



**REGIONAL APPLICATIONS FOR BIOTECHNICAL METHODS
OF STREAMBANK STABILIZATION IN TEXAS:
A LITERATURE REVIEW**

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16. Abstract Using current literature and by reviewing current practice, this project will identify bioengineering and biotechnical streambank stabilization technologies appropriate to the climatic and resource regions of Texas. Concurrently, selected TxDOT districts will be surveyed to determine the types and extent of streambank erosion problems that would be amenable to bioengineering or biotechnical solutions. Based on this information, an evaluation of the potential cost effectiveness of various methods will be prepared along with recommendations for the development of demonstration projects as a means of transferring the research findings into practice. Project results will be provided in a research report. Technical materials will be prepared in the TxDOT "on-line" document format for later insertion in the TxDOT On-line Design Manual.					
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LITERATURE REVIEW

Introduction

Traditional practices for streambank stabilization, which developed from years of scientific research and analysis, have provided TxDOT with successful solutions to erosion control objectives. Through the use of concrete and other non-biodegradable controls, stream channels have been straightened, deepened, widened, lined, reshaped, relocated, and routed through pipes, tunnels, and trans-basin diversions. What has been successful in the past is now being reevaluated due to the impact of urbanization changes and public opinion concerning the environment, as well as the suspected potential effects of traditional stabilization methods on upstream and downstream areas.

Given the potential effects traditional streambank stabilization methods have on the stability and integrity of natural systems, TxDOT launched a study to investigate bioengineering and biotechnical erosion control technologies. Bioengineering and biotechnical technologies use natural vegetation, either exclusively or in combination with additional geosynthetic materials, to achieve streambank stabilization. It appears that where natural, geologic, and biologic processes are used in place of traditional methods, they prove to be less expensive over the lifetime of the project.

Based on the scope of this study, specific objectives of this literature review are:

1. Identify bioengineering or biotechnical streambank stabilization technologies with the potential to lower the life-cycle costs of meeting erosion control objectives in Texas.
2. Develop a table of average life-cycle costs for design, construction, and maintenance of various bioengineering or biotechnical streambank stabilization methods.
3. Evaluate the potential cost effectiveness of various bioengineering and biotechnical streambank stabilization methods in relation to traditional streambank stabilization methods.

The literature review utilized a variety of literature search engines and data sets, and covered different disciplines dealing with streambank-related issues for identifying methods that have potential application to TxDOT practice. Resources included university libraries across the country, library of the U.S. Army Corps of Engineers, government documents, academic journals/periodicals, trade magazines, and on-line resources. Studied fields covered bioengineering, engineering, geomorphology, and ecology so that a better understanding of soil erosion along streambanks could be achieved. Despite the broad search, the literature review primarily focused on how streambank erosion problems can be controlled using soil bioengineering and biotechnical techniques. Additional advantages, such as wildlife habitat provision and aesthetic enhancement or issues regarding bioengineering, are beyond the scope of this project and will not be discussed in the project.

Terminology: Soil Bioengineering and Biotechnical Engineering

The literature search did not provide a consensus definition for the terms soil bioengineering and biotechnical engineering. Turrini-Smith (1994) reports that specific terminology used across the field “inherently creates a language barrier and problems for cross discipline information exchange.”

It is certain that both soil bioengineering and biotechnical slope stabilization practices involve the use of live plant materials to stabilize a streambank. Gray and Sotir (1996) regard soil bioengineering as a “subset of biotechnical stabilization.” Based on their classification, soil bioengineering uses plant parts alone to stabilize a bank or slope, whereas biotechnical engineering utilizes both plant parts and mechanical elements. This suggests that the two methods are distinguishable based on whether or not vegetation is considered an engineering material.

In contrast to Gray and Sotir (1996), Coppin and Richards (1990) view vegetation as an engineering material because it has certain physical properties that enable it to perform major engineering functions. The physical properties vary over time because of seasonal changes and growing stages, which affect strength and physical shape. Gray and Sotir’s argument is further clouded by Biedenharn, Elliott, and Watson (1997) who assert that vegetative (bioengineering) applications typically incorporate the use of structural protection.

If vegetation is an engineering material and if most “bioengineering” applications require the use of structural protection, then it would seem that all streambank stabilization practices using vegetation as part of the solution can be broadly classified as biotechnical methods. Therefore, in an effort to reduce terminology confusion, the term “biotechnical” discussed in this project will apply to all streambank stabilization methods.

Geomorphological Perspective on Streambank Stabilization

Fluvial geomorphology is the field science of rivers. It includes river behavior, sedimentation, hydraulics, restoration, fish habitat improvement, riparian grazing management, and streambank erosion. Compared with the engineering approach that is often solely related to detailed laboratory experimentation and complex mathematical procedures, fluvial geomorphology focuses on field-based research as well as engineering mathematical modeling (Gurnell and Petts 1995). Fluvial geomorphology is based on six basic concepts relating to rivers and watersheds (Biedenharn, Elliott, and Watson 1997):

1. The river is only part of a system.
2. The system is dynamic.
3. The system behaves with complexity.
4. Geomorphic thresholds exist, and when exceeded, can result in abrupt changes.
5. Geomorphic analyses provide a historical prospective, and we must be aware of the time scale.
6. The scale of the stream must be considered.

Based on stream properties, the classification of stream systems enables researchers to generalize field observations across different streams. For engineering purposes, the stream classification can facilitate the assessment of streams with regard to (1) lateral stability and (2) the guide to the future behavior of a stream (Brice and Blodgett 1978). Brice and Blodgett (1978) reported five alluvial stream types shown in Figure 1.

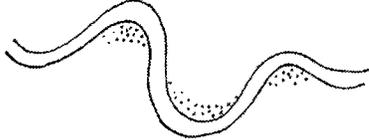
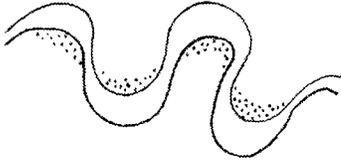
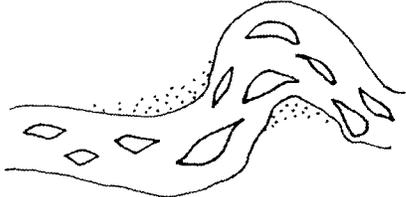
Stream Type	Schematic Plan View
Type A: equi-width, point-bar stream	
Type B: wide-bend, point-bar stream	
Type C: braided, point-bar stream	
Type D: braided stream, without point bars	
Type E: anabranching stream	

Figure 1. Brice and Blodgett’s Five Alluvial Stream Types.

Davis (1899), Leopold and Wolman (1957), Leopold (1964), and others conducted studies that created the impetus for a recent stream classification system developed by Rosgen (1996). This stream classification system is based on five parameters:

- entrenchment ratio,
- bankfull width to bankfull depth ratio,
- sinuosity,
- channel slope, and
- dominant bed material.

Rosgen (1996) also stated:

“...natural stream stability is achieved by allowing the river to develop a stable dimension, pattern, and profile such that, over time, channel features are maintained and the stream system neither aggrades nor degrades. The physical appearance and operational character of the modern-day river is a product of the adjustment of the river’s boundaries to the magnitude of stream flow and erosional debris produced from an attendant watershed.”

Engineers later adopted Rosgen’s stream classification system and the natural stability concept for designing streambank stabilization projects (e.g., Dutnell 1998, and Dutnell 1999).

