides information regarding the tolerance of various plant species to stresses, such as deposition, flooding, and drought.

3.1.2 Other Monographs

The work edited by Coppin and Richards (1990) was the outcome of a CIRIA (the Construction Industry Research and Information Association of the United Kingdom) research project, and covers much of the same material as Gray and Sotir (1996), though is differently organized with different emphases. It is less geotechnical in its orientation, its discussion of basic aspects of plants and soils is more in-depth, and treats such issues as safe working methods on slopes and contract specifications. Its UK and European perspective may limit its usefulness as far as specific details relevant to the Indiana context are concerned. It devotes a chapter section to the problem of waterways and streambanks, and distinguishes between two regions divided by the normal water level, i) that above which is subject to attack only under high flow conditions, and ii) that below which is subject to more or less continuous attack. It also presents another classification (see their Figure 6.12) according to the type of suitable plants: i) a continuously inundated aquatic plant zone, ii) a marginal zone, suitable for reed-like plants that require very wet ground but may not survive in deep water ($>$ 2 ft) for long periods, iii) a damp zone, subject to seasonal flooding, and appropriate for trees and shrubs (e.g., willows) tolerating wet root zones, and iv) a dry zone that experiences only infrequent larger floods.

A recent compilation of engineering case studies by Goldsmith, Gray, and McCullah (2013) complements Gray and Sotir (1996), and includes a number of streambank stabilization projects. The features of those implemented in the regions closest to Indiana are summarized in Table 3.1, which indicates the range of techniques applied. Most projects are either associated with the University of Michigan in Ann Arbor, Michigan, with whom Gray (one of the compilers) was long affiliated, or were designed by Goldsmith (another of the compilers), and so may represent a narrow design viewpoint. The case study on streambank stabilization in Gray and Sotir (1996) is also found in Goldsmith et al. (2013), but is not included in Table 3.1 as it is located in Texas. In some cases, bank erosion directly threatened valuable assets such as a road or a gas pipeline. The ten projects in Table 3.1 used over ten different techniques, with multiple techniques frequently being applied at each site. In most or all cases,

TABLE 3.1
Case studies located in the Midwest or Northeastern U.S. given in Goldsmith et al. (2013).

Project Location	In-Stream Structures	Hard elements	Plantings	Bioengineering Elements	Other
Fleming Cr., MI	Rock vanes		Live pole		Impinging flow
River Landing, MI		Vegetated riprap	Revegetation	Joint planting, ECB*	Regrading
Nichols Dr., MI	Rock vanes		Revegetation, live stakes, brush layers	VMSE* (rock footing)	Chimney drain
Malletts Cr., MI	Rock vanes, cross vanes	Riprap	Live stakes	ECB, coir logs	Regrading, channel modification
Mill Cr., OH		Stone toe	Live pole, live stakes, live fascines	ECB, VMSE	
Charles R., MA		Stone toe	Live stakes, live fascines	ECB, coir logs	
Connecticut R., MA		Stone toe	Live stakes, brush layer	VMSE	
Cumberland R., TN		Stone toe, gabion mattress	Live pole, live stakes, live fascines, brush layers	ECB	Slope benched and compacted
Manhan R., MA	Bendway weirs, rock vanes			Coir logs, ECB	Regrading
Creek Rd., NY	Bendway weirs, rock vanes	Longitudinal stone toe	Revegetation		Slope drainage, regrading

*ECB and VMSE refers to erosion control blankets and vegetative mechanically stabilized earth (also termed variously as soil lift, reinforced soil, vegetated geogrid).

insufficient quantitative detail is given to provide a technical basis for the choice of measures used. For example, whether a measure was essential to bank stabilization, or was more supplementary was not clear. A case in point is the use of in-stream structures, such as rock vanes and bendway weirs, chosen in 5 of the 10 projects in Table 3.1. The question may be raised whether the bank in each case might have been stabilized without the in-stream structures. The hydraulic conditions under which such structures might be effective or alternatively the effective design parameters (length, height, angle of orientation for design or off-design conditions) are still under debate, so it should not be taken for granted that they performed as intended. On the other hand, live stakes, also used in 5 of 10 cases, were considered to have failed in at least two cases in view of their low survival rates, but the projects were judged an overall success. This suggests that this technique should be considered a supplementary, i.e., to be used in combination with other techniques, rather than a primary measure. Coir logs, here considered as a primary measure, is explicitly reserved in one project for low-velocity (< 5 ft/s) conditions but in the other two projects no such explicit qualification is made. It is also notable that in almost all cases some "hard" elements were included in the design, typically to protect the critical toe region.

3.2 Government Agency Reports

A number of reports dealing with the issue of streambank stabilization have been published by government agencies, both at the federal and at the state level, and are conveniently available on the internet. Unlike the previous more general work on general slopes, those to be reviewed here are specifically focused on streambanks, and hence pay greater attention to the fluvial geomorphology and hydraulics associated with bank erosion. They may also discuss issues beyond the scope of the present work, such as stream restoration and indirect bank erosion countermeasures, such as in-stream structures. There is considerable overlap in these synthesis works, and the review highlights the unique aspects, if any, of each contribution, relevant to biotechnical or bioengineered solutions.

3.2.1 Federal Agencies and Sources

3.2.1.1 U.S. Army Corps of Engineers (USACE). Biedenharn, Elliott, and Watson (1997, to be referred to USACE1997) takes a systems approach to the streambank stabilization problem by placing it within a broader geomorphological context. It introduces basic concepts of fluvial geomorphology and distinguishes between a system-wide and a local instability. The former may require large watershed-scale intervention for long-term success, while a more localized solution may be possibly found for the latter case. Geomorphic assessment are discussed, including tools for the field, important field observations, and analyses of data, such as discharge, that could give insight into channel instabilities. A holistic approach to bank stabilization is presented considering river basin management, relocation of the threatened facility, and non-structural regulatory solutions. It is recommended that the selection of an effective bank stabilization technique be based on its durability, its ability to adjust to scour and subsidence, flow depths, foreshore limitations, channel alignment, and impacts on flowlines and erosion upstream and downstream of the project reach, as well as environmental and economic factors.

Detailed issues involved in designing erosion protection in general are then discussed, such as the upstream and downstream project limits, channel alignment, design discharge, top elevation of protection, bank slope, consequences of failure, toe protection, surface drainage, manufacturers' recommendations, and safety factors. A comment regarding toe protection when vegetative techniques are being applied is especially relevant for the present project:

> "The importance of toe protection for successful bank stabilization using vegetation cannot be overemphasized. Vegetation alone is unlikely to be successful as toe protection unless velocities during design flows are so low that little toe scour is predicted, and climate, inundation conditions, and soils are conducive to a vigorous growth at the toe."

Specific techniques are divided into surface armor (such as stone and other self-adjusting armor, rigid armor, and flexible mattresses) and indirect methods (such as dikes and other flow deflecting methods such as in-stream structures like vanes and bendway weirs). Advantages, disadvantages, typical applications, and design considerations are given for each technique covered. Although all of these techniques may be characterized as "hard," they may still be relevant in the present context, because as was seen in the case studies of Goldsmith et al. (2013), streambank stabilization with bioengineering typically involves some "hard" structural measures, whether a stone toe, or in-stream structures.

A short chapter deals with general aspects of vegetative methods, but a lengthy appendix by Allen and Leech (identical to Allen and Leech, 1997) reviews bioengineering for streambank erosion control in detail. In the short chapter, one comment may be highlighted:

> "The most serious shortcoming is that even well executed vegetative protection cannot be planned and installed with the same degree of confidence, or with as high a safety factor, as structural protection."

This is related to the present lack of reliable quantitative prediction methods and the complexities of dealing with a natural system with substantial variation in characteristics. Similar to Coppin and Richards (1990), the appendix identifies four different zones, and recommends a zonal design approach. As illustrated in Figure 3.1, the toe zone lies between the bed and the average normal stage and is inundated at least six months of the year, the splash zone lies between the normal high-water level and the average normal stage, the bank zone lies above the normal high-water level and is inundated for at least a 60-day duration once every two or three years, and the terrace zone lies inland from the bank zone. The zones are not precisely defined due to daily and seasonal variations in water level, and may depend on bank geometry. Whether such zone definitions are appropriate for Indiana (and specifically INDOT practice) remains to be determined. For the toe zone, hard armor is appropriate, but coir logs might be suitable under low-velocity conditions. On the other hand, for the splash zone, herbaceous emergent aquatic plants such as reeds and sedges are suitable, while for the bank zone, these may be mixed with flood-tolerant woody plants such as willows and dogwoods. The terrace zone is less critical with regards to bank protection, but may play an important role in surface drainage and reducing the shear load by reducing the contribution due to water weight through the effect of plant evapotranspiration. Because this region is expected to be inundated far less frequently, the required flood tolerance of the vegetation is less stringent and a wider range of species should be available for consideration.

Consistent with the recommended zonal design approach, various techniques used for each zone were discussed, with examples from actual installation. For the toe zone, examples with rock riprap, gabions, LUNKERS, bank crib with cover log, log and rootwad revetment, coir logs, and in-stream deflector structures, were presented. For the splash zone, examples with coir logs, brush mattresses, live fascines (or wattles), live stakes, brush layering, vegetated geogrids were described. Similar techniques can also be applied to the bank zone, possibly with different species, especially under high-energy conditions. This points to the gray area in the distinction between the different zones. For low-energy applications, sodding combined with a rolled erosion control product (RECP) or turf reinforcement mat (TRM) may be sufficient. In the terrace zone, special techniques are generally not necessary, but the choice of appropriate vegetation may require thought, and some guidance is given.

Two important aspects of the appendix are the discussion of partial or total failures, the diagnoses of the causes, and the characterization of techniques in terms of allowable velocities. A coir-log treatment failed in a case in Colorado due to scour at the toe, and in a case in Manhattan (after the two-year formal monitoring period) because the logs had been flanked at the upper end, leading to the unraveling of sections of the project. Protection of the toe region and proper end treatments to avoid flanking were stressed. Actually measured velocities at various sites with bioengineering treatments were reported, ranging from 10 ft/s for a log revetment case to 3.1 ft/s for a case with dormant willow post with rock toe. A U.S. Army Corps (1991) manual is cited as indicating that

> "herbaceous or woody vegetation may be used to protect channel side slope areas (depending on the frequency of inundation, velocity, and geotechnical constraints to infrequent flooding) and other bank areas where velocities are not to exceed 6 to 8 feet per second."

Another source, Hoag (1993) is cited as suggesting maximum permissible velocities for various species types, namely 3 ft/s for herbaceous species, 3-5 ft/s for woody and herbaceous mixed plantings, 5-8 ft/s for

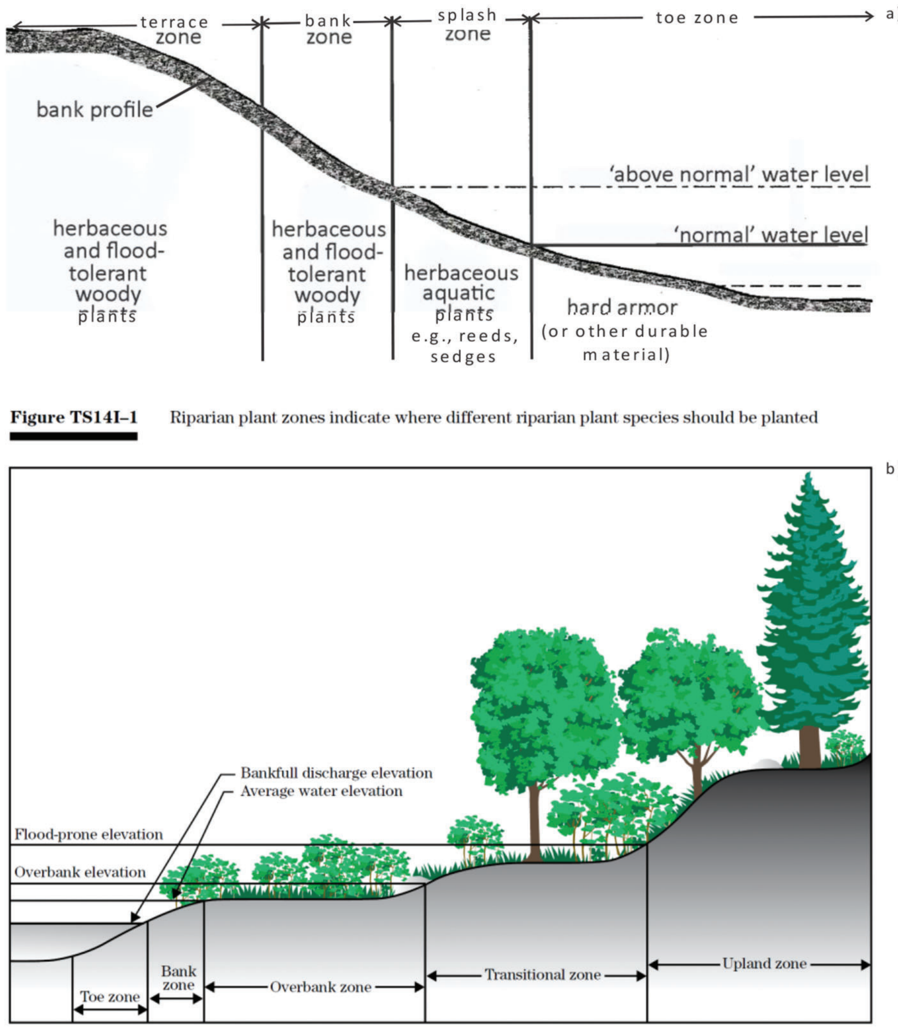

Figure 3.1 Definition of various zones according to (a) USACE1997, (b) NEH-654.

woody species alone; for velocities in excess of 8 ft/s, the more special bioengineering/biotechnical measures would be recommended.

Biedenharn et al. (1997) devote a chapter to the topic of grade control and design considerations for structures intended for such a purpose, noting that "implementation of bank stabilization measures without proper consideration of the stability of the bed can result in costly maintenance problems and failure…." Such structures are beyond the scope of this review, but may be relevant to bank stabilization. This returns to the issue of the underlying causes of bank erosion, whether system-wide or localized. Where the causes are system-wide, grade control may need to be considered.

