THE ROLE OF VEGETATED RIPRAP IN HIGHWAY APPLICATIONS

Final Report

SPR 324

THE ROLE OF VEGETATED RIPRAP IN HIGHWAY APPLICATIONS FINAL REPORT

STATE PLANNING AND RESEARCH PROGRAM PROJECT 324

by

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16. Abstract

Riprap is the most commonly used material to protect bridge abutments and highway embankments adjacent to bridge abutments from erosion. Removal of the riparian vegetation in preparation for riprap construction can lead to environmental impacts such as increased water temperature and reduction of the quality of stream habitat. A method that is commonly recommended as a mitigation measure is to plant willows in the riprap to reestablish the riparian vegetation. There are engineering concerns that the willows will reduce the stability and flexibility of the riprap and eventually cause the riprap to fail. This report addresses the review of literature on the subject.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

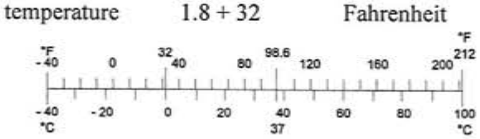
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	Inches	25.4	Millimeters	Mm
ft	Feet	0.305	Meters	M
yd	Yards	0.914	Meters	M
mi	Miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	Acres	0.405	Hectares	Ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	ML
gal	Gallons	3.785	Liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	Ounces	28.35	Grams	G
lb	Pounds	0.454	Kilograms	Kg
T	short tons (2000 lb)	0.907	Megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
Mm	millimeters	0.039	inches	in
M	meters	3.28	feet	ft
M	meters	1.09	yards	yd
Km	kilometers	0.621	miles	mi
		AREA		
Mm^2	millimeters squared	0.0016	square inches	in^2
M^2	meters squared	10.764	square feet	ft^2
Ha	hectares	2.47	acres	ac
Km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ML	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
M^3	meters cubed	35.315	cubic feet	ft^3
M^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
G	grams	0.035	ounces	oz
Kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8 + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement

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DISCLAIMER

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF PHOTOS/FIGURES

1.0 INTRODUCTION

Riprap is commonly used to protect bridge abutments and roadways from stream erosion. Removal of riparian vegetation in preparation for riprap construction may have environmental impacts such as increased water temperature and decreased quality of stream habitat. Consequently, for construction and maintenance work near waterways containing threatened and endangered species, the National Marine Fisheries Service requires that measures be taken to account for removed riparian vegetation. A commonly recommended mitigation measure is to plant native vegetation, such as willows, in the riprap. On the other hand, there are engineering concerns that vegetation growing within riprap could either displace the riprap as it grows or be pulled out during floods, in either case damaging the integrity of the riprap for protecting roadways and bridges. Such displacement-induced damage or pullout-induced damage may provide initiation sites for local scour; if left unrepaired, the scour damage zone could expand and degrade the riprap until it failed. Riprap scour may also cause further loss of fish habitat.

1.1 PROJECT OBJECTIVES

Oregon Department of Transportation (ODOT) initiated a study with faculty at Oregon State University (OSU) to investigate the stability of vegetated riprap. Objectives of the study were to:

(1) Quantify the factors critical to the potential for damage, pullout, and other problems that may occur for vegetation growing in riprap, including factors critical to specific plant species, and

(2) Provide guidance for the proper design of vegetated riprap.

The most likely vegetative species for use in each geographic region of the state were to be identified and analyzed. ODOT staff assumed that plants to be used in association with riprap should be short, bushy, and flexible and that they should grow back readily after any die-off condition occurs. This assumption was to be evaluated as part of the study. The initial phase of the study extended from August 1999 through July 2000.

1.1.1 Investigation Approach

A multidisciplinary team of faculty specialists addressed the issues of vegetated riprap, its use, and its stability. The work tasks were divided into two phases: (1) a problem analysis and (2) the development of design guidelines. The problem analysis was based in part on the available literature and in part on the past experience of the faculty investigators in dealing with erosion problems and vegetative species.