Fluvial geomorphologists insist that the complete river system must be considered if erosion problems are to be identified and appropriate solutions applied. Ultimately, examining the river’s geomorphic and hydrologic conditions will determine the channel’s ability to transport sediment and water volumes from its watershed over time without experiencing aggradation or degradation (Leopold 1964).

In an alluvial stream, the stream’s energy creates a dynamic equilibrium in which sediment loads entering a stream reach are equal to those leaving it (Riley 1998). Rosgen (1996) uses the term “natural stability” to describe “dynamic equilibrium.” This dynamic equilibrium has a fourth dimension — a natural meandering component and should be considered in channel design (Turrini-Smith 1994).

The results of fluvial geomorphologists’ research are not widely used in flood-control channel design (Williams 1990). Typical streambank stabilization engineering approaches have lacked broad fluvial morphology concepts. For example, dams have been used to control flow, which directly influences sediment transport processes. Channelization has often been undertaken to accelerate the passage of flood peaks, which often increases flooding downstream (Richards 1982).

The link between geomorphology and biotechnical methods for streambank stabilization has become stronger in the last decade. More projects and studies have recommended the use of fluvial geomorphology concepts for streambank stabilization, including: Kondolf and Micheli (1995), Larson and McGill (1997), Dutnell (1998), Dutnell (1999), Turrini-Smith (1994),

USDA/NRCS (1992), USDA/NRCS (1996), Biedenharn et al. (1997), Lagasse et al. (1995), Lagasse et al. (1997), and others.

Larson and McGill (1997) determined that integrating fluvial geomorphic principles into bioengineering techniques could provide a means of integrating nonpoint source pollution control and habitat enhancement with conventional waterway management goals.

The geomorphology stream classification system has obtained streambank stabilization engineers' acceptance, but it is uncertain whether this concept can effectively solve TxDOT's problems because:

- Natural stability or dynamic equilibrium asserted by geomorphologists is based on unchanged conditions such as land uses. If any of the hydrological and geomorphological factors change, this natural stability will not remain. Any construction may produce major changes in stream characteristics locally and throughout an entire reach. Texas is encountering a tremendous development rate in metropolitan areas. It is certain that the geomorphological factors of a stream are constantly changing, which will affect stream stability.
- Highway bridges are essentially fixed structures during their service time. The immobility of bridges cannot allow too much lateral and vertical migration of streams. While the geomorphic analysis can predict lateral and vertical stream movements, it cannot provide instant stability to bridge columns and abutments that need immediate stabilization.

Therefore, the challenge is to provide immediate and sustainable protection of highway structures without introducing new problems upstream and downstream. Geomorphic analysis of a stream is a good tool to predict stream stability. Thus, the geomorphic data will be more effective if they are applied to the bridge planning stage.

Traditional Channel Design and Bank Stabilization

The traditional armoring methods of streambank stabilization usually are stone riprap, concrete pavement, rock gabions, bulkheads made of steel, concrete, aluminum, sack revetments, asphalt mixes, and jetties (Keown 1983). Traditional channel design produces a stable channel, which means a channel never changes its plan form and cross-sections (Lane 1955). Three traditional engineering theories establish stable channel design practice: maximum permissible velocity, regime, and tractive force, all of which are based on the same assumption of steady and uniform flow in straight channels (Chow 1959). A natural stream meanders and is often characterized by unsteady, non-uniform flow, which calls into question the validity of using these assumptions for channel design.

One of the most common methods used to stabilize a streambed is channelization. Some widely used channelization techniques include widening and deepening of natural channels, channel straightening, culverts, trapezoidal cross-section channels, channels lined with hard materials, removal of riparian vegetation, etc. (Turrini-Smith 1994). A channelization project seeks to

minimize the natural erosion process and reduce meandering of a stream channel. Engineers use rock or concrete block to protect the channel bottom and banks. This practice also uses grade-control structures and energy dissipaters to dissipate the flow energy. Without careful planning and environmental assessment, stream channelization may induce numerous physical and biological impacts.

Many governmental agencies have come to favor stone and concrete riprap because over time, a high degree of precision and confidence has developed from research and analysis. Most riprap designs focus on specific stone and channel factors, including: stone shape, size, weight, durability, gradation; riprap layer thickness; and channel side slopes, roughness, shape, alignment, and invert slope (Biedenharn, Elliott, and Watson 1997). Both stone production and placement are key considerations in riprap stabilization success. Particular attention is given to stone size as it relates to the safety factor. Riprap success will be affected by hydrodynamic and/or non-hydrodynamic forces, including but not limited to: large floating debris, vandalism, inability to determine exact size for rocks, unavoidable and inevitable pockets of undersized rocks, and freeze-thaw conditions.

Concrete riprap can be installed anywhere with little consideration of regional and site conditions. In most instances, channelization is applied where streams have strong meandering tendencies and often the upstream and/or downstream impact is not considered. In addition, numerous contractors install riprap competently.

Riprap stabilization is not necessarily guaranteed to succeed even with comprehensive design specifications. Riprap with a smooth surface such as concrete is prone to accelerate stream flow, which causes erosion downstream. Riley (1998) notes that an actively meandering river can cause various failures, such as erosion, disassembling, or redirection of the flow. Although failure is always possible, Racin et al., (1996) observed that most (riprapped) sites are not normally field-evaluated after they are built. Consequently, there has been little investigation and even less documentation of a benefit-to-cost relationship. Despite this lack of documentation, engineers considered riprap economical given the lack of adequate alternatives (Simons, Li, and Associates 1982).

Riprap requires clearance of natural vegetation for construction, resulting in a significant reduction in the aesthetic value of the surroundings. Analogous with the loss of vegetation is a loss of habitat diversity, a dramatic impact on wildlife, changes in water quality, and aquatic life.

In addition to the aesthetics impact, channelization usually violates the basic physical equilibrium of streams. Riley (1998) claims that channelization projects “reduce the rates of change in equilibrium cycles and create more uniform channel conditions, depths, and velocities...” In the past, engineers have generally assumed that once the traditional methods are in place, the project was complete. Therefore, project engineers placed little emphasis on important follow-up evaluations. For the past 50 years, many channelization projects failed and unfortunately engineers learned few lessons because post-project evaluations were rarely performed.

Fundamental Concepts of Biotechnical Streambank Stabilization

The physical vegetative coverage on streambanks provides underground soil reinforcement and surface protection from scour. Hydraulically, a stream's flow characteristics will change depending on the vegetative cover of its banks. The level of vegetation for protecting the soil depends on the combined effects of roots, stems, and foliage (Coppin and Richards 1990). Dense shrubs and trees on streambanks can decrease flow velocities with their stems and foliage, and dissipate flow energy by redistributing the flow pattern and direction. On the other hand, excessive foliage can lead to the reduction in channel capacity, causing a greater flood potential upstream. Coppin and Richards (1990) analyzed vegetation's engineering functions and determined that its effects are both adverse and beneficial, depending on the circumstances. Vegetation reduces surface erosion because its engineering properties can:

- intercept raindrops, prevent soil compaction, and maintain infiltration;
- slow surface runoff;
- restrain soil particle detachment via shallow, dense root systems, consequently reducing sediment transport; and
- delay soil saturation through transpiration.