Fischenich and Allen (2000) cover many of the same topics as Biedenharn et al. (1997), though it is more structured and accessible, with a more pronounced stream restoration/ecological orientation. Basic aspects of fluvial geomorphology, hydraulics and sediment transport, and geotechnical slope stability are compressed into a brief chapter, while stream ecology and its characterization receive more attention in a separate chapter. Steps in analyzing bank erosion are combined in a single chapter. Much of the material specifically on soil bioengineering is reproduced from Allen and Leech (1997). A helpful feature of the presentation is the frequent distillation of the main points into short slide-like form. Two examples summarizing criteria for the selection of stabilizing approaches are shown in Figure 3.2 and Figure 3.3, according to erosion or bank instability mechanisms. A chapter on design for bank stabilization discusses both "hard" elements, such as stone armor and in-stream deflector structures, and "soft" vegetative elements, such as coir logs, live stakes, fascines, and brush layering.

3.2.1.2 Natural Resources Conservation Service (NRCS, USDA). The main documents, the result of a collaborative effort by several federal agencies, are NEH-653 (Federal Interagency Stream Restoration Working Group, 1998/2001) and NEH-654 (USDA National Resources Conservation Service, 2007), that address in a rather comprehensive manner the technical issues surrounding stream corridor restoration. As with the USACE reports dealt with above, they cover the topics

Table 6.5 Selection of Appropriate Structural Solutions for Erosion Processes

Failure Type	*Structural Considerations*	*Options for Structural Protection*
Parallel flow (fluvial entrainment)	Structures may either increase erosion resistance by armoring the bank with a non-erodible layer or reduce the intensity of attack by deflecting currents away from the bank. Flow attack is usually concentrated on the lower half of the bank	Revetments are used to provide surface armoring. Deflectors may be formed by dikes or groins. Soft systems use vegetation, hybrid systems use geogrids, geotextiles and cellular blocks with vegetation. Heavy protection uses riprap, armorstone and gabions at the toe, often with lighter protection on the upper bank.
Impinging flow (fluvial entrainment)	Impinging flow generates very high turbulence, secondary currents and elevated local velocities. Instantaneous shear stresses and near bank scour depths are large, but unpredictable.	Uncertainties associated with the intensity of attack by impinging prescribe the use of heavy protection. Use of soft or hybrid protection is inadvisable unless the channel is realigned to eliminate flow impingement. Realignment will have other benefits.
Boatwash	Chronic or severe boatwash erosion may persist at vulnerable places even in well-managed waterways. These locations may require structural protection.	Hard protection using a vertical wall protects the bank but may reflect wave energy against unprotected banks. Porous revetments and emergent vegetation are excellent energy dissipators. In most cases there is scope for use of wet berms and soft engineering.
Wind-waves	Wind-waves have a wider wavelength than boat waves but are rarely a spectrum of heights and serious problem on British inland waterways.	Structural protection should be designed to absorb and dissipate wave energy without significant erosion and without reflecting it. A wet berm with emergent vegetation is recommended.
Rills and gullies (surface erosion)	Rills and gullies pose threats to the integrity of the bank surface including any surface protection.	Surface drainage may be controlled to prevent erosion using buffers, pipes, drop structures and lined channels.
Piping (seepage erosion)	Piping erosion is a common cause of failure of structural bank protection. A notch produced by piping is easily misinterpreted as due to boatwash.	A structural solution must allow free subsurface drainage while preventing loss of soil particles. This is best achieved by use of a granular, geotextile or vegetative filter.

Figure 3.2 Appropriate techniques for different erosion processes according to Fischenich and Allen (2000).

of fluvial geomorphology, hydraulics and hydrology, and sediment transport. In the present context of bank stabilization, only the chapter (Chap. 14 in NEH-654) on treatment technique design, and its technical supplement will be discussed. The chapter itself only provides a brief introduction to the technical issues, reserving the details required for design for the lengthy technical supplement. The latter start with characterizing soil properties, particularly those related to the geotechnical bank stability, proceed to scour calculations and stone armor sizing, the use of geosynthetics, soil anchors, and pile foundations, grade control design, and in-stream flow deflecting structures. Worked examples are frequently given, but unfortunately not in the section devoted to streambank soil bioengineering, no doubt due to the lack of quantitative results. Similar to the USACE approach, various zones along the bank are identified (Figure 3.1b), but the zones are defined differently, and perhaps more clearly from a practical viewpoint. Like Fischenich and Allen (2000), the section makes effective use of tables to present important points. For example, Figure 3.4 shows a table illustrating the relationship between the tolerance for bank movement and the appropriate bank stabilization technique. For all but one of the project conditions, Figure 3.4 recommends some hard (inert) elements in the stabilization solution. The table in Figure 3.5 lists questions that should be answered to obtain an effective local bioengineering-oriented solution. Most of the questions focus on diagnosing the main cause or mechanism of bank erosion in order to select the appropriate type of countermeasure(s). This is similar in function to the tables of Fischenich and Allen (2000; see Figures 3.2 and 3.3).

The section provides a compilation of literature values for permissible levels of shear stress and velocity for various treatments (Figure 3.6). It distinguishes between initial and fully established states, as some time is required for vegetation growth as well as the qualification for each technique. The empirical support for the application of these values to general conditions is a concern as they presumably were obtained through field measurements for specific conditions. In contrast, the application of rock riprap is supported by, not only numerous careful small-scale and near-field-scale laboratory measurements obtained under controlled conditions, but also by sound theory.

NEH-654 also compiles in a separate volume a number of case studies (see Table 3.2 for a sample) with a level of detail frequently exceeding that in Goldsmith et al. (2013), including cost details. The case studies were intended to illustrate stream restoration techniques in general, and so emphasized in-stream structures. The influence of Rosgen's approach or at least its terminology is evident – an entire chapter in NEH-654 is devoted to the Rosgen approach. Bendway weirs, J-hooks, cross-vanes, and rock vanes, appear frequently in the case studies, but rock riprap remained prominent. A frank discussion of (partial) failures and construction

Table 6.6 Selection of Appropriate Structural Solutions for Failure Mechanisms

Failure Type:	*Structural Considerations*	*Options For Structural Protection*
Shallow slide	Shallow slides occur because the bank angle exceeds the angle of repose. Surface armor installed to prevent erosion.	The best solution is to regrade the bank to an angle lower than the slides can disrupt angle of repose and protect the toe from further erosion. If space is limited a vertical wall can be used but deep toe scour will occur.
Rotational slip	This type of deep-seated failure threatens protection structures and surface treatments. It is not amenable to shallow solutions.	Major regrading coupled with toe protection and improved drainage will be necessary to achieve geotechnical stability. If limited space precludes regrading, a retaining wall must be constructed and protected against deep toe scour and positive pore water pressures
Slab-type failure	Slab-failure planes pass below the rooting layer and shallow stabilization measures or positive pore pressures may be critical.	Regrading to a lower bank angle will eliminate tension cracks. Tension cracks protection is installed to prevent further over-steepening. If limited space precludes this, a retaining wall must be constructed and protected against deep toe scour and positive pore water pressures.
Cantilever failure	Cantilevers are produced by erosion of a weak layer in the bank.	Measures that may be applied include armoring of the bank to prevent undermining of the weak layer, installation of a filter to prevent piping, and re-vegetation to increase soil tensile strength.
Soil fall	Soil fall occurs on steep, undercut banks of low cohesion. It adds to bank retreat due to flow, wave or piping erosion.	Soil fall may be eliminated by regrading the bank to a lower angle and protecting the surface with vegetation, a geotextile or a riprap. If lack of space precludes this, the steep bank may be stabilized by a vertical wall with suitable allowance for deep toe scour.
Dry granular flow	Dry granular flow is a surface failure that occurs on undercut banks, which have no effective cohesion.	Dry granular flow is dealt with by soil reinforcement using a geogrid, geotextile or vegetation coupled with toe protection to prevent further undercutting and active management to prevent trampling or mechanical damage to the upper bank.
Wet earth flow	Wet earth flow and liquefaction may pose a threat to bank protection and structural stabilization schemes.	Improvement of subsurface drainage is the key to prevention of wet earth flows. Steps involved include installation of pipes or drains to remove water and filters to retain soil particles.

Figure 3.3 Appropriate techniques for different bank instability mechanisms according to Fischenich and Allen (2000).

difficulties is also often given. For example, some rootwads installed in the Rose River project disappeared, while complete sections of the rock toe in the Red River project were washed away. Fascines and entire rootwads that were supposed to be protected by the rock toe were pulled from the bank. The precise causes of the failures (or indeed the successes) often are difficult to determine.

Table TS14I–2 Relationships between type of streambank stabilization project and type of site

Site description	Tolerance for movement	Type of project
Eroding streambank threatening a home or municipal sewage treatment plant	None—streambank must be made static	Relies primarily on hard or inert structures, but may include a vegetative component for adjunctive support, environmental, and aesthetic benefits
Eroding streambank adjacent to a secondary road	Slight—road must be protected for moderate storms, but some movement is allowed	Rely on streambank soil bioengineering measures that incorporate hard or inert components
Eroding streambank threatening hiking trails in a park	Moderate—a natural system is desired, but movement should be slowed	May rely entirely on vegetative protection, but more likely on streambank soil bioengineering measures that incorporate some hard or inert components
Eroding streambank in rangeland	Relatively high—but erosion should be reduced	Rely on fencing, plantings, or streambank soil bioengineering measures—perhaps ones that incorporate some hard or inert components in areas that have suffered significant damage
Erosion on a wild and scenic stream system	High—but erosion should be reduced	Do nothing or rely on plantings and vegetative streambank soil bioengineering measures

Figure 3.4 Table taken from NEH-654 indicating the range of choices of streambank stabilization techniques depending on site and project implications.

Table TS14I–3 Questions to ask before starting a streambank soil bioengineering project

Question	Issue
What is the land use conversion trend for the drainage area?	Past and future land use conversion significantly alters hydrology. Streambank protection measures of any kind may not be successful because of high stresses created by changing hydrologic conditions. The watershed, as well as the site, should be investigated. Designs should consider the effects of potentially new or altered flow, as well as sediment conditions in the watershed
Is a management plan in place and being maintained?	Locally, determine the land use in the immediate area of the site and whether the landowner has a working management plan in place. In some cases, changing the management plan (livestock grazing plan, proper farming techniques, buffer width, conservation logging techniques) may be all that is needed to allow the stream to recover on its own. This is the least expensive alternative and may have less overall impact on the stream. However, if the impact is from upstream development, this approach may have a negative impact because the erosion will continue
Is the purpose of the streambank soil bioengineering project to protect critical structures such as a home, business, or manufacturing site?	In an emergency situation, select soil bioengineering treatments that incorporate sound engineering design components into the overall design. In this case, hard or inert structures (rock, geogrid) are necessary. The use of a soil bioengineering solution can significantly improve surface protection, internal reinforcement strength, aesthetics, habitat, and water quality benefits (table TS14I–2)
Are both sides of channel unstable?	This condition may indicate that the channel is incised or that a large-scale adjustment is occurring in the stream channel, possibly from a systemwide source. These conditions can generate flash flooding, excessive velocity, and shear stress, making it difficult to establish any solution until the correct cross-sectional area and planform has been established. For more information, refer to the channel evolution model (Simon 1989) and NEH654.03
Is the channel grade stable?	If the channel bed is downcutting, any bank treatment may be ineffective without some measure taken to stabilize the grade. Headcuts, overfalls, and nickpoints are indicators of unstable channel grades (NEH654 TS14G)
Is local scour on the bends an issue?	Any bank treatment may be ineffective unless toe and bed protection can be provided below the anticipated scour depth. Depending on the event (1-, 2-, 5-, 10-year event), a general rule of thumb is to add 2 to 5 feet to the deepest depth of water at the eroding outside meander bends. This will be a rough indication of potential scour depth. Specialists need to be involved in the assessment, design, and installation (NEH654 TS14B)
What is the bank height?	When the bank is high, slope stability factors typically add complexity to the design and need to be analyzed, designed, and installed by specialists such as geotechnical engineers. The bank height generally becomes an issue above 6 feet
What is the velocity of the stream at design flows?	The ability of soil bioengineering measures to protect a streambank in part depends on the force that the water exerts on the boundary during the design event. When velocity (or shear) forces exceed a threshold for the type of treatment being considered, other measures or materials may be required in conjunction with the treatment to ensure stability. More details on this important issue are presented later in this document
What is the depth of the water?	Most woody plant species do not grow in standing water. The level and durations of frequent flooding (every 1 to 2 years) will help determine the elevation needed for toe protection and vegetative components

Figure 3.5 Questions that should be asked in planning a soil bioengineering approach to streambank stabilization and the implications for the responses (taken from NEH-654). (*Figure continued on next page*.)

A chapter (Chapter 16) on streambank and shoreline stabilization (to which Sotir is acknowledged as a major contributor) in another NRCS document, the Field Engineering Handbook or NEH-650 (National Resources Convention Service, 1996) should also be mentioned. The presentation is much concise and more easily accessible than the more expansive NEH-654. The common soil engineering techniques for streambank stabilization, e.g., live stakes, fascines, brush mattress, vegetated geogrid (or soil lift), are covered, each with details on applications and effectiveness, construction guide lines, and installation. Other "hard" structural techniques, including riprap and rock gabions and in-stream structures such as stream barbs (a variant of the bendway weir) and jetties, are also dealt with in the same manner. A strength of the NEH-650 chapter compared to NEH-654 is the more extensive use of detailed sketches, which are more helpful than photographs. These sketches have appeared either in its original or a modified form in other documents, such as state DOT design manuals. Example sketches from NEH-650 of various measures are given in Appendix B. An appendix to Chapter 16 of NEH_650 also gives a comprehensive compilation of the soil bioengineering characteristics of plant species.