1.1.2 Documents Developed

Several reports were prepared for ODOT in draft form during project work, to provide a continuing status report and supplement the brief quarterly reports. These reports were:

Vegetated Riprap Stability: Literature Review, Problem Analysis, Research Needs, and Possibilities for Use -- Phase 1 Study Report. Working Draft, October 15, 1999.

Vegetated Riprap Stability: Supplemental Notes 1. January 22, 2000.

Up-Rooting Resistance of Trees. January 26, 2000.

Vegetated Riprap Stability: Supplemental Draft Notes for Vegetation Section of Literature Review Report. May 17, 2000. Revised July 14, 2000. Both prepared by John Wilson under guidance of David Hibbs and Boone Kauffman

Vegetated Riprap Stability: Supplemental Notes 3. May 25, 2000.

Use of Vegetated Riprap – Draft Opinion Paper. June 5, 2000.

Vegetated Riprap Stability: Problem Analysis, Possibilities for Use, and Research Needs -- Draft Phase 1 Study Report. June 5, 2000 (replaces working draft of October 15, 1999 and supplements).

Vegetated Riprap Stability: Literature Review, Synthesis, and Interpretation -- Part of Phase 1 Study Report. June 5, 2000 (replaces working draft of October 15, 1999 and supplements).

An unedited synthesis discussion paper was also prepared, but not distributed to ODOT, to guide faculty discussion for Phase 2 of the project:

The Role of Vegetated Riprap in Highway Applications. September 19, 2000.

This present paper is a revision of the September 19, 2000 paper, specifically prepared for distribution to ODOT.

2.0 SCOPE OF CONCERN OVER HIGHWAY PROTECTION FROM STREAMS

Adequate transportation systems are basic to the social and economic welfare of a thriving modern society. From the beginnings of a barter economy through to the specializations that characterize the production of consumer goods today, transportation has been an essential part of how human societies and economies function.

2.1 LIMITED FUNDS LEAD TO COMPROMISES ON ENVIRONMENTAL FACTORS

Despite the importance of Federal and State highway systems and the even more extensive systems of county roads, it has always been a challenge to provide funding adequate for the full serviceability of these systems. The chronically limited resources provided for construction and maintenance of modern transportation systems has led to compromises in some aspects of highway design and maintenance. In particular, environmental factors have typically been viewed as constraints rather than design objectives, because of the added costs of their full inclusion in design. Although some aspects of designs can easily accommodate multiple objectives, other aspects clearly require trade-offs when costs are an issue. This produces individual sub-optimal results in order to obtain an overall optimal result, based on the direct and tangible costs.

2.1.1 Illustrative Example

For example, selection of a new highway alignment that maximizes the full functioning of the ecosystem of an adjacent floodplain could require that the roadway bench be excavated along the adjacent hillside above the floodplain. The likely results of this alternative, from a highway viewpoint, are substantially increased construction cost and sub-optimal roadway alignment. Similarly, an alignment that is placed entirely on fill in the floodplain may produce the least cost and best alignment for the highway, but have the result of greatly reduced ecological and hydrologic functioning of the floodplain, especially during floods. A compromise design (between highway and environmental factors) that balances the section at the base of the hillside and has only limited encroachment on the floodplain may be viewed as sub-optimal for both the highway and the stream, but may be considered optimal on the whole.

2.2 HISTORICAL PRECEDENT FOR HIGHWAYS IN STREAM CORRIDORS

Highways near streams pose particular difficulties and compromises between transportation and environmental factors. This situation largely stems from the historical use of rivers as exploration and migration routes and as highways of commerce, and the associated development of communities, towns and cities in river floodplains. With the advent of the automobile, trails connecting such settlements became roads and later highways. Thus, much of today's transportation network is based on and historically rooted in the proximity to water. Bridging of streams became commonplace, replacing ferries and fords. Floods may have caused some communities to move higher on floodplains, but floodplain occupancy remained a fact of life, both for agricultural and industrial societies. Similarly, trails along narrow stream corridors in hilly areas became roads; these roads were widened to accommodate changing vehicle characteristics and traffic loads. Hence, the basis for much highway "conflict" with streams has deep roots that go back one or more centuries in the U.S. and much longer in Europe and Asia.