Throughout the literature, studies conclude that vegetation slows runoff velocities, increases runoff concentration times, and decreases peak flow rates. Few, if any, have provided data that will predict, with any certainty, the relationship between a stream's behavior and vegetation's ability to stabilize a streambank. Equations have been devised to provide a value for water-surface elevation of flood flows or channel capacities to carry flows. Manning's equation is able to represent only the conditions found at a single cross-section and cannot depict non-uniform reaches (Riley 1998). Furthermore, Manning and other sediment transport equations do not cover all three methods of transport (Styczen and Morgan 1995).

Woody vegetation installed on slopes and streambanks provides resistance to shallow mass-movement by counterbalancing local instabilities. The primary mechanisms include (Gray and Sotir 1996):

- reinforcing the soil with tensile fibers of the root mass,
- increasing shear strength by reducing pore-pressures through transpiration, and
- anchoring the slope through deep root penetration into more stable strata.

Root systems aid streambank stabilization through soil-root interaction. Gray and Leiser (1982), Coppin and Richards (1990), and others have developed theoretical models of root-reinforced soils. Coppin and Richards (1990) state that the mechanics of root-reinforcement are similar to the basic mechanics of reinforced-earth systems.

Biotechnical Streambank Stabilization Literature Summary

The nature of vegetation as a living and changing structure indicates that it can be a valuable, timesaving erosion control method on one hand and a complex obstacle on the other. Research

efforts throughout the literature reflect this paradoxical view. There is a strong foundation of scientific theory behind the use of biotechnical methods. In contrast, there is a consistent lack in widely available selection criteria, engineering design guidelines, analyses, technical information, maintenance, and post-project evaluation. Thorne et al. (1997) distinguishes knowledge of the hydraulic effects of woody riparian vegetation into three categories: theoretical derivation, flume studies, and field experience. They further state, "No large, quantitative data sets exist from which to derive prediction capability, especially capability that can be applied under the conditions encountered along natural streams and rivers."

This lack of technical information remains an obstacle to broader use of the technology. Most biotechnical slope stabilization studies fail to expand on or challenge any existing theories. In fact, upon his investigation of the literature, Gerstgraser (1999) determined that few studies produced original, evaluative data. He described the available literature as significantly lacking in original source citations. Researchers appear to have assumed general biotechnical information is accurate and as complete as attainable.

Where most sources agree that structural stabilization methods require minimum pre-evaluation of the site in order to accomplish erosion control objectives, biotechnical methods require a systematic site analysis in order to attain appropriate selection and design. Gray and Sotir (1996) state that a site analysis must include information about microclimate, soils, topography, and surrounding vegetation. A site analysis should then be matched with the actual properties of a given bank stabilization technique to determine the suitability of a specific technique for a site.

When a biotechnical method is determined environmentally compatible to a site, the stabilization effectiveness must be deemed adequate. Biedenharn, Elliott, and Watson (1997) describe effectiveness factors as:

- durability,
- adjustment to scour or subsidence,
- river depths,
- foreshore limitations,
- channel alignment,
- impact on flowlines, and
- impact on erosion upstream and downstream.

Within each of the effectiveness factors, there are many sub-factors that must be considered before design takes place.

Even an involved and detailed site analysis leaves uncertainty in crucial design factors. Kelly (1996) stated "many case studies exist, but there is a need to compare and quantify the characteristics of a population of sites to determine the factors which favor the successful use of these vegetative techniques." A designer must determine the most suitable and effective solution to the problem that will match the strength of protection against strength of attack and will perform most efficiently when tested by the strongest process of erosion and most critical

mechanism of failure (Biedenharn, Elliott, and Watson 1997). Unfortunately, this is not an easy task.

Throughout the literature, vegetative protection is noted as being subordinate to structural protection because design and installation is not as precise and cannot yield as high a safety factor due to the uncertainties that have yet to be completely understood. Design recommendations repeatedly occur in the form of installation guidelines or very broad statements of what factors influence design, but there are no specific plans and specifications that detail how to design a particular method given a specific situation. Ideally, research studies would have documented plans and specifications and included material descriptions and specifications, construction methods and tolerances, as well as plans and typical sections. Furthermore, researchers compared the few studies that did include documented plans and specifications, but inconsistencies throughout made it impossible to identify a specific method ideally suited to a particular situation.

Maintenance

The majority of literature sources recognize that maintenance of biotechnical installations is important. Despite this, the literature reflects a deficiency in maintenance recommendations. Furthermore, it appears that lack of maintenance and repair is a mistake made frequently among soil bioengineering projects. Maintenance guidance found in the literature ranges broadly from claims that biotechnical stabilization methods require “little maintenance” (Sotir 1998) to general long-term maintenance goals, such as: maintenance of existing vegetation, vegetative enhancement, and habitat improvement and maintenance access (Johnson and Stypula 1993). Perhaps this generality can be attributed to what Fischenich and Baker (1993) claim are “infinite variables that could go wrong.”

Morgan and Rickson (1995) determined that lack of “vegetation management” could result in, “interference with angling, navigation and recreation as well as impairing the passage of water.” Thorne et al. (1997) outlines considerations that should influence a maintenance plan, including: the requirements of channel capacity for flood conveyance, bank erosion protection, water quality, fish and wildlife habitat functions, and scenic amenity. Sources advocate performing specific maintenance tasks, but these are typically geared toward one particular planting method.

Schiechtl and Stern (1996) recommend the following maintenance operations are conducted during the development phase, usually between two and five growing seasons:

- fertilizing,
- irrigation,
- ground prep,
- mulch and mowing (depending on site conditions),
- pruning,
- staking and tying, and
- pest and disease control.

Additional sources that were found to contain specific maintenance recommendations did not vary significantly from Schiechl and Stern's list and were not as comprehensive (Gray and Sotir 1992, 1996; Allen and Leech 1997). Even with specific maintenance tasks described, sources fail to provide solid criteria that outline how to identify areas in need of maintenance, with what frequency and intensity maintenance activities should occur, or potential methods that might make maintenance more effective and/or reduce the need for further activities.

Post-Project Evaluation

Post-project evaluation of streambank stabilization projects is needed for several reasons including cost, lack of baseline data, and absence of monitoring guidelines. Biedenharn, Elliott, and Watson (1997) point out that cost often demarcates monitoring activities. Kondolf (1995) reported that sponsoring agencies preferred funding tangible construction projects rather than supporting intangible monitoring and evaluation studies.

Often, where efforts are made to perform post-project evaluations, there are no baseline data with which to compare current activity. Kelly (1996) noted comparisons on a before/after basis were unattainable because, "most of the study sites were poorly documented regarding condition of the site before remediation." This statement is true for most research studies. This lack of comparable data can be traced to the onset of many stabilization projects where evaluation criteria and techniques are not considered until after the project has been designed and implemented (Kondolf and Micheli 1995).

The "shortage of reliable technique assessment" (Turrini-Smith 1994) has prompted researchers to consider criteria for post-project monitoring. Kelly (1996) describes several evaluative methods: field observation and survey of the site; channel cross-sections; bankfull channel characteristics; longitudinal slope; radius of the bend curvature; and division of the bend into three sectors. Evaluation variables described by Shields and Knight (1995) include mean daily discharge, sediment load, base flow depth, average maximum scour hole depth, fish sampling, and cutting survival rate. Kondolf and Micheli (1995) analyze success or failure of channel capacity and stability based on channel cross-section, flood stage surveys, width-to-depth ratio, rates of bank or bed erosion, and aerial photography interpretation. Although all have some evaluation techniques in common, no sources agree on which variable is the most important or the best indicator of a success or failure.