McCullah and Gray (2005, also to be referred to as NCHRP-544) resulted from NCHRP Project 24-19. It identified a large number (44) of environmentally sensitive channel- and bank-protection techniques of interest. The terse literature review is useful in its extensiveness and wide variety of sources, especially those on the internet. In the report itself, the description of the techniques is also terse, consisting of thumbnail sketches in an appendix. A more detailed treatment is given in the accompanying CD-ROM, which also discusses a broad range of related topics, such as harvesting/handling of woody cuttings, geotextiles and root penetration, and optimal compaction and other strategies, as well as case studies. Each technique is ranked in a three-level rating system (Figure 3.7). Level I techniques being "well-established, well-documented (good performance and monitoring data available), reliable design criteria based on lab/field studies". Level II techniques are intermediate, associated with "greater uncertainty (used frequently but do not have the level of detail, quality of information, and reliability that characterize Level I); little or inadequate monitoring", and Level III techniques are emerging, but do not have "the track record and level of information

Table TS14I–3 Questions to ask before starting a streambank soil bioengineering project—Continued

Question	Issue
Is a noncohesive soil layer present in the slope?	Noncohesive soil layers may require special design measures. The lower in the slope the weak layer occurs, the more comprehensive the design will need to be to stabilize the bank (NEH654 TS14A)
Is bank instability due to piping or ground water sapping?	Soil bioengineering measures can assist in controlling piping and sapping. An intensive investigation into the reason for the streambank erosion is important to ensure that the actual cause is treated, instead of a symptom (NEH654 TS14A)
Will mature vegetation adversely affect the stream hydraulics?	Changes in flood elevations due to flow resistance on vegetative banks may not be allowable in some settings. This is especially true in urban areas where the stream channel is narrow and flood plains are limited
Is there a stable bank to tie into at each end of the treatment area?	Any streambank protection measure is susceptible to flanking if it is not properly tied into stable points. It is important that both the upstream and downstream ends of the treatment are well keyed-in and protected
What site conditions may inhibit plant growth?	Soil tests are recommended to determine the presence of plant establishment opportunities. Soil texture, restrictive layers, and limiting factors (pH, salts, calcic soils, alkalinity) should be evaluated. The amount and seasonal availability of water, regional extremes in temperature, wind (affects growth and survival, desiccation), and microclimate (cold pockets, solar radiation pockets, wind turbulence, and aspect) are also significant factors to be considered. In many situations, these issues may be overcome by installing native plant materials that grow in or near the area
Is there anything in the stream water or surface runoff that will inhibit plant growth?	Adverse water quality can inhibit plant growth. Check any stream monitoring records for possible problems, and investigate the watershed for sources of potential contaminants. In some cases, the use of plant materials will improve water quality
Will the site be shaded during the growing season?	If the site will be shaded, choose plant species that tolerate and thrive in shade conditions
Is there significant surface runoff from above the streambank?	Identify sources of surface runoff during the site inventory. In some cases, a diversion or waterway may need to be installed to control runoff and erosion. In other cases, vegetated soil bioengineering filter strips or constructed wetland systems can be designed to intercept and treat the water before it enters the stream
Are beaver, muskrats, moose, elk, or deer present in the area?	Browsing animals can damage the vegetation used in soil bioengineering treatments. If these animals are in the area, special precautions may be required to ensure the installations are able to establish. This is especially important during the first growing season. If established during the first year, they will continue to grow and survive. Typically, temporary plant protection measures are all that is needed
Are adequate plant materials available from the natural surrounding area or from local nurseries?	Soil bioengineering techniques require large quantities of plant materials. Locating an adequate nursery or harvesting source of plant material is essential to the success of the project. This source should be as close as possible to the site to ensure that adapted plants are used. Plants can be harvested at higher elevations and brought down to lower elevations, but do not take materials from low elevations and move them to higher elevations (Hoag 1997)
Are invasive species present in the area?	Aggressive invasive species may out-compete the soil bioengineering species and make it difficult for them to get established. It is necessary to eradicate the invasive species prior to the soil bioengineering installation

Figure 3.5 (Continued).

characterizing Level I or II". As with any such classification scheme individual ratings for certain techniques may be disputed.

In view of the number of available techniques, one of the main contributions of NCHRP-544 is the attempt to develop guidance for selecting suitable streambank bioengineering technique for given project conditions. An "expert"-systems computer program, GREENBANK, was developed, in which the user responds to a questionnaire regarding the project and site (so in this respect similar to the NEH-654 list of questions, Figure 3.5), and recommendations about suitable techniques are made based on the responses. The questionnaire is lengthy and cumbersome to use, in part reflecting the complexities involved in technique selection and the attempt to provide rather comprehensive guidance. Based on the input regarding environmental objectives and bank movement consequences, erosion processes, fluvial geomorphology, geotechnical and hydraulic data, the 44 techniques are screened using a matrix approach and given a letter grade from A to F (A being the most appropriate). As emphasized by the authors, the software "is intended not to provide detailed design criteria, but rather to offer a list of techniques that match (1) dominant erosion processes and (2) environmental resources of special concern at the site…." Due to the large uncertainties in the inputs, together with the controversies about individual ranking criteria, it is difficult to assess how reliable or comprehensive are the recommendations.

3.2.1.3 National Cooperative Highway Program (NCHRP) and Federal Highway Administration (FHWA). The main focus of Lagasse et al. (2006, also to be referred to as NCHRP-568) is traditional riprap design, but it does include a subchapter on hybrid approaches, specifically riprap with various types of vegetation, such as willow bundles, poles, brush layers, relying much on NCHRP-544. Other FHWA publications deal in part with issues that may be relevant to streambank bioengineering techniques. Kilgore and Cotton (2005, HEC-15) covers the hydraulics of channels with flexible linings, including natural vegetation as well as rolled erosion control products (RECPs) and turf reinforcement mats (TRMs). Bridge scour and stream instability countermeasures are the main topics in the two-volume Lagasse et al. (2009, also known as HEC-23), but includes a brief chapter on biotechnical techniques, relying heavily on NCHRP-544 and Biedenharn et al. (1997).

Table TS14I–4 Compiled permissible shear stress levels for streambank soil bioengineering practices

Practice	Permissible shear stress (lb/ft²)*	Permissible velocity (ft/s)*
Live poles (Depends on the length of the poles and nature of the soil)	Initial: 0.5 to 2 Established: 2 to 5+	Initial: 1 to 2.5 Established: 3 to 10
Live poles in woven coir TRM (Depends on installation and anchoring of coir)	Initial: 2 to 2.5 Established: 3 to 5+	Initial: 3 to 5 Established: 3 to 10
Live poles in riprap (joint planting) (Depends on riprap stability)	Initial: 3+ Established: 6 to 8+	Initial: 5 to 10+ Established: 12+
Live brush sills with rock (Depends on riprap stability)	Initial: 3+ Established: 6+	Initial: 5 to 10+ Established: 12+
Brush mattress (Depends on soil conditions and anchoring)	Initial: 0.4 to 4.2 Established: 2.8 to 8+	Initial: 3 to 4 Established: 10+
Live fascine (Very dependent on anchoring)	Initial: 1.2 to 3.1 Established: 1.4 to 3+	Initial: 5 to 8 Established: 8 to 10+
Brush layer/branch packing (Depends on soil conditions)	Initial: 0.2 to 1 Established: 2.9 to 6+	Initial: 2 to 4 Established: 10+
Live cribwall (Depends on nature of the fill (rock or earth), compaction and anchoring)	Initial: 2 to 4+ Established: 5 to 6+	Initial: 3 to 6 Established: 10 to 12
Vegetated reinforced soil slopes (VRSS) (Depends on soil conditions and anchoring)	Initial: 3 to 5 Established: 7+	Initial: 4 to 9 Established: 10+
Grass turf—bermudagrass, excellent stand (Depends on vegetation type and condition)	Established: 3.2	Established: 3 to 8
Live brush wattle fence (Depends on soil conditions and depth of stakes)	Initial: 0.2 to 2 Established: 1.0 to 5+	Initial: 1 to 2.5 Established: 3 to 10
Vertical bundles (Depends on bank conditions, anchoring, and vegetation)	Initial: 1.2 to 3 Established: 1.4 to 3+	Initial: 5 to 8 Established: 6 to 10+

* (USDA NRCS 1996b; Hoag and Fripp 2002; Fischenich 2001; Gerstgrasser 1999; Nunnally and Sotir 1997; Gray and Sotir 1996; Schiechtl and Stern 1994; USACE 1997; Florineth 1982; Schoklitsch 1937)

Figure 3.6 Permissible velocities compiled in NEH-654 for various bioengineering treatments.

Volume 2 may be more useful in its treatment of the more traditional hard or structural techniques, with design guidance for bendway weirs and articulated concrete blocks.

3.2.1.4 Other Federal Agencies: U.S. Forest Service and FEMA. Eubanks and Meadows (2003) produced an on-line guide to soil bioengineering for streambank and lakeshore stabilization for the U.S. Forest Service. The well-illustrated general discussion tends to be non-technical, and seems aimed at an audience broader than the engineering community. It is still careful to emphasize the importance of protecting the bank toe and keying into the bank to prevent flanking of the treatment. The specific chapter on soil bioengineering techniques borrows liberally from Chapter 16 of NEH-650, and is almost identical in its organization in terms of discussing applications and effectiveness and construction details. Figure 3.8 shows their table of biotechnical measures and their typical applications. Some subtle differences in sketches and guidelines are found, but the basis for them is not clear.

Another on-line document produced for FEMA presents a series of non-technical reports of projects carried out in Washington where alternative streambank stabilization techniques, many using large woody debris as a major element, were applied. With few or no engineering details, the document does not provide guidance with regards to designing or implementing the techniques. Further, it is debatable whether the techniques popular in the Pacific Northwest is optimal for the Midwest. Soil bioengineering techniques commonly used in Indiana, such as soil lifts, coir logs, and fascines are not at all discussed.

3.2.2 State Agencies and Sources

3.2.2.1 Departments of Transportation (DOTs). For this review, it was of interest to determine to what extent soil bioengineering (or other alternative streambank

TABLE 3.2
Case studies in Midwestern and Northeastern states from NEH-654 in which soil bioengineering features were particularly emphasized.

Project Location	In-Stream Structures	Hard elements	Plantings	Bio-eng'g Elements	Other
Silver Cr., NY		Stone facing		VMSE	
Rose R., VA	Rock weirs	Rock riprap		Rootwads	Channel modification, regrading
Red R., ND		Rock riprap	Willow plant, live fascines	Rootwads	Regrading, surface drainage issues
Merrimack R., NH		Green gabions		Envirologs, reno mattress	

TABLE 1 Final list of technique guidelines

Category	Technique	Level
River Training		
Transverse Structures	Spur dikes	I
	Vanes	I
	Bendway weirs	I
	Large woody debris structures	II
	Stone weirs	II
Longitudinal Structures	Longitudinal stone toe	I
	Longitudinal stone toe with spurs	I
	Coconut fiber rolls	II
	Vegetated gabion basket	I
	Live cribwalls	II
	Vegetated mechanically stabilized earth	I
	Live siltation	II
	Live brushlayering	I
Channel Planform Measures	Vegetated floodways	II
	Meander restoration	II
Bank Armor and Protection		
Groundcovers	Vegetation alone	II
	Live staking	I
	Willow posts and poles	II
	Live fascines	I
	Turf reinforcement mats	II
	Erosion control blankets	II
	Geocellular containment systems	II
Revetments	Rootwad revetments	II
	Live brush mattress	I
	Vegetated articulated concrete blocks	I
	Vegetated riprap	I
	Soil and grass covered riprap	II
	Vegetated gabion mattress	II
	Cobble or gravel armors	II
	Trench fill revetment	II
Riparian and Stream Opportunities		
Top-of-Bank Treatments	Live gully repair	III
In-Stream Habitat Improvements	Vanes with J-hooks	I
	Cross vanes	I
	Boulder clusters	II
	Newbury rock riffles	II
Slope Stabilization		
Drainage Measures	Diversion dike	II
	Slope drain	II
	Live pole drain	III
	Chimney drain	II
	Trench drain	II
	Drop inlet	II
	Fascines with subsurface drain	II
Bank Regrading	Slope Flattening	II
In-Situ Reinforcement	Stone-fill trenches	II

Figure 3.7 Level classification of various bank stabilization measures according to McCullah and Gray (2005, NCHRP-544).

stabilization) techniques have already been adopted in DOT design manuals, particularly in nearby states with similar geographical and climatic features. The most in-depth treatment was produced for the Tennessee DOT (or TDOT). In their 2012 drainage manual (TDOT, 2012, to be referred to as TDOT2012), a chapter, Chapter 11, gives extensive coverage of natural stream design, with stream relocation and mitigation projects primarily in mind. It also provides a detailed account of practices frequently encountered in bank stabilization. Ten techniques: i) coir logs, ii) vegetated riprap, iii) willow cuttings and posts, iv) live fascines, v) live siltation, vi) longitudinal stone toe, vii) vegetated gabions, viii) vegetated mechanical stabilized earth (VSME, elsewhere termed vegetated geogrid or soil lifts), ix) articulated concrete blocks, and x) brush mattresses, are described systematically, each with sections on definition and purpose, appropriate applications, limitations, planning and design criteria, and an example application (with computations where appropriate). In-stream structures such as boulder clusters, rock vanes, and spur dikes are also covered in the same manner. A series of tables in the appendix also give guidance on techniques according to the main aim of the project. An example, shown in Figure 3.9, for low-gradient alluvial streams with non-cohesive banks, suggests that for purposes of preventing bank erosion on a permanent basis, the only appropriate soft armoring measures are willow posts, VMSEs, and brush mattresses.

Applications	Branch Packing	Brush Layering	Brush Mattress	Coconut Fiber Log	Erosion Control Fabric	Hay Bale Breakwater	Joint Planting	Jute-mat Log	Live Cribwall	Live Fascine	Live Post	Liv	Live Stake	Log Breakwater	Plant Mat	Plant Roll	Root Wad	Rooted Stock	Snow Fence	Terraced Crib	Tree and Log Revetment	Trench Pack	Vegetated Geogrid
Aides natural regeneration colonization	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Appropriate above and below OHW/bankfull				x				x			x					x	x				x		
Branches add tensile strength to the bank	x	x									x	x	x										x
Deflects strong or high flows when placed close together											x						x						
Facilitates drainage on wet sites, dries excessively wet sites			x							x						x	x						
Filter barrier to prevent erosion and scouring of the bank	x	x	x	x	x	x		x		x			x			x	x		x	x		x	x
Flexible, can be molded to existing contours				x	x			x								x	x						x
Good on lakes where water levels fluctuate						x					x			x					x				
Helps establish sods and grasses					x	x									x	x	x		x				
Immediate protective cover for the bank			x		x				x						x					x			x
Instant habitat improvement														x	x				x				
Little site disturbance	x			x	x	x	x	x		x					x			x					
Maintains a natural bank appearance	x	x	x	x	x			x		x	x	x	x	x	x	x		x	x		x	x	
Manufactured in the field	x	x	x			x	x	x	x	x	x	x	x	x		x				x	x	x	x
Minimum site disturbance		x		x	x	x	x						x	x	x	x		x	x				
Maximum site disturbance during construction		x							x								x						x
Rapid reestablishment of riparian vegetation	x	x	x				x	x	x	x	x	x	x		x	x		x				x	x
Protects banks from shallow slides	x			x			x	x	x	x	x		x							x			
Reduces a long beach wash into shorter segments										x		x				x	x	x				x	
Reduces slope length	x	x		x				x		x	x		x			x				x			x
Reduces surface erosion		x		x				x		x					x								x
Reduces toe erosion			x	x		x		x	x	x			x		x	x	x	x		x	x	x	x
Reduces wind and water velocities hitting bank						x					x	x		x			x		x			x	
Retains moisture					x	x		x							x	x							
Roots stabilize banks	x	x	x				x		x	x	x	x	x		x	x		x				x	x
Survives fluctuating water levels											x												
Traps sediment	x	x	x	x	x	x	x	x	x	x		x			x	x	x	x	x		x	x	x
Useful where spaces is limited			x	x				x	x	x	x	x	x			x	x	x			x	x	x
Lakes and shorelines	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Figure 3.8 Table of appropriate techniques for different applications compiled by Eubanks and Meadows (2003).