Biedenharn, Elliott, and Watson (1997) break down monitoring activities into five levels. Level 1 focuses on visual observation and involves the least intensive activity. The intermediately intensive levels 2, 3, and 4 involve a photographic record, physical measurements, and a comprehensive survey, respectively. Level 5, the most intensive effort, includes focused survey, measurements, and analysis of a site. However, there is no recommendation as to when a project would be best monitored at Level 5 (most expensive and time consuming) over Level 1 or 2. This monitoring system does not outline which particular level is sufficient for specific plantings, project locations, etc.

Kondolf's five elements for effective evaluation of stream restoration describe a monitoring plan that will indicate a study conducted in the interest of documenting the effort and outcome. This plan involves:

- clear objectives,
- baseline data,
- good study design,
- commitment to long term (at least 10 years), and
- willingness to acknowledge failures.

Kondolf and Micheli (1995) inferred that the absence of systematic post-project evaluation might result from inherent difficulties in measuring stream restoration success. Regardless, with no post-project evaluation and broad dissemination of results, little technical information can be established for future references. This prevalent lack of evaluation guidelines contributes to the design discrepancies and ultimately to system failures.

Biotechnical Methods Overview

This overview introduces the most widely accepted and used techniques collected from the literature. It should be noted that the extent of biotechnical methods includes the applications from basic surface protection such as hydroseeding, to intermediate surface treatment such as live cuttings, to high strength bank and slope reinforcement such as live crib walls. Schiechl and Stern (1997) describe biotechnical methods in two categories: bank protection techniques and bank stabilization techniques, in which bank protection is mainly seeding, and bank stabilization techniques cover woody planting as well as combined application of planting and artificial structures. Since the purpose of this project is to explore the use of biotechnical streambank stabilization, and also because the Texas Department of Transportation knows and has applied the hydroseeding technique, this overview focuses on bank stabilization techniques only (see Appendix).

Available Biotechnical Stabilization Guidelines

Researchers have documented case histories that describe specific projects implemented in different sites. Most of them are only for successful examples with hardly any failed cases. Tendencies found in the literature follow.

First, publications in this field tend to promote the positive side of biotechnical methods over traditional ones but cautiously warn of the risks associated with them. For publications entitled "manual" or "guidelines," most provide an overview of biotechnical methods and more or less general design considerations and plant selection.

Second, the Corps of Engineers (COE) and the Natural Resources Conservation Services (NRCS) are two leading federal agencies in disseminating knowledge of this field. While COE has strong engineering research support, NRCS specializes in plant selections.

Third, technical information has been well developed for structural elements including artificial and natural materials. Research in earth slope stability, strength of a root system, and a man-made structure has been investigated. However, for combined effects of artificial and vegetative materials, there is no information as to how these designs behave and how strong they are.

Last, the evaluation methods and criteria are usually unclear or subjective. Researchers tend to base conclusions on short-term observation or measurement. Despite deficiencies cited above regarding some aspects of biotechnical application, useful information can be located in the literature. Table 1 lists these references.

Advantages of Biotechnical Stabilization

The advantages of biotechnical streambank stabilization over the use of traditional methods, according to Schiechl and Stern (1997), have four aspects: geotechnical, ecological, economic, and aesthetic. Some of these aspects are measurable and can demonstrate direct advantage in using biotechnical streambank stabilization over traditional methods, and some aspects are intangible and require focusing on value over a quantifiable benefit.

Geotechnical. Traditional methods have demonstrated performance problems causing increases in channel slope, resulting in an increase in the velocity of the water (Riley 1998). Biotechnical stabilization avoids straight channelization, which maintains similar hydraulics and geomorphology before and after the implementation of the technique. Vegetation creates flow resistance, which affects the transport capacity of runoff by controlling its volume and velocity (Thorne et al. 1997). The maintenance of stream characteristics reduces the upstream and downstream impact. Furthermore, this method enhances the level of performance through the establishment of a soil-root matrix, which provides improved strength and structural stability over time, thereby increasing the safety factor (Biedenharn, Elliott, and Watson 1997).

Ecological. Reports indicate the use of vegetation in biotechnical stabilization helps protect the ecological integrity and biodiversity of aquatic systems in freshwater resources. Henderson (1986) cited flow depths and velocities, as well as streambed and streambank conditions, as factors impacting habitat diversity when traditional methods are used. Biotechnical stabilization strives to produce a more natural fluvial channel, with slack-water areas, eddies, and scour holes, which will in turn provide a diversity of aquatic habitats. Kondolf and Micheli (1995) describe two evaluation techniques that can measure the ecological success of biotechnical stabilization:

1. creation of physical habitat features, such as pools and riffles or riparian nesting areas; and
2. increases in organism populations.

They point out that numbers of fish may be completely unrelated to geomorphic changes, and otherwise dependent upon numerous biological and abiotic factors.

Table 1. Overview of Biotechnical Stabilization Guidelines.

Year	Authors/Publishers	Title	Remarks
2000	Fischenich, J. C., and Allen, H.	<i>Stream Management</i>	<ul style="list-style-type: none"> • Design by zones (toe, splash, bank, and terrace) • Structural design guidelines for stone riprap, geotextile, and deflection structures • Handling of plant materials • Details (drawings and construction procedures) of biotechnical methods • Corps of Engineer's other references cited for advanced technical information
1998	Bentrup, G., and Hoag, J. C.	<i>The Practical Streambank Bioengineering Guide: User's Guide for Natural Streambank Stabilization Techniques in the Arid and Semi-arid Great Basin and Intermountain West</i>	<ul style="list-style-type: none"> • Information mostly cited from other references • General overview of biotechnical methods • Details (drawings and construction procedures) of biotechnical methods
1997	Schicchtl, H. M., and Stern, R.	<i>Water Bioengineering Techniques for Watercourse, Bank and Shoreline Protection</i>	<ul style="list-style-type: none"> • Brief planning and design considerations • General overview of biotechnical methods • Details (drawings and construction procedures) of biotechnical methods • Cost information
1997	Biedenharn, D. S., Elliott, C. M., and Watson, C. C.	<i>The WES Stream Investigation and Streambank Stabilization Handbook</i>	<ul style="list-style-type: none"> • Part of this report incorporated into "Stream Management" • Cost information
1997	Allen, H. H., and Leech, J. R.	<i>Bioengineering for Streambank Erosion Control</i>	<ul style="list-style-type: none"> • Former Chapter 5 of "Stream Management"
1996	Natural Resources Conservation Service	<i>Engineering Field Handbook Chapter 16: Streambank and Shoreline Protection</i>	<ul style="list-style-type: none"> • General overview of biotechnical methods • Details (drawings and construction procedures) of biotechnical methods • Described effectiveness of biotechnical methods
1996	Gray, D. H., and Sotir, R.B.	<i>Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control</i>	<ul style="list-style-type: none"> • Thorough technical information on geotechnical engineering • Strength of vegetative elements • General overview of biotechnical methods • Details (drawings and construction procedures) of biotechnical methods • Cost information
1995	Morgan, R. P. C., and Rickson, R. J.	<i>Slope Stabilization and Erosion Control: A Bioengineering Approach</i>	<ul style="list-style-type: none"> • Technical data for vegetation and geotextile • Geotechnical slope stability analysis • Scientific vegetation strength research
1993	Johnson, A. W., and Stypula, J. M.	<i>Guidelines for Bank Stabilization Projects: In the Riverine Environments of King County</i>	<ul style="list-style-type: none"> • Planning and design considerations • General overview of biotechnical methods • Details (drawings and construction procedures) of biotechnical methods • Cost information • Permits and policies issues
1993	Fischenich, J. C.	<i>Streambank Erosion Control Manual</i>	<ul style="list-style-type: none"> • Part of this report incorporated into "Stream Management"
1990	Coppin, N. J., and Richards, I. G.	<i>Use of Vegetation in Civil Engineering</i>	<ul style="list-style-type: none"> • A U.K. publication • Scientific research results of vegetation properties • Brief introduction of biotechnical methods