Other chapters in the manual, particularly that on Erosion Prevention and Sediment Control which covers erosion control and turf reinforcement mats, may also be relevant in the present context. In terms of detail, these sections in the TDOT Drainage manual offer a good starting point for development of INDOT design standards.

By comparison, the design manuals of other nearby states offer little or no guidance regarding biotechnical approaches to streambank stabilization. The Illinois DOT Drainage Manual (Illinois DOT, 2011) devotes a single page to biotechnical scour countermeasures simply referring to the FHWA HEC-11 (and including a sketch of vegetated riprap/joint planting from that reference). Examination of the online Drainage or Soil Erosion and Sediment Control Manuals of Michigan, Ohio, Pennsylvania, Kentucky did not find any specific discussion of biotechnical solutions (some established techniques such as erosion control or turf reinforcement mats in erosion control or articulated concrete mats were discussed).

3.2.2.2 Other State Departments. Although the DOTs of nearby states may not have formally included biotechnical techniques in their design manuals, other state (and/or county or municipality) agencies have publications describing and advocating the use of such techniques. Publications by the Iowa Department of Natural Resources (2006) and the Pennsylvania DEP (2012) may be noted. The former is devoted almost entirely to biotechnical approaches, while the latter has only a section of a chapter covering a more limited number of techniques. Both rely heavily on NEH-650, and so will not be discussed further.

The Washington State Aquatic Habitat Guidelines Program (2002) published its Washington 2003 Integrated Streambank Protection Guidelines (referred to as WISPG 2003), which was jointly funded by the Washington Departments of Fish and Wildlife, Ecology, and Transportation, and it was endorsed by the U.S. Army Corps of Engineers District. Although it deals with a Pacific Northwest geography quite distinct from that of Indiana, it merits mention because its scope is quite comprehensive (e.g., it considers flow redirection, structural, as well as biotechnical techniques), and the material is presented differently from that found in other standard sources such as NEH-650. It groups similar techniques together, e.g., it considers woody plantings together, including live stakes, live fascines, joint plantings, etc. Thus, in addition to woody plantings, it covers herbaceous plantings, soil reinforcements (e.g., soil lifts), coir logs, and bank reshaping (basically regrading). A description is given for each technique, followed by discussion of its appropriate application, its intended effects, the relevant

Description of Stream:	Type	Gradient	Bed Material	Banks
	Alluvial	Low	Sand / Silt	Non-cohesive

Stream Mitigation Measure	APPLICATION									
	Temporary cover to establish permanent vegetation	Create / encourage pool and riffle structure	Introduce other flow complexity	Velocity Control	Prevent bank erosion	Restore eroded banks	Prevent mass wasting of banks	Capture sediment	Encourage aquatic habitat	Enhance riparian corridor
Boulder Clusters	0	1	3	0	0	0	0	0	3	0
Log Deflectors and Vanes	0	0	0	0	0	0	0	0	0	0
Log Drop	0	1	1	1	1	0	0	0	1	0
Step Pool	0	0	0	0	0	0	0	0	0	0
Rock Vanes	0	1	1	1	1	0	0	0	3	0
Spur Dikes	0	1	1	1	1	0	0	0	1	0
Constructed Riffles	0	3	3	1	0	0	0	0	3	0
Large Woody Debris	1	0	2	0	2	1	0	0	2	0
Coconut Fiber (Coir) Rolls	2	0	0	0	2	1	0	1	0	1
Vegetated Riprap	0	0	0	0	3	3	3	1	0	1
Willow Cuttings (Posts and Poles)	1	0	0	0	3	1	0	3	0	3
Live Fascines	1	0	0	0	1	1	0	3	0	3
Live Siltation	1	0	0	0	1	1	0	3	0	3
Longitudinal Stone Toe	0	0	0	0	3	3	3	0	0	1
Vegetated Gabions	0	0	0	0	3	3	3	1	0	1
Vegetated MSE Walls	0	0	0	0	3	3	3	1	0	1
Articulated Concrete Blocks	0	0	0	0	3	3	3	0	0	0
Brush Mattresses	3	0	0	0	3	1	0	3	0	3

Key:

- 0 = Measure is unsuitable or does not apply in this setting
- 1 = Measure must be applied with supporting measures to achieve the desired purpose
- 2 = Measure is effective on a temporary basis
- 3 = Measure is effective on a permanent basis

Table 11A-2a
Stream Mitigation Measure Selection Table for Low Gradient Alluvial Streams

Figure 3.9 Various biotechnical techniques, including in-stream structures, and the recommended uses according to the TDOT 2012 "Natural Stream Design" manual.

design issues, its biological considerations, risks, construction details, maintenance and monitoring. Three selection matrices are presented to aid in the choice of particular techniques. These are based on i) site conditions, ii) reach conditions, and iii) impacts. As an example, the detailed matrix based on site conditions is shown in Figure 3.10. With the exception of soil reinforcement techniques, such as VMSEs, the level of suitability for biotechnical techniques against *any* failure mechanism other than toe (bank) erosion due to reduced vegetative bank structure does not rise above G2, i.e., "good in combination with a technique rated G or in low to moderate risk situations". The appendix (H) on "Planting considerations and erosion control fabrics" could also be helpful.

3.2.2.3 Research Reports for State DOTs. A study by Mohseni, Weiss, Cantelli, and Wilson (2004), performed for the Minnesota Dept. of Transportation, included a literature review, and examined a number of sites where biotechnical techniques were implemented. It was aimed primarily at identifying specific research needs on the topic, and outdoor sites where detailed experiments could be conducted. A comprehensive literature review (Admiraal, Schemper, & Strahm, 2007) for the Nebraska Department of Roads discusses the streambank erosion problem in general, and then examines the literature on traditional as well as biotechnical approaches. It is highly recommended for its coverage of material up to 2003 (two of the more recent references will also be discussed in

MATRIX 1: SCREENING TREATMENTS BASED ON SITE CONDITIONS
Refer to Chapter 2 for Site-Based Assessment Information

Potential Suitability of Bank-Protection Techniques

Is This Occurring at My Site? (Yes or No)	Mechanism of Failure	No Action	Other Techniques		Flow-Redirection Techniques							Structural Techniques							Biotechical Techniques					Internal Bank-Drainage Techniques	Avulsion-Prevention Techniques		
			Channel Modifications	Riparian-Buffer Management	Groins	Buried Groins	Barbs	Engineered Log Jams	Drop Structures	Porous Weirs	Remove or Reduce Feature	Anchor Points	Roughness Trees	Riprap	Log Toes	Roughened Rock Toes	Log Cribwalls	Manufactured Retention Systems	Woody Plantings	Herbaceous Cover	Soil Reinforcement	Coir Logs	Bank Reshaping	Subsurface Drainage Systems	Floodplain Roughness	Floodplain Grade Control	Floodplain Flow Spreader
	TOE EROSION																										
	Reduced Vegetative Structure	F	I	G	G	G	G	G	F	F	-	D*	G	F	G2	G2	F	F	G	G2	G	G	G2	-	-	-	-
	In a Smoothed Channel	F	G	G2	G	G	F*	G	G2	G2	-	I	G	F	G2	G2	F	F	G2	F2	F	G2	G2	-	-	-	-
	Along a Bend	G	D	G2	G	G	G	G	F	F	-	D*	G	G	G	G	G*	G	G2	G2	G	G2	G2	-	-	-	-
	SCOUR																										
	Local Scour																										
	At a Tailout or Backwater Bar	G	I	G2	F*	F	F	D	F	F	G	G	G	G	G	G	G	D*	G2	G2	G2	G2	F2*	I	I	I	I
	Associated with an Obstruction	G	I	G2	P*	F	F	D	F	F	G	G	G	G	G	G	G	D*	G2	G2	G2	G2	F2*	I	I	I	I
	Constriction Scour																										
	Associated with Large Woody Debris Jam	G	F	G2	F*	F	F*	G*	P*	P*	G	G*	F*	F	G*	F*	F	D*	G2	G2	G2	G2	F2	I	I	I	I
	At a Bridge Crossing	F	I	I	D*	I	D*	D*	D*	P*	G	I	I	G	P	G	I	G*	I	I	I	I	G2	I	I	I	I
	At Existing Bank Feature	G*	G	G2	D*	G	D*	D*	P*	P*	D*	G*	F*	F	G	F	F	D*	G2	G2	G2	G2	F2	I	I	I	I
	Drop/Weir Scour	G	D	G2	D	I	I	D	F*	P*	D	F	G*	F	G	F	F	D*	G2	G2	G2	G2	F2	I	I	I	I
	Jet Scour																										
	At a Lateral Bar	G	D	G2	D	F	D	D	F	F	F2	G	G	P*	G*	F*	G	D*	G2	G2	G2	G2	F2	I	I	I	I
	At a Side Channel or Tributary	G	D	G2	G*	G	I	D	I	I	D*	G	G	F	G2	G2	G	D*	G2	G2	G2	G2	F2	I	I	I	I
	Subchannels in a Braided Channel	G	D	G2	P	P	P	P	I	I	I	P*	F	F*	F2*	F2*	F*	D*	G2	G2	G2	G2	F2	I	I	I	I
	At a Channel Bend (Energy Sink)	G	D	G2	D	I	I	D	F2*	F2*	I	G	G	F	G2	G2	G	F*	F2	F2	G	F2	F2	I	I	I	I
	SUBSURFACE ENTRAINMENT																										
	Groundwater Seepage	G	D	I	F	F	F	F	P	P	F	I	F	G2	G	G	G2	G2	G2	G2	G2	G2	G2	G	I	I	I
	Rapid Drawdown	G	D	I	F	F	F	F	P	P	F	I	F	G2	G	G	G2	G2	F2	F2	F2	F2	F2	G	I	I	I
	MASS FAILURE																										
	Saturated Soils	G	D	I	F*	I	F*	F*	P	P	-	I	F2	F*	G2*	G2*	F	G*	D*	I	P	I	G2	G	I	I	I
	Increased Surcharge	F	S	I	P*	I	P*	P*	P*	P*	G	I	P*	F*	P*	P*	F	G*	P*	P*	F	I	G2*	I	I	I	I
	Lack of Root Structure	F	D	G2	I	I	I	I	I	I	I	I	I	F*	G2	G2	F	F	G2	P	F	F2	G2	I	I	I	I
	Undercutting/Removal of Lateral/Underlying Support	D	D	I	I	I	I	I	I	I	I	I	I	F*	G	G	F	F	F2	P	F	F2	G2	I	I	I	I
	AVULSION POTENTIAL																										
	In Mature Floodplain	G	D	G	I	I	I	I	I	I	-	I	I	I	I	I	I	I	I	I	I	I	I	-	F	P	F
	In Channel Floodplain	I	D	G	I	I	I	I	I	I	-	I	I	I	I	I	I	I	I	I	I	I	I	-	G	G	G
	CHUTE-CUTOFF POTENTIAL																										
	In Mature Floodplain	G	D	G	G	G	G	G	F	F	-	I	G	G	G	G	G	G	G2	G2	G	G2	F	-	F	I	I*
	In Channel Floodplain	I	D	G2	G	G	G	G	F	F	-	I	G	G	G	G	G	G	G2	G2	G	G2	F	-	G	G	G
	Suitability of Each Technique Suitable/Unsuitable																										

Level of Suitability
* = See Figure 5-1 (b) for additional explanation
G = Good. Directly addresses human-caused mechanism of failure, site-based, or reach-based cause, or allows mechanism of failure to correct itself, or allows mechanism of failure to continue when appropriate, or directly the addresses (corrects) hydraulic condition created by the reach-based cause.
G2 = Good in combination with a technique rated G or in low to moderate risk situation.
F = Fair. Does not address mechanism of failure, site-based, or reach-based cause. Is not as good a bank protection solution as "good."
F2 = Fair in Combination with a Technique Rated for G.
P = Poor. Does not address mechanism of failure, site-based, or reach based cause. Not as good a bank protection solution as "fair."
I = Inappropriate. Does not work, and does not address mechanism of failure, site-based, or reach-based cause.
D = Dependent upon Site Conditions. Too varied to generalize in this matrix.
- = Not Applicable.

Notes:

1. The matrix ratings are general.; there will be situations that are exceptions to the matrix ratings. Each should stimulate further discussion. The ratings don't compare feasability, cost or risk.
2. The tables following each of the matrices include explanations of some of the ratings in the matrices. Explanations are given for those ratings that are not obvious or are incomplete without some explanation.
3. See Chapter 5 for instructions on how to use this matrix.

Figure 3.10 One of the decision matrices (this one based on site characteristics) for choosing a streambank protection technique, taken from the state of Washington 2003 Integrated Streambank Protection Guidelines.

the next chapter). One of its conclusions, particularly of interest for the present work, is that

> "Biotechnical slope stabilization of streambanks is not likely to succeed without structural (non-biotechnical) means to reduce fluvial erosion of the bank toe. Thus, in order to be successful, biotechnical streambank erosion techniques should be used in combination with structural methods."

3.3 Summary and Implications for Design Guidelines

Of relevance to the choice of bank stabilization strategy, the synthesis works reviewed have stressed i) the clear formulation of project goals and priorities, and the tolerance to bank movement, ii) the consideration of the broader fluvial geomorphological context, whether the bank instability is a localized issue, amenable to a local solution, with possible upstream and downstream consequences, and iii) an identification of the important erosion or instability mechanisms at work. Whether a traditional pure hard-armor or a greener biotechnical approach is chosen, these preliminary steps are required to ensure long-term project success.

If a biotechnical approach is preferred, then the synthesis works describe a number of measures in sufficient detail as to be comparable to what might be included in an INDOT design standard (in this regard, the sources in Appendix A should also be included). One aspect of the standard presentation, such as in NEH-650 or TDOT2012, is that the individual techniques are usually discussed separately, yet as has been seen in the case studies (and even in detailed sketches of NEH-650, see appendix B), different techniques are often used together at the same time. With the number of possible options available, especially when multiple measures are often combined at a specific site, the basis for a selection of an effective technique becomes less clear. Although conceptual models of the effects of vegetation on bank stability are available, a quantitative design procedure for biotechnical measures, comparable in reliability to the traditional riprap design procedure discussed in Chapter 2.2, remains to be achieved. For example, whereas Figure 2.1 refers to a factor of safety for riprap revetment, there is nothing of comparable quantitative precision that can be given for most or all of the softer more purely vegetative options. Some progress in defining permissible shear stresses and velocities has been made, though the empirical basis is certainly not as extensive as that for rock riprap, for which there is also a stronger theoretical support. The compiled permissible velocities can be variable, and the added complication that they vary from the initial planting to when the vegetation becomes more fully established must also be confronted.

A zonal approach is widely accepted but how the different zones along the bank should be defined is still debatable. There is a recognition that the toe zone is critical. A biotechnical approach combining the more predictable hard armor in the toe zone (and locations where vegetation is often not sustainable) and softer vegetation options on the upper bank may be the most attractive strategy.

Because of the many techniques available, an aid to the selection of the appropriate techniques would be valuable, and the various classification of techniques is aimed at providing this aid. Classification according to levels of established use (McCullah and Gray (2005) scheme in Figure 3.7), or applications (the Eubanks-Meadows scheme in Figure 3.8), or the TDOT scheme (Figure 3.9), or erosion or failure mechanisms (and other considerations) as in the WISPG2003 matrices (Figure 3.10)) have been proposed The expert-systems software of McCullah and Gray (NCHRP-544) also aims to provide similar guidance. The multi-matrix approach of WISPG2003 and the expert-systems software seem rather at odds in the present context of developing reasonably simple INDOT design standards and guidelines. Some simplification might be sought in i) narrowing the scope of the problem, and ii) minimizing the number of techniques to be considered. The distinction between primary techniques that can be applied in isolation, e.g., VMSEs, and those that are used in combination with the first class of techniques, e.g., live stakes, might also be useful for design guidance.

4. WORKS OF NARROWER SCOPE

The works discussed in the preceding chapter synthesized the state of knowledge up to the year 2000, covering a broad range of topics related to biotechnical (and other) approaches to streambank stabilization. The more recent publications discussed in this chapter are narrower in scope, though some may give an overview of a specific topic. While closely related to biotechnical approaches, the themes that have attracted recent attention, such as the ecological effects of riprap and alternatives, may not have as direct and immediate implications for practical design.

4.1 Ecological Effects of Riprap and Alternatives

The widely cited review by Fischenich (2003) covers the literature up to 2000. Although its title refers to riprap, its scope is broader than riprap revetment, since it considers riprap for flow deflection, grade control, slope stabilization, as well as streambank armoring. The reviewed literature gave rather mixed results regarding ecological impact, but Fischenich suggested that the impact depended on whether hard substrate, similar to riprap, was already abundant at a site. If so, addition of riprap for bank stabilization would likely degrade or at least not enhance the quality of aquatic habitat. In view of the mixed conclusions from different studies, Fischenich argues that impacts on various stream functions or features, namely, morphology, hydrology, sediment transport, habitat, and chemical and biological processes, should be examined. Based on his literature review and personal experience, a qualitative ranking of the different riprap uses was given according to the severity of impact for each stream function (Figure 4.1). A difficulty is seen in that in the overall effect, considering the impacts on the various functions, it is not clear that the differences between armoring, flow deflection, and slope stabilization (essentially toe protection) techniques are significant. Some of the impact could from some perspective be considered positive rather than negative, e.g., with regards to the energy reduction techniques, which would be in-stream structures such as weirs. Fischenich also makes the point that vegetative armoring techniques may have similar impacts, e.g., on sedimentation or morphological processes. Figure 4.1 is primarily useful if the aim is to minimize any impact, positive or negative. Further, as Fischenich emphasized in the summary chapter, "The evidence presented in the literature strongly suggests that the impacts from riprap are very site-specific."

Sudduth and Meyer (2006) studied the effects of bioengineering streambank stabilization techniques by examining six sites in the same watershed along the same urban (Atlanta, GA) stream, within the context of urban stream restoration. A reference site was located in a nature preserve (close to "natural" conditions), and another was an unstabilized site with inadequate riparian zone and eroding banks. As is often the case, at each site different biotechnical techniques were combined, including live cuttings, tree revetments, and geotextile logs. At one site, which had been previously armored with riprap, joint planting was applied. They performed a visual bank habitat assessment and collected macroinvertebrates for biomass measurements, and found rather slight differences between the sites. Only the site with the joint planting exhibited significantly lower scores, but as the authors note, that site at the time had only been treated a short time (3 years), and "it is possible that over a longer

Table 8
Relative Impact of Erosion Control Methods on Stream and Riparian Functions (Scaled 1 to 10 with 1 Representing the Most Severe Impact)

Function	Armor Techniques	Flow Deflection	Slope Stabilization	Energy Reduction	Average	Rank
Morphologic Evolution						
Stream Evolution Processes	3	6	3	7	4.75	1
Energy Processes	9	6	9	4	7.00	9
Riparian Succession	3	6	4	6	4.75	2
Hydrologic Balance						
Surface Water Storage Processes	10	8	10	5	8.25	14
Surface/Subsurface Water Exchange	10	10	10	7	9.25	15
Hydrodynamic Character	10	7	10	4	7.75	12
Sediment Continuity						
Full Sedimentation Processes	5	5	5	4	4.75	3
Substrate and Structural Processes	8	5	7	5	6.25	6
Quality and Quantity of Sediments	7	7	7	6	6.75	8
Habitat Provision						
Biological Communities and Processes	6	5	7	5	5.75	5
Necessary Habitats for all Life Cycles	6	5	6	5	5.50	4
Trophic Structures and Pathways	8	9	8	6	7.75	13
Chemical Processes &Pathways						
Water and Soil Quality Processes	8	9	7	5	7.25	11
Chemical Processes & Nutrient Cycles	7	9	7	5	7.00	10
Landscape Pathways and Processes	4	9	5	9	6.75	7
Average	6.9	7.1	7.0	5.5		
Rank	2	4	3	1		

Figure 4.1 Qualitative impacts of various streambank stabilization approaches according to Fischenich (2003).

time period, the trees could become a more important component of bank habitat, and joint planting could create more organic habitat." They suggest that in a heavily impacted urban stream environment, other sources of impairment might dominate and biotechnical stream stabilization techniques should not be expected to yield dramatically positive ecological results compared to "natural" conditions.

The study of White, Gerken, Pauker, and Makinster (2009) did not consider biotechnical techniques, but rather compared fish communities in stream segments with riprap and other segments with more "natural" substrates, namely, mudflats and logjams, in the Kansas River (a large seventh-order river). Fish communities were sampled at four sites using boat-mounted electrofishing, and the corresponding shoreline habit was identified as being riprap, mudflat, or logjams. The data were analyzed for measures of species diversity, richness, and abundance. Somewhat surprisingly, the riprapped reaches were always found to be associated with highest number of species and the highest diversity, while certain species were most abundant in the riprapped reaches, but others were most abundant in the logjam reaches. Thus, their study indicated that

> "at a local scale, riprap had increased fish species richness and diversity, and did not have lower abundances of many fluvial specialist and dependent species, at least for the primarily large-bodied species collected in our study."

In spite of their data, they *speculated* that the effects of riprap may be scale-dependent, namely that, at the local scale, effects may be negligible or even positive, but that at the larger, e.g., watershed, scales, the overall effect of riprap may still be negative. An alternative though similar explanation might be that, for larger streams, streambanks may be proportionately less important as fish habitat.

The two studies of Moerke and Lamberti (2003) and Moerke, Gerard, Latimore, Hellenthal, and Lamberti (2004) dealt with the broader questions of stream restoration and its effects rather than specifically bank stabilization, but is of interest as it examines two Indiana sites (Juday Creek and Potato Creek, both in northern Indiana). The Juday Creek (a third-order stream with a drainage area of 98 km^2) restoration project did involve streambank stabilization using biodegradable erosion control blankets (ECBs) and revegetation including a mixture of grasses and forbs as well as buttonbush and dogwood trees. The studies involved habitat surveys and backpack electrofishing. It was concluded that, for Juday Creek, fish community metrics "seldom exceeded the levels of the unrestored, channelized reaches", and this was attributed to a watershed-scale sedimentation issue. This led the authors to suggest that the traditional stream management strategies, such as bank stabilization, focusing on local impact, may be ineffective at addressing problems with larger-scale origins.

4.2 Geotechnical Modeling of Vegetative Effects on Bank Stability

In Chapter 3, it was noted that the mechanical effect of vegetation on the geotechnical bank stability can be explained in terms of the root reinforcement of the soil through an apparent increase in soil cohesion. Abernethy and Rutherfurd (2000, 2001) performed a detailed geotechnical slope stability analysis of two sites on the Latrobe River in Australia, including the effect of root reinforcement by two species of trees or shrubs. This required field and laboratory work to determine the spatial distribution of roots and their sizes, as well as tensile-strength tests. The high variability of the results for these characteristics can be seen in the low values of correlation coefficients, e.g., in a power-law model of the variation of tensile strength with root diameter, the value of R^2 was reported as 0.41, and coefficients of variation (standard deviation/mean), 0.73 for the root diameter, and 1.06 for the tensile strength. After the root reinforcement effects due to a particular species were quantified, they were incorporated into a geotechnical slope-stability numerical model, with additional information regarding bank geometry and hydraulic conditions. The effect on bank stability is characterized by a factor of safety (a factor less than 1 implies an unstable bank). In view of the added cohesion attributed to root reinforcement, an increase in the factor of safety was found when the factors for observed banks with and without root reinforcement were compared. As the authors admit, observed banks must be stable at the time of observation to have been observed, and hence "analyses of these bank sections do not demonstrate the stabilizing influence that tree roots impart to an otherwise unstable bank."

Whereas Abernethy and Rutherfurd (2000) considered only the positive mechanical effect of root reinforcement due to trees on bank stability, Simon and Collison (2002) emphasized the hydrologic effects of vegetation. Their study site was located at Goodwin Creek in northern Mississippi, and consisted of three vegetation test plots on an unstable incised streambank. The three vegetation treatments were a control (short cropped turf/bare), eastern gamma grass and a mature riparian tree stand with a mixture of sycamore, river birch, and sweetgum trees. They also obtained additional root data on black willow and Alamo switch grass. They characterized the root reinforcement effect similar to the approach of Abernethy and Rutherfurd (2000), though their geotechnical slope stability model was different. They also measured pore-water pressures using tensiometers, streamflow levels, and open sky rainfall, stemflow, and canopy through-fall using rain gauges. The characteristics of four tree species (sycamore, river birch, sweetgum, and black willow) and two grass species (gamma grass and Alama switch grass) were determined. They found that "Root tensile strength varies widely, both within and between species, with two orders of magnitude variability". Of the tree species, river birch and sycamore had the strongest root network, while somewhat surprisingly switch grass had the strongest of any species (on average twice as large as the strongest tree root network), attributed to their high root area ratio rather than to higher tensile strengths. The authors also argue that hydrologic effects may be equally important as the mechanical root reinforcement effects, and should be considered in species selection. Model predictions of instability (factors of safety less than one) seem to have been borne out in observed bank instabilities, and so give stronger support for a detailed modeling approach. While progress has been made in modeling and predicting the stability of streambanks in their existing vegetated state, the problem of predicting stability with future vegetation is more formidable and the results more uncertain, as it would involve predicting the root-reinforcement effects of a future vegetative state.

4.3 Effectiveness of Biotechnical Streambank Stabilization Methods

Only a single study (Karle, Moore, & Emmett, 2003), performed for the Alaska DOT, was found which was solely concerned with evaluating the performance of bioengineered bank stabilization. Eleven sites using common techniques such as root wads, live stakes, brush layers, and coir logs were studied, including velocity measurements and HEC-RAS one-dimensional flow simulations. Its main conclusions were that:

- "On streams where large tractive forces during flooding conditions will initiate bed and bank particle movement, current designs and techniques for BECSs [bioengineered erosion control structures] do not provide adequate protection from toe erosion in flooding conditions. This can result in erosion of the bank toe upon which the structure is located. Such erosion may lead to partial or total failure of the BECS. Current design methodology for such structures does not provide any self-healing features for such structures in the event of severe toe erosion. In contrast, a properly designed riprap structure will include either a stone toe trench placed beneath the expected depth of maximum scour, or a self-launching stone toe, which will launch stone into the eroded area as scour occurs."
- "Until current designs of BECSs are improved, the use of such structures should occur only in areas of low erosion potential, or for areas where failure results in insignificant consequences."

Among the recommendations was the "Development and testing of a hybrid structure, which incorporates both a properly design riprap toe up to ordinary high water, and a BECS above the rock base." Despite Alaska being quite different geographically from Indiana, the main result in identifying the problem of toe erosion seem to be independent of geography.

The study of Miller and Kochel (2009) assessed the effectiveness of in-stream structures, such as cross vanes, double wings, rock-vanes, J-hooks, and rootwad revetments for stream restoration. They examined data from annual cross-sectional surveys at 221 locations along 26 randomly reconfigured river reaches in North Carolina for changes in cross-sections and rates of erosion and deposition. In addition, a rapid assessment protocol was used to evaluate structures at 26 other sites in that state. Changes in excess of 35% in the areas (capacity) of individual cross-sections were generally found 3 years after project completion, while about 24% of the evaluated structures were damaged, impaired, or failed. Of the structures, cross vanes and double wings exhibited the greatest damage, while ≈41 % of the rootwads were impacted. Impairment was "primarily associated with bed and bank erosion and/or deposition, rather than through movement of the materials of which the structures were composed." The authors emphasize the importance of a thorough geomorphologic analysis to determine whether the channel is highly dynamic, where the likelihood of a successful project may be small.

4.4 Screening of Bank Stabilization Methods

Screening of the various biotechnical techniques has been discussed from different perspectives. Li and Eddleman (2002) proposed a strength-cost matrix combined with the USACE (see Allen and Leech (1997) and Figure 3.1) zone classification. They gave descriptions of twelve common biotechnical techniques, and Figure 4.2 shows two examples (for live stakes and vegetated geogrids) of their classification scheme. Their scheme is based on the conventional literature, and is certainly a simplification of the matrices that have been previously proposed (see Chapter 3, e.g., the three-matrices approach in WISPG2003 or Figure 3.10). Yet there is little account of the effectiveness of the individual techniques. It also seems aimed at a non-technical audience, as it lumps technical aspects into the concept of strength, but does not provide much guidance as to when a stronger approach might be appropriate or how strength could be quantified.