In addition to the ecological advantage, vegetation has been reported to positively impact water quality. Sediment and nutrients are trapped and removed during high flow events (Schiechtl and Stern 1997). Nutrients capable of being eliminated by anaerobic bacteria to a gaseous by-product could be reduced in well-managed riparian zones before polluting stream flow (Manci 1989). Larson and McGill (1997) support integrating fluvial geomorphic principles with bioengineering techniques in order to provide a means of combining nonpoint source pollution control with conventional waterway management goals.

Economic. Traditional methods have been considered economically appropriate but much of the cost information disregards all factors influencing economic feasibility. Riley (1998) states that maintenance programs for concrete and riprap systems should be “constant and expensive” or the protection works will quickly deteriorate. While the front-end installation cost of biotechnical stabilization can be higher than that of traditional methods, evidence suggests that the lifetime cost of biotechnical stabilization is lower. Unlike traditional methods that experience progressive deterioration from natural elements causing them to degrade and grow weaker over time, live plants have the ability to be self-healing and self-reinforcing (Turrini-Smith 1994). Gray and Sotir (1996) argue that labor tends to be less expensive due to the required timing of the installation phase of biotechnical stabilization projects.

Aesthetic. A dramatic aesthetic transformation occurs when a natural environment is altered by the use of concrete, riprap, and metal (Riley 1998). With continued emphasis on preservation of nature, biotechnical stabilization has been stressed as the environmentally sensitive approach to streambank erosion control. Conventional engineering designs visually intrude into the landscape, whereas native vegetation designs begin with and maintain visual appeal. And evidence indicates that the aesthetic value increases over time as the vegetative system becomes better established. (Turrini-Smith 1994).

Limits of Biotechnical Stabilization

Biological, technical, and time constraints are three limitations when using biotechnical methods (Schiechtl and Stern 1997), which means (1) the suitability and availability of plants, (2) applicability of biotechnical methods, and (3) construction timing. Live materials create the ultimate stabilization mechanism, but associated problems are not unlikely, as noted below.

1. Survival rate of living material used in biotechnical stabilization is related to many variables such as the handling of the materials, installation care, and weather.
2. Biotechnical stabilization requires longer time to gain full strength while traditional methods reach designed intensity soon after completion.
3. Construction is restricted to dormant periods or growing seasons depending on the selection of vegetation. In general, seeding is performed in growing seasons, and woody live cutting during dormant periods. For catastrophic failures that need instant repair, biotechnical methods may not be applicable. For streams that are frequently inundated during plants' dormant periods, it is more difficult and risky to implement biotechnical methods.

4. For certain regions that have shorter growing seasons, longer time is required for biotechnical methods to reach full strength.
5. Certain aquatic plants have limited habitats, raising doubts about whether the biotechnical method will succeed.
6. Biotechnical methods are not new technology but only a few technical design guidelines are available. In addition, there are fewer contractors that are qualified for biotechnical construction.
7. Even well executed vegetative protection may not achieve the same degree of confidence or with as high a safety factor as structural protection.

Common Failure Causes of Biotechnical Methods

In a biotechnical streambank stabilization project, an exact point or cause of failure is difficult to assign. If Kondolf and Micheli (1995) find inherent difficulties when trying to measure success of a project, it stands to reason that these difficulties might impede failure analysis as well. It is generally thought that processes causing streambank erosion will also contribute to failure causes in a streambank stabilization project. Simons, Li, and Associates (1982) attribute failure and erosion of riverbanks to:

- hydraulic forces that remove erodible bed or bank material,
- geotechnical instabilities that result in bank failures, and
- combination of hydraulic and geotechnical forces.

These general categories of failure can be further broken down into the following specific causes (Keown, et al. 1977):

- erosive attack at the toe of the underwater slope, leading to failure of the overlying bank,
- erosion of the soil along the banks, caused by currents,
- sloughing of saturated cohesive banks incapable of free drainage,
- flow slides (liquefaction) in saturated silty and sandy soil,
- erosion of soil by groundwater seepage out of the bank,
- erosion of the upper bank or the river bottom due to wave action,
- freeze-thaw action,
- abrasion by ice and debris, and
- shrinking and swelling of clays.

Properly planned and executed biotechnical stabilization projects attempt to stop these erosion processes and have been noted for doing so. There are those that have not performed as desired. Sources that documented failure cited the following causes:

- flood – large enough to wash out project before root system established and stabilized bank;
- drought – inadequate rainfall during plant establishment;
- soil conditions unsuitable for plantings to root and proliferate (Gray and Sotir 1996);

- soil moisture extraction and other hydrologic effects of woody vegetation not taken into account when bank stabilized (Gray and Sotir 1996);
- failure of structural materials...external and internal stability requirements, wall shape, inclination and drainage conditions (Gray and Sotir 1996);
- inadequate site preparation...grading and drainage control (Gray and Sotir 1996);
- insect infestation; and
- plant disease.

Certain failure causes are easier to prevent or control than others. Since it is the vegetation that creates the stabilizing force, it would seem that significant effort should be exerted to keep the plants in optimal condition. Therefore, data on plant survival and growth have been the most commonly used parameters to measure project success (Manci 1989). However, Kelly (1996) stated that plant survivorship was not necessarily indicative of success. Furthermore, he also noted that low survivorship did not necessarily result in bank failure. Instead of focusing primarily on vegetation, Kelly advocated narrowing focus to fluvial processes, which he felt were responsible for treatment success above all else.

All biotechnical stabilization projects risk failure. Unfortunately, the literature is as uncertain about failure causes and solutions as it is about technical guidelines or selection criteria. In terms of avoiding failures, Riley (1998) claims that balance is the key. A stream's channel width, depth, and meander should be in balance with its slope, channel bed material, and discharge, otherwise stabilization efforts achieve little success.

Ultimately, project managers should anticipate and plan for failures during the initial phases of the project. A multi-disciplinary approach often offers the best chances of avoiding failure and documenting a project success.

Cost of Biotechnical Methods

When calculating the costs of a biotechnical method, the main considerations are:

- method of implementation: time needed to implement measure, investment costs (e.g. material), necessity of contracting out or external guidance, etc.;
- availability of resources; for example, plants, labor, etc.; and
- maintenance and post-project evaluation.