Frothingham (2008) proposed a more technical quantitative screening approach based on a stability threshold, namely for permissible shear stress or velocity, concepts that are familiar from traditional hydraulics of flexible linings (see HEC-15). This approach does require information regarding permissible shear stresses or velocities for biotechnical techniques; such information is either associated with large uncertainties, or not available. Frothingham used the data compiled by Fischenich (2001), which includes common biotechnical techniques such as coir logs, live fascines, live willow stakes, brush layers, as well as permanent rolled erosion control products (mats). In the Fischenich table (see Figure 4.3; values given are largely comparable to those in the NEH-654 table in Figure 3.6, which in fact cited Fischenich's work), permissible shear stresses could differ by a factor of 2, which Fischenich (2001) attributes to "multiple sources of data or different testing conditions". This screening approach also raises the problem of estimating either a design shear stress or velocity, or a design condition. Frothingham chose the bankfull condition for design, and used relationships for uniform-flow conditions in a straight channel to estimate the design shear stress or velocity. These choices or assumptions may be debatable for any specific site though might be acceptable for first screening. While the work of Frothingham (2008) explains the procedure and applies it to an actual creek, it does not provide any evidence confirming that the results of the screening lead to effective design choices.

The work of Fischenich (2001) on stability thresholds for various types of boundaries has already been referred to above. This was updated by Miller et al. (2012) to include recent developments in rolled erosion control products (RECPs) technology, namely high performance turf reinforcement mats (HPTRMs) and anchored reinforced vegetation systems (ARVSs), and the corresponding design considerations for their use. ARVSs are typically HPTRMs combined with a deep anchoring system that provides greater resistance to slope instability or geotechnical mass failure. The features of the different levels of TRMs are summarized in their table (Figure 4.4) comparing the hydraulic and geotechnical capabilities, as well as other aspects. The different and quantifiable

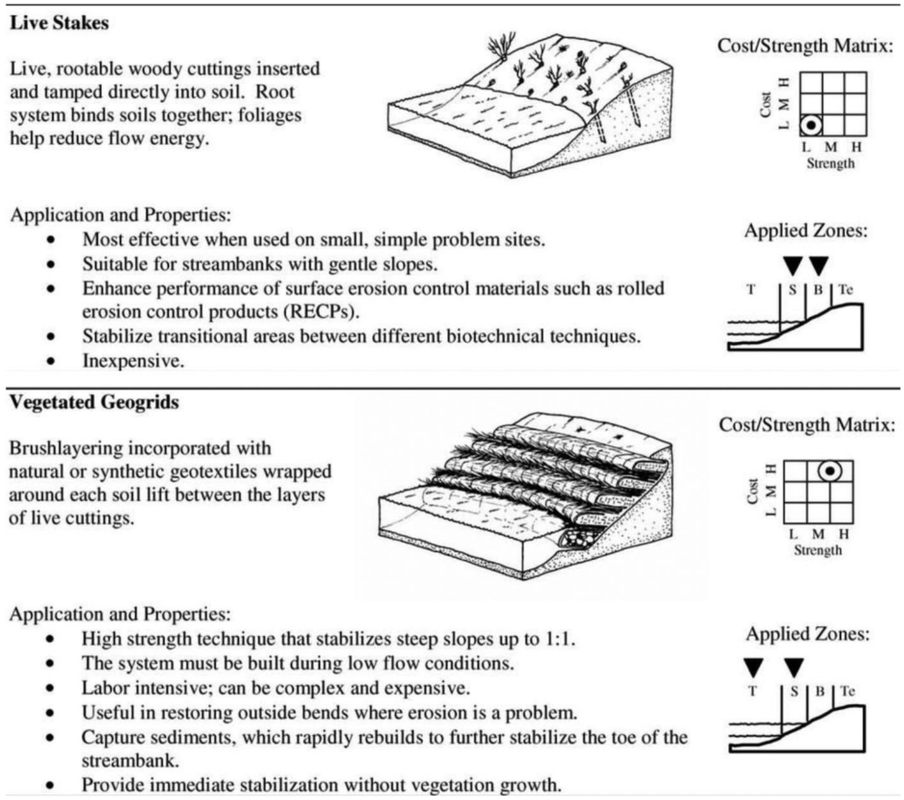

Figure 4.2 Example of application of cost-strength matrix combined with the Allen and Leech (1997) USACE zonal definition as proposed by Li and Eddleman (2005).

Table 2. Permissible Shear and Velocity for Selected Lining Materials[1]

Boundary Category	Boundary Type	Permissible Shear Stress (lb/sq ft)	Permissible Velocity (ft/sec)
<u>Vegetation</u>	Class A turf	3.7	6 – 8
	Class B turf	2.1	4 - 7
	Class C turf	1.0	3.5
	Long native grasses	1.2 – 1.7	4 – 6
	Short native and bunch grass	0.7 - 0.95	3 – 4
	Reed plantings	0.1-0.6	N/A
	Hardwood tree plantings	0.41-2.5	N/A
<u>Temporary Degradable RECPs</u>	Jute net	0.45	1 – 2.5
	Straw with net	1.5 – 1.65	1 – 3
	Coconut fiber with net	2.25	3 – 4
	Fiberglass roving	2.00	2.5 – 7
<u>Non-Degradable RECPs</u>	Unvegetated	3.00	5 – 7
	Partially established	4.0-6.0	7.5 – 15
	Fully vegetated	8.00	8 – 21
<u>Soil Bioengineering</u>	Wattles	0.2 – 1.0	3
	Reed fascine	0.6-1.25	5
	Coir roll	3 - 5	8
	Vegetated coir mat	4 - 8	9.5
	Live brush mattress (initial)	0.4 – 4.1	4
	Live brush mattress (grown)	3.90-8.2	12
	Brush layering (initial/grown)	0.4 – 6.25	12
	Live fascine	1.25-3.10	6 – 8
	Live willow stakes	2.10-3.10	3 – 10

Figure 4.3 Permissible velocities for various natural boundary materials as compiled by Fischenich (2001) and used by Frothingham (2008).

Table 6. Flexible channel and slope armoring generalized design and product selection guidelines.

Standard UV Resistance and Tensile Strength Recommendations for Product Classes and Estimated Product Design Life				
Standard Recommendations[1]	**Ordinary TRM**	**Advanced TRM**	**High Performance TRM (HPTRM)**	**Anchor Reinforced Vegetation System (ARVS)**
Estimated Product Design Life	Up to 5 years	Up to 25 years	Up to 50 years	Up to 50 years
Tensile Strength-Minimum Average Roll Values, ASTM D 6818	125 x 125 lb/ft^2 (6 x 6 kN/m^2)	1,500 x 1,500 lb/ft^2 (71.8 x 71.8 kN/m^2)	3,000 x 3,000 lb/ft^2 (143.6 x 143.6 kN/m^2)	3,000 x 3,000 lb/ft^2 (143.6 x 143.6 kN/m^2)
Tensile Strength Retained-All Components, ASTM D 4355	90% at 500 hr	90% at 2,500 hr	90% at 5,000 hr	90% at 5,000 hr
SELECTED HYDRAULIC CONSIDERATIONS				
Selected Performance Considerations	**Ordinary TRM**	**Advanced TRM**	**HPTRM**	**ARVS**
Maximum Permissible Design Velocity[2] **(Vegetated – 70% to 100%)**	≤ 12 ft/s (3.7 m/s)	≤ 16 ft/s (4.9 m/s)	≤ 20 ft/s (6.1 m/s)	≤ 20 ft/s (6.1 m/s)
Maximum Permissible Design Velocity[2] **(Partially Vegetated – 30% to 70%)[3]**	N/A	N/A	≤16 ft/s (4.9 m/s)	≤16 ft/s (4.9 m/s)
Maximum Permissible Design Velocity [2] **(Minimally vegetated – up to 30%)[3]**	N/A	N/A	≤ 12 ft/s (3.7 m/s)	≤ 12 ft/s (3.7 m/s)
Maximum Permissible Design Shear Stress[2] **(Vegetated – 70% to 100%)**	≤ 6 lbs/ft^2 (287 N/m^2)	≤ 10 lbs/ft^2 (0479 N/m^2)	≤ 14 lb/ft^2 (670 N/m^2)	≤ 14 lb/ft^2 (670 N/m^2)
Maximum Permissible Design Shear Stress[2] **(Partially Vegetated – 30% to 70%)[3]**	N/A	N/A	≤ 12 lb/ft^2 (575 N/m^2)	≤ 12 lb/ft^2 (575 N/m^2)
Maximum Permissible Design Shear Stress [2] **(Minimally Vegetated – up to 30%)[3]**	N/A	N/A	≤8 lbs/ft^2	≤8 lbs/ft^2
Permissible Wave Height[5] **(Inland Conditions Only, i.e. Canals & Reservoirs)**	N/A	N/A	≤ 12 in. (30.5 cm)	≤ 12 in. (30.5 cm)
Flow Frequency[4]	Intermittently Loaded	Intermittently Loaded	Intermittently Loaded	Intermittently Loaded & Continuous Flow
SELECTED NON-HYDRAULIC CONSIDERATIONS				
Vehicular Traffic/Mowing Limits	Push Mower	Push Mower	Rubber-tired Vehicles / Rider Mower	Rubber-tired Vehicles / Rider Mower
Vegetation Establishment	Minimum 90% Coverage Required	Minimum 65% Coverage Required	Vegetation Beneficial but Not Required	Vegetation Beneficial but Not Required
Wildlife Entrapment Minimization	Average opening size of 5 mm^2 (maximum)	Average opening size of 5 mm^2 (maximum)	Average opening size of 5 mm^2 (maximum)	Average opening size of 5 mm^2 (maximum)
Applicable Climate Conditions	Temperate	Temperate	Temperate, Semi-Arid, Arid	Temperate, Semi-Arid, Arid
High Loading and/or High Survivability Required	No	No	Yes	Yes
Material Matrix Configuration	Fused monofilaments, Stitch-bonded, Woven	Woven	Woven	Woven + Anchors
Material Composition	Polypropylene, Bio-Degradable, Nylon, Polyester, Recycled, Other Synthetics	Polypropylene	Polypropylene	Polypropylene
GEOTECHNICAL CONSIDERATIONS[6]				
Soil Type	**Site Specific**	**Site Specific**	**Site Specific**	**Site Specific**
Erosion or Failure Mechanism Treatable	Erosion	Erosion	Erosion	Erosion and/or Surficial Slumping
Angle of Repose Can be Exceeded	No	No	No	Yes
Seepage Concerns	No	No	No	Yes

1 All values *minimum average roll value* (MARV), defined as two standard deviations below the mean per ASTM D 4439
2 Reference product-specific product data sheet and apply minimum safety factor of 1.3 to account for short-duration maximum velocity or instantaneous flume testing results that may exceed real world performance (see Figure 6 for duration effects). All values reported less than the maximum value for this reason.
3 Note that additional maintenance may be required during vegetative establishment period. For unvegetated conditions or applications (0%) a non-woven geotetxtile fabric should be considered for use beneath TRM.
4 Non-woven geotextile fabric is recommended beneath ARVS for continuous flow applications and for unvegetated conditions or applications (0%).
5 Wave Action numbers for Inland conditions are based on significant field experience. Wave Action in Non-Inland, coastal or estuarine conditions needs further testing.
6 Site-specific geotechnical considerations including soil type, surficial slumping, global stability, angle of repose, seepage, saturation considerations, etc. must be included as part of the product selection analysis, particularly if a more structural approach may be warranted. An anchored reinforced vegetation solution (ARVS) should be considered where shallow plane sloughing and/or seepage may occur. For areas where global stability is of concern, consult a geotechnical engineer for proper slope evaluation.

Figure 4.4 Table of features of various levels of turf reinforcement mats (TRMs) compiled in Miller et al. (2012).

erosion resistance of the various TRMs offers a promising flexible solution that broadens the applicability of vegetative options, though with minimal compromise in environmental impact. Miller et al. (2012) also provide a qualitative ranking (Figure 4.5) of the environmental impact of the various streambank stabilization techniques. In general, the various permanent mats (TRMs, HPTRMs, ARVSs) have similar impacts, which are better than the hard-armor techniques, and worse than the pure bioengineering techniques. As usual, the basis of the ranking of any individual technique is open to debate, e.g., articulated concrete blocks (ACBs) are generally deemed worse than riprap, though consultation with the Indiana Dept. of Natural Resources (personal communication) suggested that ACBs would be preferred as being more wildlife-friendly.

Table 4. Generalized environmental impact of selected streambank stabilization measures on aquatic and terrestrial habitat elements compared with bare or eroding streambanks. **Note: impacts represent typical applications – actual performance may be enhanced through good design and construction practices.**

Ecological Performance Factor	Vegetation Temporary RECP (ECB)	Bioengineering – brush layers, VRSS, log crib	Ordinary / Advanced TRM	HPTRM / ARVS	Riprap	ACB	Hard Armor – gabions concrete, sheet pile
Wildlife access	☺	😐/☺	😐/☺	😐/☺	😐/☹	😐/☹	☹
Aquatic habitat complexity	😐/☺	😐/☺	😐	😐	😐/☺	😐/☹	☹
Riparian / veg. habitat complexity	☺	😐/☺	😐/☺	😐/☺	😐/☹	😐/☹	☹
Shade, temperature	😐/☺	😐/☺	😐	😐	😐/☹	😐/☹	☹
Cover, refugia	😐/☺	😐/☺	😐/☹	😐/☹	😐/☺	😐/☹	😐/☹
Nutrient cycling	☺	☺	😐/☺	😐/☺	☹	☹	☹
Surface-groundwater connection	😐	😐	😐	😐	😐	😐/☹	☹
Water quality – pollutant removal	☺	☺	☺	☺	😐/☹	😐/☹	😐/☹
Water quality – overland sed. capture	☺	☺	😐/☺	😐/☺	😐/☺	😐/☹	😐/☹
Soil development	☺	😐/☺	☺	😐	☹	☹	☹
Construction impacts	😐	😐/☹	😐	😐	😐/☹	☹	☹
Maintenance impacts	😐	😐	😐	😐	😐/☹	😐/☹	😐/☹

☺	Beneficial
😐/☺	Neutral to Beneficial
😐	Neutral
😐/☹	Neutral to Detrimental
☹	Detrimental

Figure 4.5 Qualitative ranking of environmental impacts for various streambank stabilization techniques according to Miller et al. (2012).

An interesting point is made regarding the importance of design flow duration because manufacturers' specifications of maximum permissible shear stresses and velocities rely on short-duration testing. Under application conditions, the product may be exposed for longer periods on the order of hours or even days, and their performance, particularly under the fully vegetated condition could deteriorate (Figure 4.6). The authors further note that TRMs and HPTRMs have been applied to stabilizing the banks of canals and streams, where loadings are intermittent (e.g., during floods), but that ARVSs are more appropriate for continuous flow (which means always submerged) applications. They also indicate that combination designs, in which versions of TRMs could be combined with bioengineering as well as hard-armor techniques, should also be considered in designing streambank stabilization.

4.5 Summary and Implications for Design Guidelines

The recent literature considered in this chapter does not have implications for the development of INDOT design guidelines different from those offered in the preceding chapter. Significant and immediately noticeable improvement in local environmental/ecological quality should not be expected from the adoption of biotechnical approaches to streambank stabilization. This applies particularly if the factors for the degradation of environmental quality are system-wide rather than localized, such as may be the case in an urban environment. Thus, in a highly urbanized setting, the use of the traditional pure hard-armor approach may be less objectionable than in a more natural setting, particularly if the tolerance for bank movement may be very low.

Advances have been made in the modeling and prediction of bank instabilities due to geotechnical failures, but the models require information that can only be obtained with substantial effort for existing banks with existing vegetation. Much uncertainty would be associated with predictions of bank instabilities for future vegetation, as would be the case in a practical design situation. A more promising development that might lend itself to a more quantitative design procedure is afforded by the advances in rolled erosion control products, such as high performance turf reinforcement mats and anchored reinforced vegetative systems, with higher (and quantified) resistance to erosion as well as geotechnical failures.

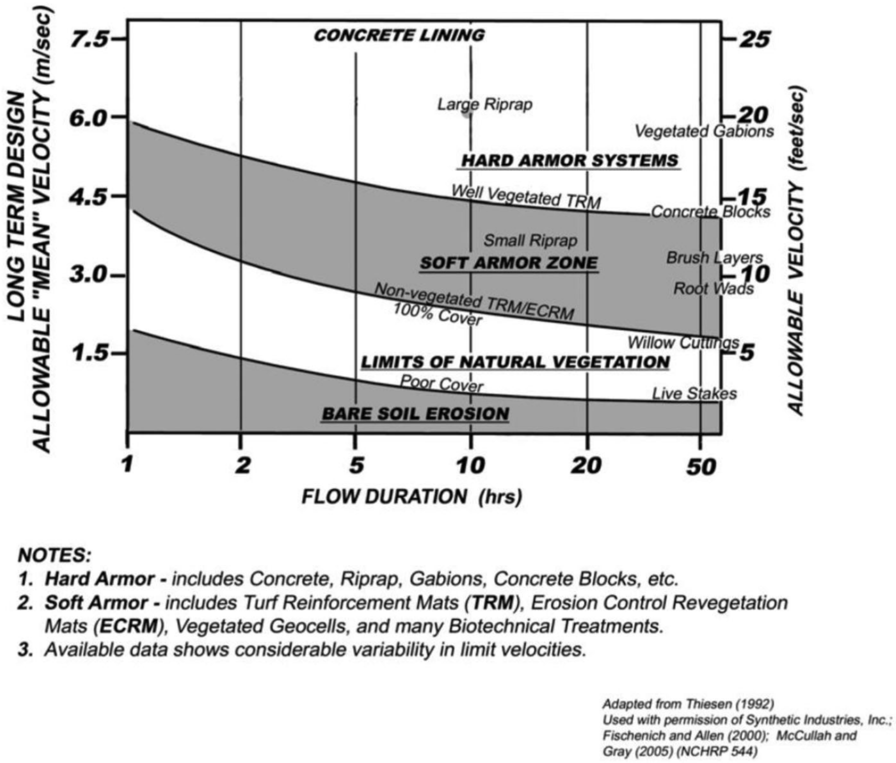

Figure 4.6 Variation of permissible velocities with flow duration according to Miller et al. (2012).

5. SUMMARY AND CONCLUSIONS

A review of the literature related to bioengineering/ biotechnical approaches to streambank stabilization was undertaken, with particular interest on works that might be relevant to the development of design standards for INDOT use. A number of synthesis works were found that outlined the general technical basis of these approaches, described in some detail individual techniques and their range of application, and gave some guidance as to the selection of appropriate techniques or class of techniques. Studies of narrower scope related to the ecological effects of riprap and bioengineered surfaces, the detailed geotechnical modeling of vegetation effects on streambank stability, and effectiveness and screening of appropriate biotechnical measures were also reviewed.

Several points specifically related to the development of simple design guidelines and standards for INDOT might be highlighted:

- Prior to any design of a bank stabilization scheme, whether hard-armor or biotechnical:
  - The project goals, priorities, and the tolerance for bank movement should be clearly formulated,
  - Fluvial geomorphology aspects should be considered to assess the extent to which a local solution will be adequate, and potential upstream and downstream consequences of a local solution,
  - The main mechanisms and processes contributing to bank movement should be identified as precisely as possible.
- The toe zone often represents the region critical for the success of bank stabilization (whether by hard or soft armoring techniques), and merits special attention.
- The problem of flanking of the bank stabilization scheme (again arising in both hard and soft approaches) has been identified as one of the most frequent causes of failure, and so proper end treatments should be emphasized.
- At the present state of knowledge, a biotechnical strategy combining hard and soft elements will likely be the most widely applicable and more conservatively reliable approach; in special cases, e.g., due to local site conditions, when there might be high tolerance for bank movement, a soil bioengineering approach relying entirely on vegetative effects might be more acceptable:
  - In seeking to develop design guidelines and standards, it may be worthwhile to consider only the most common erosion processes and bank failure mechanisms, e.g., toe scour and mass failure, rather than to try to address all possible processes and mechanisms,
  - Some techniques, such as vegetated geogrids (also known as soil lifts, or VSMES), seem to play a more central role in bank stabilization, offering immediate protection, and so might be considered primary, while others, such as live stakes or live fascines, may be desirable more for their environmental/ecological benefits (though may also ultimately contribute to bank stabilization) and may be considered secondary or supplementary,
  - Techniques that might be amenable to more precise quantification, such as in terms of the permissible velocities and shear stresses, e.g., those involving the various forms of turf reinforcement mats, might be preferred.

5.1 Implementation Plan

The results of this literature review will be implemented:

- In developing draft design guidelines and standards for INDOT,
- As a reference for INDOT Engineering Services and Design Support, and
- By its broader dissemination through INDOT Environmental Services.

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APPENDIX A: RESOURCES FOR DEVELOPING STANDARD DESIGNS

The following are narrowly-focused short documents, available on-line, that might prove useful in developing standard designs for individual biotechnical techniques. These are in addition to those in the main text.

A.1 ASTM Standards

ASTM D6599-00(2008) Standard Practice for Construction of Live Fascines on Slopes (http://www.astm.org/Standards/D6599.htm)

ASTM D6765-13 Standard Practice for Live Staking (http://www.astm.org/Standards/D6765.htm)

ASTM D6939-03 Standard Practice for Brushmattressing (Withdrawn 2012) (http://www.astm.org/DATABASE.CART/WITHDRAWN/D6939.htm)

ASTM D6825-14 Standard Guide for Placement of Riprap Revetments (http://www.astm.org/Standards/D6825.htm)

A.2 USACE Design Guidelines

Allen, H., & Fischenich, J. C. (2001). Brush mattresses for streambank erosion control (Report No. ERDC TN-EMRRP-SR-23). Washington, DC: U.S. Army Corps of Engineers. Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/sr23.pdf

Fischenich, J. C., & Allen, H. H. (2000). *Coir geotextile roll and wetland plants for streambank erosion control* (Report No. ERDC TN-EMRRP-SR-04). Washington, DC: U.S. Army Corps of Engineers. Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/sr04.pdf

Fischenich, J. C., & Morrow, J. V., Jr. (2000). *Streambank habitat enhancement with large woody debris* (Report No. ERDC TN-EMRRP-SR-13). Washington, DC: U.S. Army Corps of Engineers. Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/sr13.pdf

Fischenich, J. C., & Seal, R. (2000). *Boulder clusters* (Report No. ERDC TN-EMRRP-SR-11). Washington, DC: U.S. Army Corps of Engineers. Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/sr11.pdf

Freeman, G., & Fischenich, C. (2000). *Gabions for streambank erosion control* (Report No. ERDC TN-EMRRP SR-22). Washington, DC: U.S. Army Corps of Engineers. Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/sr22.pdf

Goldsmith, W., Silva, M., & Fischenich, J. C. (2001). Deter mining optimal degree of soil compaction for balancing mechanical stability and plant growth capacity (Report No. ERDC TN-EMRRP-SR-31). Washington, DC: U.S. Army Corps of Engineers. Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/sr31.pdf

Sotir, R. B., & Fischenich, J. C. (2001). Live and inert fascine streambank erosion control (Report No. ERDC TN-EMRRP-SR-31). Washington, DC: U.S. Army Corps of Engineers. Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/sr31.pdf

Sotir, R. B., & Fischenich, J. C. (2003). Vegetated reinforced soil slope streambank erosion control (Report No. ERDC TN-EMRRP-SR-30). Washington, DC: U.S. Army Corps of Engineers. Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/sr30.pdf

Sotir, R. B., & Fischenich, J. C. (2007). *Live stake and joint planting for streambank erosion control* (Report No. ERDC TN-EMRRP-SR-35). Washington, DC: U.S. Army Corps of Engineers. Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/sr35.pdf

Sylte, T.L., & Fischenich, J. C. (2000). Rootwad composites for streambank erosion control and fish habitat enhancement (Report No. ERDC TN-EMRRP-SR-21). Washington, DC: U.S. Army Corps of Engineers. Retrieved from http://el.erdc.usace.army.mil/elpubs/pdf/sr21.pdf

APPENDIX B: SOME BIOTECHNICAL TECHNIQUES USED IN INDIANA

The following sketches are taken from NEH-650, and illustrate basic features of biotechnical measures that have been applied on Indiana streams. For completeness, an example of an in-stream structure, the stream barb, is included though it is not strictly a biotechnical measure, but such structures are often used as an element of a biotechnical solution. The technique of bank regrading (termed bank reshaping in WISPG2003) combined with revegetation is rarely discussed in detail but should also be considered as a bioengineering option. The sketches often include elements other than the main technique, e.g., in the sketch of live stakes, both a hard-armor rock toe as well as an erosion control blanket (with some seeding of herbaceous species) are also shown. They are also typically shown in a fully established mature state rather than in their initial planted state.

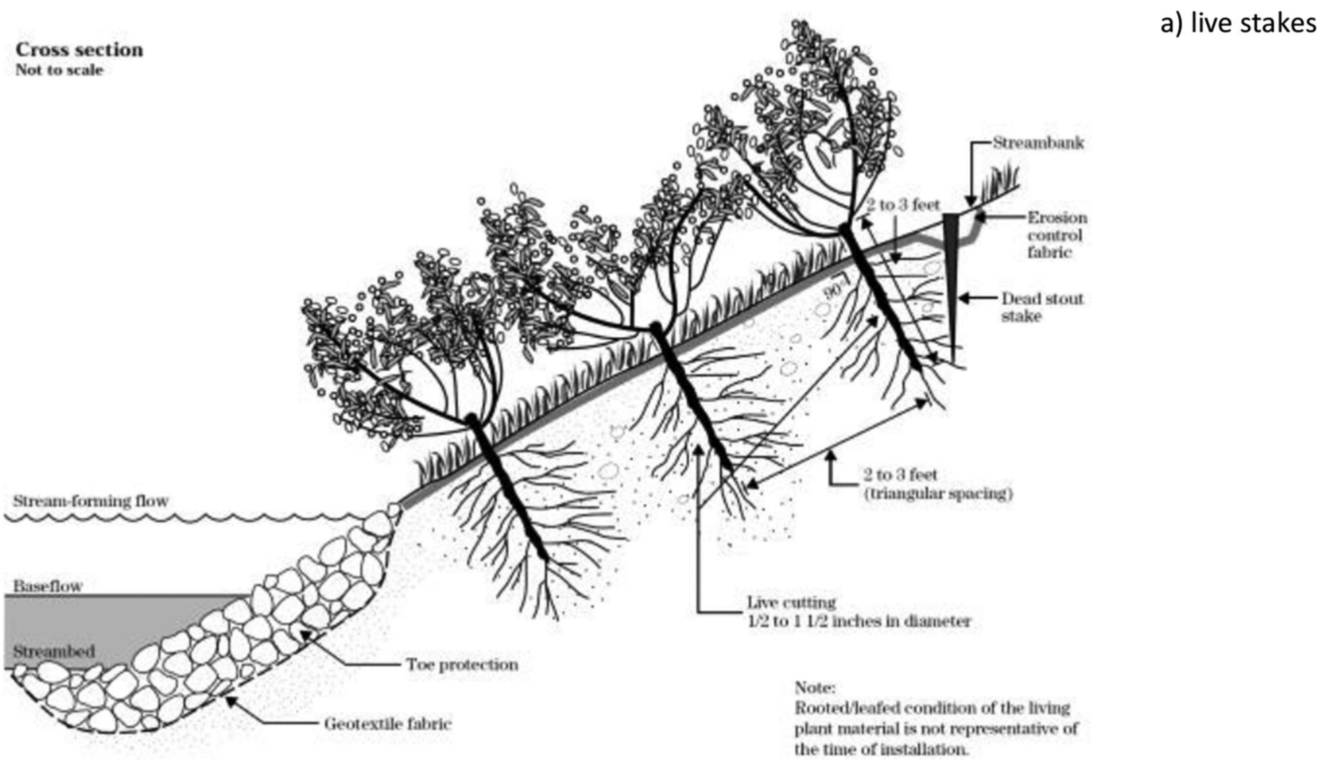
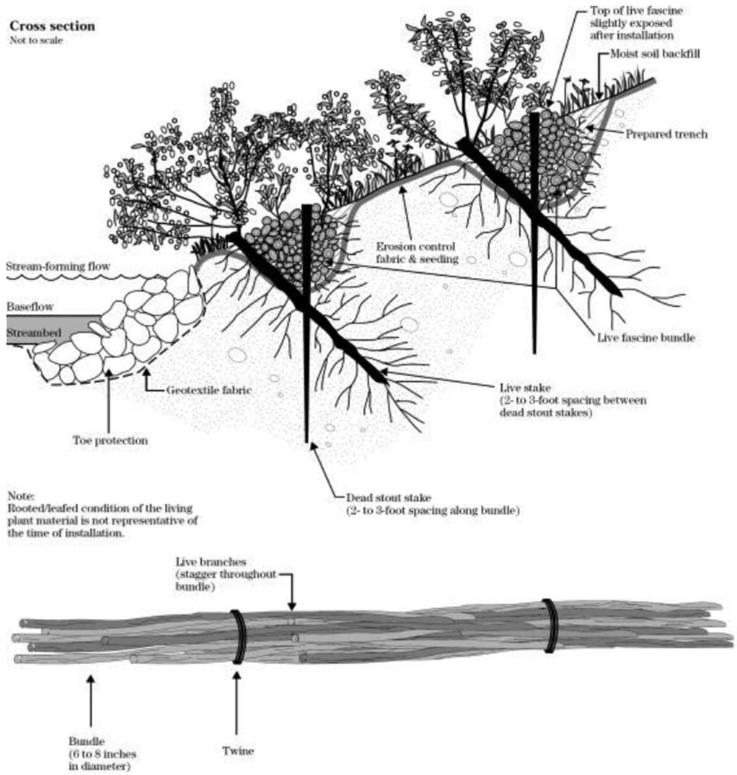
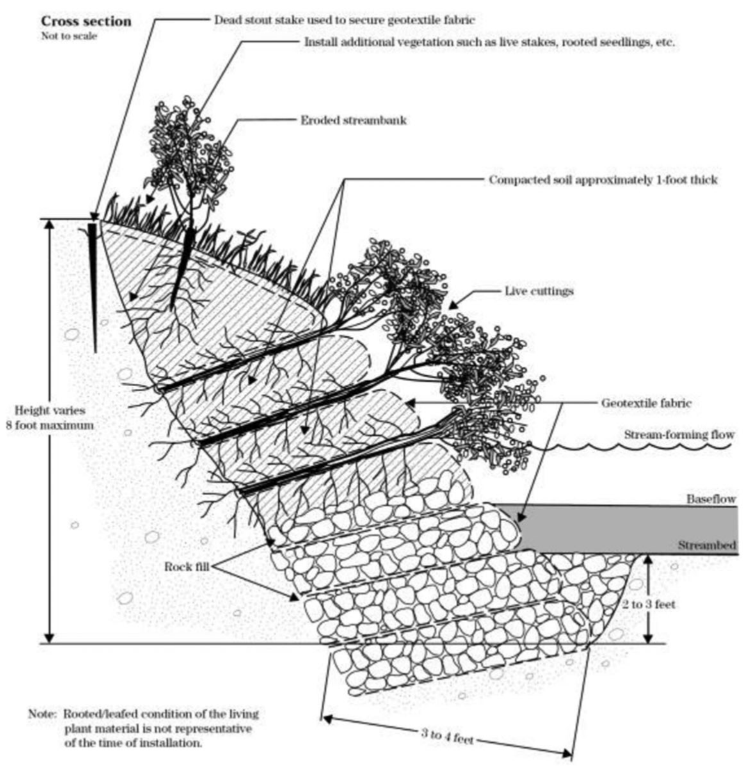