There may be numerous benefits associated with a particular streambank stabilization method, but ultimately, cost will determine and justify using any engineering method. The literature has pointed out that traditional engineering methods do experience failures occurring sooner than what designers had predicted. Texas bridge cases in Brice and Blodgett (1978) indicated that the bridge abutments area, including upstream and downstream banks, showed signs of failure within 15 years and even as early as one to three years after construction. As a result, cost for that specific engineering application increases beyond what was originally planned. What engineers either did not understand or commonly ignored is that full life-cycle costs should be considered in design. Gaining insight from past mistakes, the literature now considers full life

cycle, including labor, materials, maintenance, and future repair costs. Generally, the analysis of cost-effectiveness seems to favor biotechnical methods over traditional ones on a long-term basis. Coppin and Richards' (1990) cost model (Figure 2) best illustrates this concept.

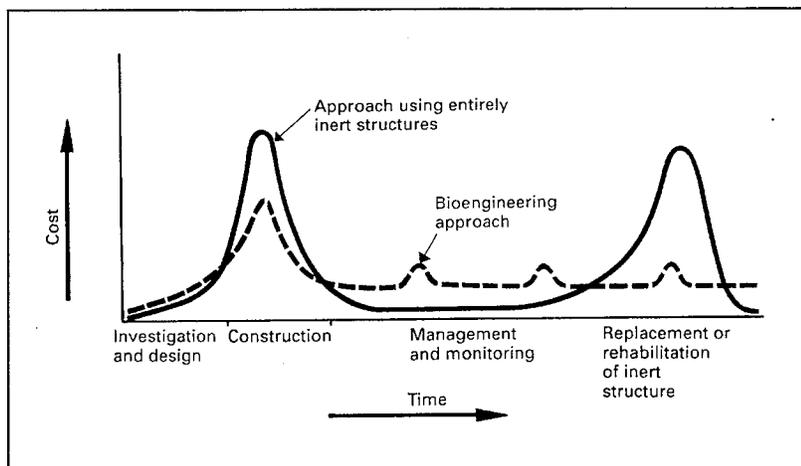


Figure 2. Illustrations of Long-Term Cost Profiles of Inert Structures and Bioengineering Works (Source: Coppin and Richards 1990).

No research proves the cost model illustrated by Coppin and Richards (1990), yet it is frequently cited in the literature. Another weakness of the model is the indefinite serviceable life that biotechnical methods would have. This might not be true for certain species used in biotechnical methods that have a relatively short life, which would require costly substantial replacement of vegetative elements.

While it is possible to draw some general inferences about components of economic returns and costs, a comprehensive assessment of the net benefits from greater use of biotechnical stabilization is not feasible. Many researchers document costs, but the information is presented in a varied and general manner. Reviewing what cost information is available in the literature reveals that detailed costs for specific methods cannot be compiled. In some cases, the total cost of an entire construction is documented while typically a biotechnical streambank stabilization project is involved with more than one method. Hence, a general form of cost data is either: (1) a unit price per linear foot cost derived from total construction costs divided by treated length of the streambank (e.g., Gray and Sotir 1996, and Schiechl and Stern 1997), or (2) a unit man-hour cost calculated from treated length of the streambank divided by estimated man hours (e.g., Biedenharn, Elliott, and Watson 1997). Gray and Sotir (1996) asserted that the combined use of vegetative and structural systems is more cost effective than the use of either system alone. Costs can also vary dramatically due to availability of materials, hauling distances, prevailing labor rates for the geographic area, and other factors (Biedenharn, Elliott, and Watson 1997). Furthermore, the cost information appears contradictory with some sources citing biotechnical engineering is less expensive than structural methods (e.g., Allen and Leech 1997) and some saying that it is considerably more expensive in some cases (e.g., Schiechl and Stern 1997).

Gray and Sotir (1996) provide biotechnical costs in per method, installed unit cost. These cost estimates appear to be more accurate for the simplest biotechnical method, live staking, where the range is \$1.50 to \$3.50 per installed stake, than for alternatives such as brushlayering, which ranges from \$12.00 to \$25.00 per lineal foot installed. At most, these cost data provide a general estimate from which to obtain the least expensive method and the most expensive method and those that fall in between the two.

Alternatively, Tetteh-Wayoe (1994) provides construction costs categorically broken down into materials and supplies, vegetation crew camp cost, and engineering. This information narrows the cost data but does not document the costs according to the installed biotechnical method. One site, Kananasis Backslope, utilized several methods from live staking to brush layering and branch packing. With more than one method installed on a site, a cost number for materials and supplies proves to be more general than originally thought and therefore insufficient as a tool to prepare a cost-effectiveness ratio.

Most research has recognized that cost is a significant and determining factor in the selection and installation of a biotechnical method. In addition, several sources point out that labor costs tend to be one of the most expensive aspects of any installation. Weather influences project costs as well, and the relative difficulty of a particular method can make it more expensive compared to a simpler installation (Tetteh-Wayoe 1994). Generally, site-specific geotechnical and hydraulic conditions along with other environmental, engineering, and maintenance factors influence project costs (Henderson 1986).

Summary

The literature summary provided an overview and relative comparison of the amount of information available related to biotechnical streambank stabilization. The literature frequently discussed some general aspects but it lacks and needs selection criteria information. Much remains to be learned about the incorporation of fluvial concepts into biotechnical streambank stabilization designs. Fluvial geomorphologists insist that the complete river system must be considered if erosion problems are to be identified and appropriate solutions applied. This information is crucial for developing adequate biotechnical stabilization plans and techniques.

Few, if any, sources provided data that will predict with any certainty the relationship between a stream's behavior and vegetation's ability to stabilize a streambank. Kelly (1996) stated "many case studies exist, but there is a need to compare and quantify the characteristics of a population of sites to determine the factors which favor the successful use of these vegetative techniques." Although there is a strong foundation of scientific theory behind biotechnical methods, there is a consistent lack in widely available selection criteria, engineering design guidelines, analyses, technical information, maintenance, and post-project evaluation.

In most studies, selection criteria are exclusively site specific. It appears that the best method available for matching a vegetation plan to a biotechnical method and the suitability of a particular site is to perform a comprehensive site analysis for each project. Clearly, the

development of a selection matrix would streamline the site analysis process and could help identify potential site problems.

Just as selection of a biotechnical method is site specific, so too is the design of a biotechnical method for a particular project. Studies that utilized biotechnical methods did not document the design in terms of plans and specifications, including material descriptions, construction methods and tolerances, and typical sections. Without these detailed design guidelines, successful projects lose repeatability, further fueling the uncertainties and lack of confidence that exists in biotechnical stabilization methods.

Some case studies performed specific maintenance tasks but sources fail to provide solid criteria outlining how to identify areas in need of maintenance, with what frequency and intensity maintenance activities should occur, or potential methods that might make maintenance more effective and/or reduce the need for further activities. Ideally, a comprehensive maintenance program would help determine what the fundamental causes of maintenance problems are so they can be further examined with a view to improving maintenance techniques in general, tracing maintenance problems back to selection and design, and reducing the long-term costs. This type of program would identify maintenance priorities as well as the lowest level of maintenance that would still provide optimum operation and economic use of resources.

Clearly, success of a particular project cannot be properly evaluated without detailed baseline data, careful and thorough post-project monitoring, and an analysis of the data obtained over a long period of time. There are many successful stories but results of vegetative streambank stabilization projects frequently include minimal data based on, at most, two to four growing seasons. This amount of monitoring and documentation is likely not enough time from which to draw any conclusions beyond that time or beyond the range of variables studied. The biotechnical methods, if there are any, have been monitored for a very short period of time and the evaluation methods are either unclear or subjective. Ultimately, the effectiveness and long-term application of most methods are still unknown, and there may be significant implications in using established but limited data for making predictions about project successes. Effective research needs extended project documentation to project changes over time, improve the success rate of future projects, and provide scientific evidence of the successes or failures of biotechnical streambank stabilization methods.