Figure B.1 Selected biotechnical measures used in Indiana: (a) live stakes, (b) live fascines, (c) vegetated geogrids, (d) joint planting, (e) coconut fiber rolls (or coir logs or biologs), (f) vegetated gabions, (g) rootwads, (h) stream barbs. (*Figure continued on next page.*)



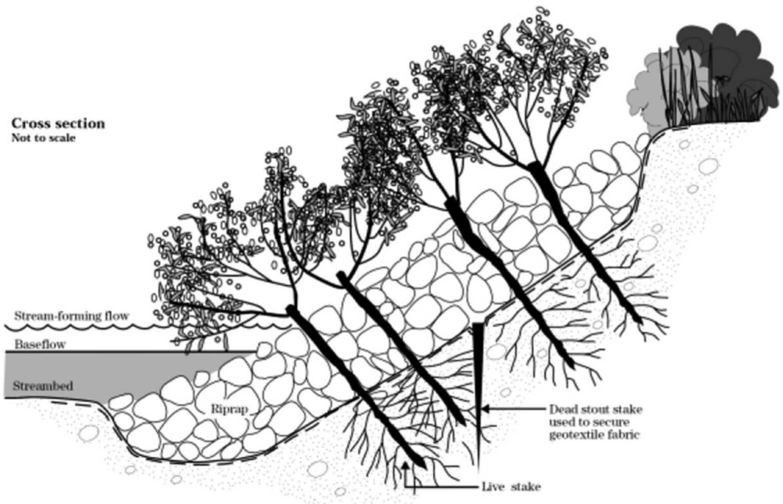
b) live fascines



c) vegetated geogrid (also known as or similar to soil lifts, vegetated mechanically stabilized earth (VSME), vegetated reinforced soil slope (VRSS))

Figure B.1 (Continued).

d) joint planting



e) coconut fiber rolls
(also termed coir logs, or bio-logs)

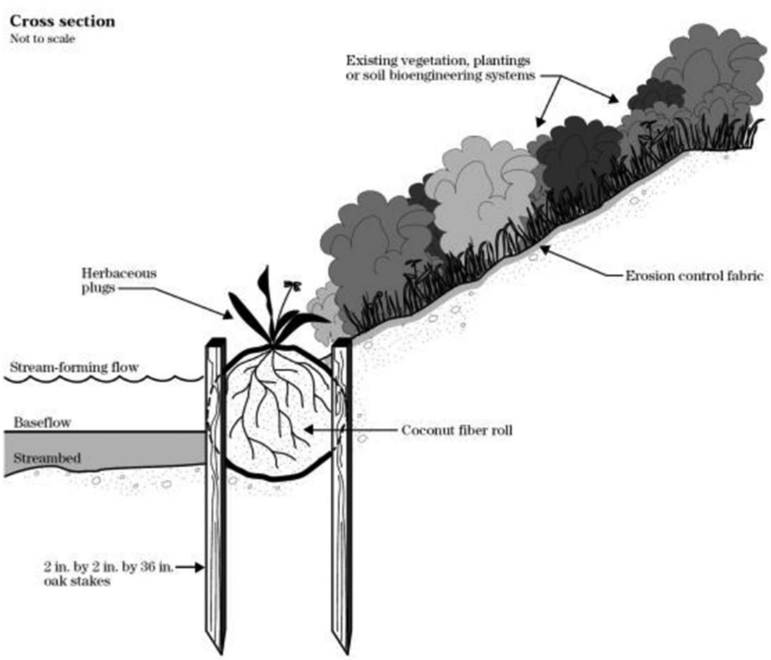
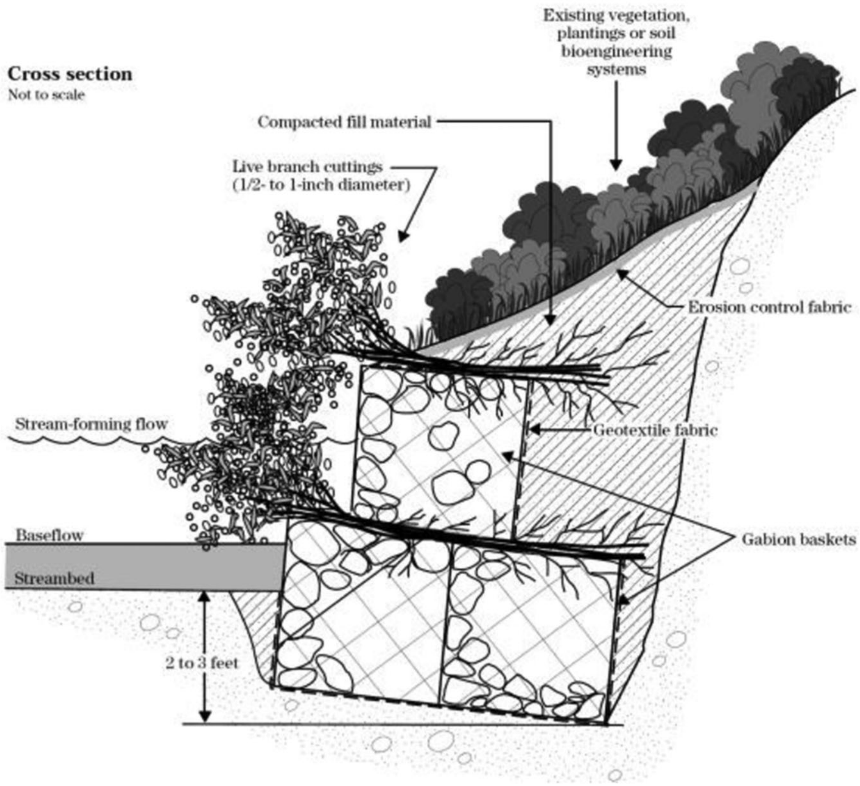
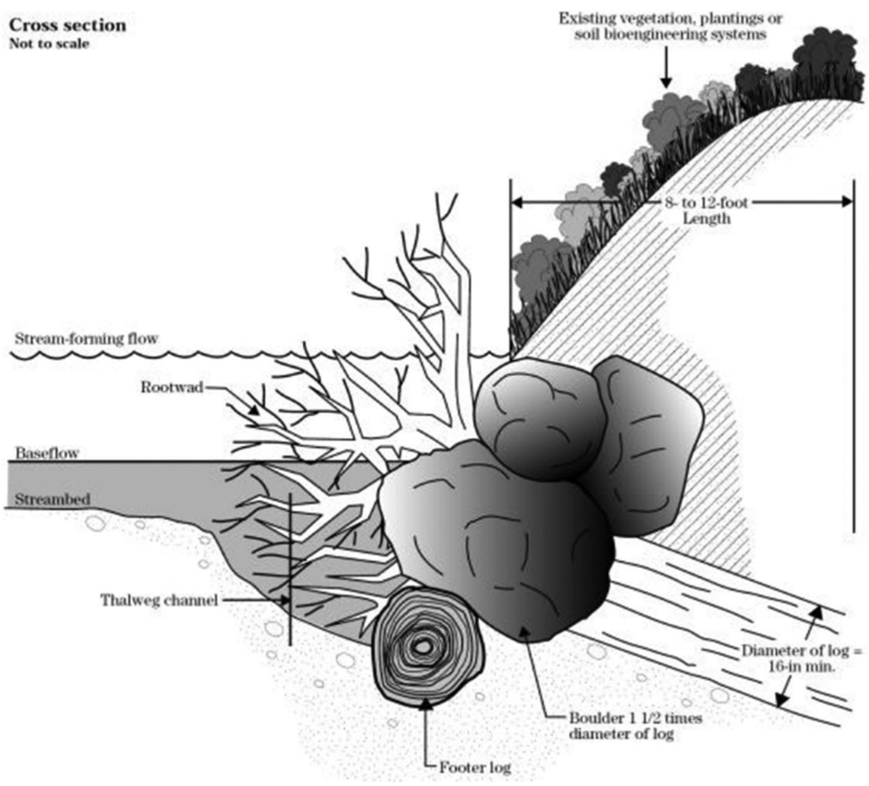


Figure B.1 (Continued).



f) vegetated gabions



g) root wads (with boulders and footer log)

Figure B.1 (Continued).

h) stream barbs (these are similar to but not identical to bendway weirs, and to a lesser extent, rock vanes)

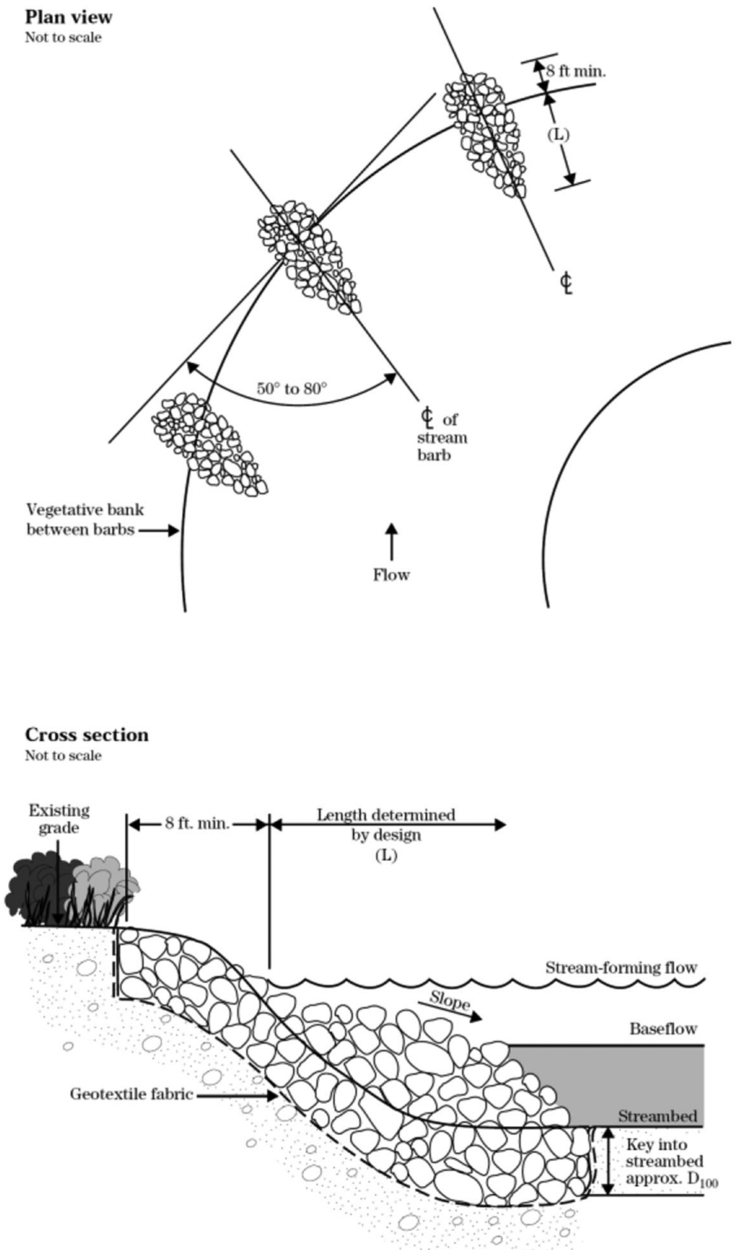


Figure B.1 (Continued).

About the Joint Transportation Research Program (JTRP)

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

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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