At best, the literature review provided some general inferences about cost-effectiveness. Studies lack and need cost-to-benefit analyses in order to enhance support for future implementation of vegetation streambank stabilization projects. Most sources considered biotechnical methods more cost-effective than traditional methods. This view, not yet proven, remains subjective and hypothetical. Cost evaluation is complicated by the difficulty in placing monetary values on the resources and by the uncertainties (success/failure) associated with vegetative stabilization efforts. As engineers and researchers attempt more projects and collect more data, uncertainty about associated costs will likely diminish, which will aid in planning future projects.

To consider biotechnical streambank stabilization over traditional structural methods requires evaluating the “cycle” of uncertainties that revolve around geomorphological processes, lack of

technical knowledge, uses of vegetation, and other important issues. Some of these aspects are measurable and can demonstrate direct advantage in using biotechnical streambank stabilization over traditional methods; some aspects are intangible and require focusing on value over a quantifiable benefit. Regardless, these uncertainties should not preclude the use of biotechnical methods for streambank stabilization. Schiechl and Stern (1997) concluded that due to reluctance over using biotechnical techniques initially, they have been hastily resorted to and implemented when structural methods fail. Hasty implementation lacks proper planning and preparation and is rarely, if ever, effective. They advocate that from the project's onset, biotechnical techniques should be integrated into traditional engineering methods and given the opportunity to provide solutions to erosion problems. Ultimately, the knowledge base of biotechnical streambank stabilization must be increased in order to provide the necessary data, which will enable informed decisions concerning utilization of these methods.

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APPENDIX

CATALOG OF BIOTECHNICAL METHODS

Source: United States Department of Agriculture, Natural Resources Conservation Service.
Engineering Field Handbook. Chapter 16. 2nd ed. 1996

Cost-Strength Matrix Explanation

Although it is difficult to consistently summarize cost data from the literature due to aforementioned reasons, it is necessary that level of cost within biotechnical applications be provided so that alternatives can be compared. Therefore, cost and strength of biotechnical methods are provided with the overview. Cost and strength data extracted from various literature sources include but are not limited to:

- *Bioengineering for Streambank Erosion Control; Report 1, Guidelines*
- *Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control*
- “The Effect and Resistance of Soil Bioengineering Methods for Streambank Protection” *Proceedings of IECA 1999*
- *Water Bioengineering Techniques for Watercourse, Bank and Shoreline Protection*

The following graphic example is the cost-strength matrix that includes two axes with three levels: low (L), medium (M), and high (H). The location of the bull’s eye circle indicates the cost-strength information for specific biotechnical methods, in which the dark circle is located approximately at the mean value, and the large circle covers most of the varied values from the literature. It should be noted that the strength of biotechnical methods enhances with time. For those methods that have much weaker strength at the early stage after completion, a gray bull’s eye that indicates the early strength is shown. The units for “Cost” and “Strength” are dollars per linear foot, and pounds per square foot, respectively, with the relative values shown on Figure 3.

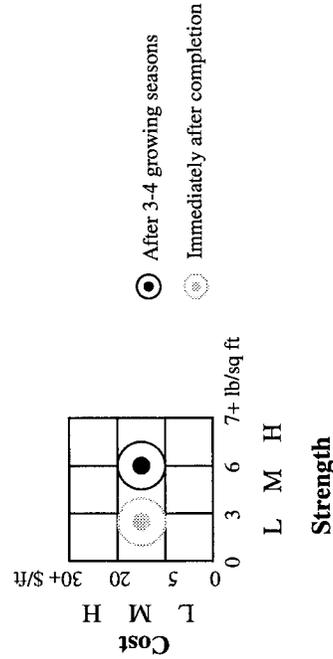
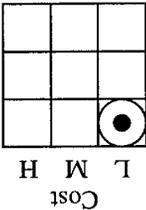
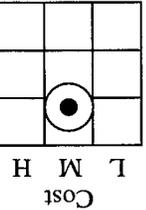
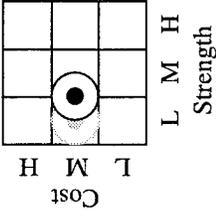
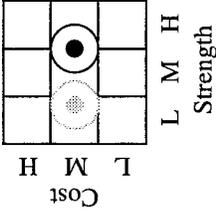
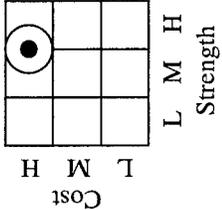
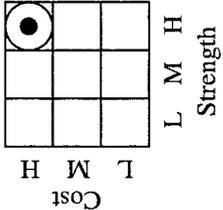
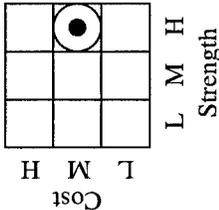
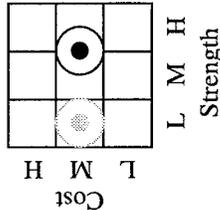


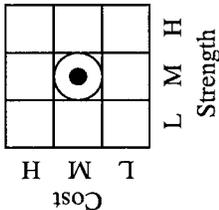
Figure 3. Cost-strength matrix example.

Biotechnical Method	Description	Application and Effectiveness
<p>Live-Stakes</p> 	<p>Live, rootable vegetative cuttings inserted and tamped directly into ground. Living root mat reinforces and binds soil particles together to extract excess soil moisture.</p>	<ul style="list-style-type: none"> • Peg down and enhance performance of surface erosion control materials. • Enhance conditions for natural colonization of vegetation from the surrounding plant community. • Stabilize intervening areas between soil bioengineering techniques, such as live fascines. • Produce streamside habitat. • Most effective when used on small, simple problem sites. • Cuttings may be planted quickly. • Most willow species root rapidly and begin to dry out a bank soon after installation.
<p>Live-Fascines</p> 	<p>Rootable branch cuttings tied together in long cylindrical shaped bundles.</p>	<ul style="list-style-type: none"> • Apply typically above bankfull discharge (stream-forming flow) except on very small drainage area sites (generally less than 2000 acres). • Protect slopes from shallow slides (1 to 2 foot depth). • They should be placed in shallow contour trenches on dry slopes and at an angle on wet slopes to reduce erosion and shallow sliding. • Effective stabilization technique for streambanks. When properly installed, this system does not cause much site disturbance. • Offer immediate protection from surface erosion. • Capable of trapping and holding soil on a streambank by creating small dam-like structures, thus reducing the slope length into a series of shorter slopes. • Serve to facilitate drainage where installed at an angle on the slope. • Enhance conditions for colonization of native vegetation by creating surface stabilization and a microclimate conducive to plant growth.

Biotechnical Method	Description	Application and Effectiveness
<p>Brushlayering</p> 	<p>Live cut branches interspersed between layers of soil in crisscross or overlapping pattern.</p>	<ul style="list-style-type: none"> • Tips of branches protrude just beyond the face of the fill, where they retard runoff velocity and filter sediment out of the slope runoff. • Root along lengths and act immediately as horizontal slope drains. • Stabilize slopes against shallow sliding or mass wasting and provides erosion protection. • Can be more effective than live fascines because the orientation of stems provides better earth reinforcement and mass stability. • Preferred on fill rather than cut slopes because longer stems can be used. • Stabilize and reinforce outside edge or face of drained earth buttresses placed against cut slopes or embankment fills.
<p>Branchpacking</p> 	<p>Alternating layers of live branches and compacted backfill used to repair small, localized slumps and holes in streambanks.</p>	<ul style="list-style-type: none"> • Effective and inexpensive method to repair holes in streambanks that range from 2 to 4 feet in height and depth. • Produces a filter barrier that prevents erosion and scouring from streambank or overbank flow. • Rapidly establishes a vegetated streambank. • Enhances conditions for colonization of native vegetation. • Provides immediate soil reinforcement. • Live branches serve as tensile inclusions for reinforcement once installed. As plant tops begin to grow, the branchpacking system becomes increasingly effective in retarding runoff and reducing surface erosion. Trapped sediment refills the localized slumps or hole, while roots spread throughout the backfill and surrounding earth to form a unified mass. • Typically branchpacking is not effective in slump areas greater than 4 feet deep or 4 feet wide.

Biotechnical Method	Description	Application and Effectiveness
<p>Vegetated Geogrids</p> 	<p>Natural or synthetic geotextile materials are wrapped around each soil lift between the layers of live branch cuttings (similar to branchpacking).</p>	<ul style="list-style-type: none"> • Used above and below stream-forming flow conditions. • Drainage areas should be relatively small (generally less than 2000 acres) with stable streambeds. • The system must be built during low-flow conditions. • Can be complex and expensive. • Produce a newly constructed, well-reinforced streambank. • Useful in restoring outside bends where erosion is a problem. • Capture sediments, which rapidly rebuild to further stabilize the toe of the streambank. • Function immediately after high water to rebuild the bank. • Produce rapid vegetative growth. • Enhance conditions for colonization of native vegetation. • Benefits are similar to those of branchpacking, but a vegetated geogrid can be placed on a 1:1 or steeper slope.
<p>Live Cribwall</p> 	<p>Box-like interlocking arrangement of untreated log or timber members. Structure is filled with suitable backfill material and layers of live branch cuttings that root inside the crib structure and extend into the slope. Once the live cuttings root and become established, the subsequent vegetation gradually takes over the structural functions of the wood members.</p>	<ul style="list-style-type: none"> • Effective on outside bends of streams where strong currents are present. • Appropriate at the base of a slope where a low wall may be required to stabilize the toe of the slope and reduce its steepness. • Appropriate above and below water level where stable streambeds exist. • Useful where space is limited and a more vertical structure is required. • Effective in locations where an eroding bank may eventually form a split channel. • Maintains a natural streambank appearance. • Provides excellent habitat. • Provides immediate protection from erosion, while established vegetation provides long-term stability. • Supplies effective bank erosion control on fast-flowing streams. • Should be tilted back or battered if the system is built on a smooth, evenly sloped surface. • Can be complex and expensive.

Biotechnical Method	Description	Application and Effectiveness
<p>Joint Planting</p>  <p>Cost H M L</p> <p>Strength L M H</p>	<p>Live stakes tamped into joints or open spaces in rocks that have been previously placed on a slope. Alternatively, the stakes can be tamped into place at the same time that rock is being placed on the slope face.</p>	<ul style="list-style-type: none"> • Useful where rock riprap is required or already in place. • Live cuttings root in soil beneath riprap, reinforce bank, and anchor riprap. • Roots improve drainage by removing soil moisture. • Provides immediate protection and is effective in reducing erosion on actively eroding banks. • Dissipates some of the energy along the streambank.
<p>Brushmattress</p>  <p>Cost H M L</p> <p>Strength L M H</p>	<p>Combination of live stakes, live fascines, and branch cuttings installed to cover and stabilize streambanks.</p>	<ul style="list-style-type: none"> • Application typically starts above stream-forming flow conditions and moves up the slope. • Forms an immediate, protective cover over the streambank. • Useful on steep, fast-flowing streams. • Captures sediment during flood conditions. • Rapidly restores riparian vegetation and streamside habitat. • Enhances conditions for colonization of native vegetation.
<p>Tree Revetment</p>	<p>Constructed from whole trees (except rootwads) that are usually cabled together and anchored by earth anchors, which are buried in the bank.</p>	<ul style="list-style-type: none"> • Uses inexpensive, readily available materials to form semi-permanent protection. • Captures sediment and enhances conditions for colonization of native species. • Has self-repairing abilities following damage after flood events if used in combination with soil bioengineering techniques. • Not appropriate near bridges or other structures where there is high potential for downstream damage if the revetment dislodges during flood events. • Has a limited life and may need to be replaced periodically, depending on the climate and durability of tree species used. • May be damaged in streams where heavy ice flows occur. • May require periodic maintenance to replace damaged or deteriorating trees.

Biotechnical Method	Description	Application and Effectiveness
<p>Log, Rootwad, and Boulder Revetment</p>	<p>Logs, rootwads, and boulders are systems that provide excellent overhead cover, resting areas, shelters for insects and other fish food organisms, substrate for aquatic organisms, and increased stream velocity that results in sediment flushing and deeper scour pools.</p>	<ul style="list-style-type: none"> • Used for stabilization and to create instream structures for improved fish rearing and spawning habitat. • Effective on meandering streams with out-of-bank flow conditions. • Will tolerate high boundary shear stress if logs and rootwads are well anchored. • Suited to streams where fish habitat deficiencies exist. • Should be used in combination with soil bioengineering systems or vegetative plantings to stabilize the upper bank and ensure a regenerative source of streambank vegetation. • Enhance diversity of riparian corridor when used in combination with soil bioengineering systems. • Have limited life depending on climate and tree species used. Some species, such as cottonwood or willow, often sprout and accelerate natural colonization. Revetments may need eventual replacement if natural colonization does not take place or soil bioengineering methods are not used in combination.
<p>Dormant Post Plantings</p> 	<p>Form a permeable revetment that is constructed from rootable vegetative material placed along streambanks in a square or triangular pattern.</p>	<ul style="list-style-type: none"> • Well suited to smaller, non-gravelly streams where ice damage is not a problem. • Quickly reestablish riparian vegetation. • Reduces stream velocities and causes sediment deposition in the treated area. • Enhance conditions for colonization of native species. • Self-repairing, damaged posts can develop multiple stems. • Can be used in combination with soil bioengineering systems. • Multiple installation methods. • Unsuccessfully rooted posts at spacings of about 4 feet can provide some benefits by deflecting higher streamflows and trapping sediment.

Biotechnical Method	Description	Application and Effectiveness
Coconut Fiber Rolls	Cylindrical structures composed of coconut husk fibers bound together with twine woven from coconut. Most commonly manufactured in 12-inch diameters and lengths of 20 feet. Staked in place at the toe of the slope, generally at the stream-forming flow stage.	<ul style="list-style-type: none"> • Protect slopes from shallow slides or undermining while trapping sediment that encourages plant growth within the fiber roll. • Flexible; product can mold to existing curvature of streambank. • Produces a well-reinforced streambank without excessive site disturbance. • Prefabricated materials can be expensive. • Manufacturers estimate product has an effective life of 6 to 10 years.