2.3 RIPRAP HAS BECOME A COMMON EROSION CONTROL TOOL

The protection of roadways against damage from running water has been a classic struggle involving engineering design techniques, field maintenance measures, and emergency actions. Inevitably, use of dumped or placed material has been one of the standard methods for erosion control. Dumped material (e.g., rubble) is usually not "designed" but instead consists of whatever matter is conveniently available; it typically ranges in composition from dirt to used concrete to industrial waste products (e.g., car bodies and tires). Dumping is usually the consequence of an emergency action or occurs through thoughtless landowner or maintenance actions. The intention is to halt active erosion as quickly as possible and with the least possible cost. Placed material (as contrasted with dumped material) is often "designed" for a specific site or is based on past design applications elsewhere and on 'standards of practice' for particular erosion control techniques. Riprap (angular quarry rock) is one of the most common types of placed materials. Its use is widespread wherever erosion is a threat or may be regarded as a future threat. There are places where riprap has been used indiscriminately, often with the idea that "if a little is good, more is better!"

2.3.1 Riprap in Modern Design

Today, riprap is often a necessary component of structural design for highways and other waterfront uses. It may be found at bridge piers, at bridge abutments, at the bases of retaining walls, along banks of streams that border roads, and at other locations where steep slopes may threaten a future bank failure. Riprap is commonly part of the original design for a roadway project, not just a later maintenance add-on feature.

2.3.2 Riprap Changes Stream Banks and Riparian Zones

From an environmental perspective, a particular concern about riprap is its impact on the character of a stream bank and the broader effects that such impact may have on stream and riparian ecosystems. Direct effects at the site are the most apparent -- change of bank character, loss of vegetation, associated loss of shade and nutrients, potential shifts in the types of plant and animal species present, etc. The indirect and off-site effects are more difficult to identify and quantify. Nevertheless, there is an ecological concern over any excessive and indiscriminate use of riprap as an erosion control measure. Furthermore, past poor use of riprap has alienated many people to the use of riprap for any application.

2.4 FINDING A BALANCE BETWEEN HIGHWAYS AND STREAMS

One way to reduce the amount of required riprap as a part of original design may be to select alignments that have the least interface with streams. This may be practical for new highways, but is difficult to apply to the existing road system, An overlay of Oregon's stream system on a map showing cities and towns will show the near impossibility of avoidance of streams, particularly in the broadest sense which includes their corridors and floodplains. Instead, what can be done is to select and design the interface between the highway and stream in such a way as to limit undesirable outcomes. The balance of this paper discusses ideas and concepts about the interface between highways and streams, with the intention of proposing ways to limit undesirable outcomes. In the following discussion, the words 'stream' and 'river' are used interchangeably to mean a significant water course.

3.0 STRUCTURAL ASPECTS OF HIGHWAYS AND THEIR FOUNDATIONS

We often think of a highway in terms of its most visible element, the pavement. However, pavement requires the support of an earth structure. This overall structure can extend well beyond the pavement edges, extending for some distance in the up-slope and down-slope directions. This may be visible and obvious in the case of engineered cut-slopes and fill-slopes. But natural slopes and floodplain soil or rock materials beneath and beyond the toe of a highway fill may be just as important to the structural integrity of the highway (Figure 3.1). Highway loads are transferred downward and outward from vehicles through pavement to the foundation, progressively spreading out and diminishing in intensity with distance below the wheels. In general, local site conditions determine the extent of the highway structure. This may be narrow for rocky soils but quite wide for soft soil and mud.

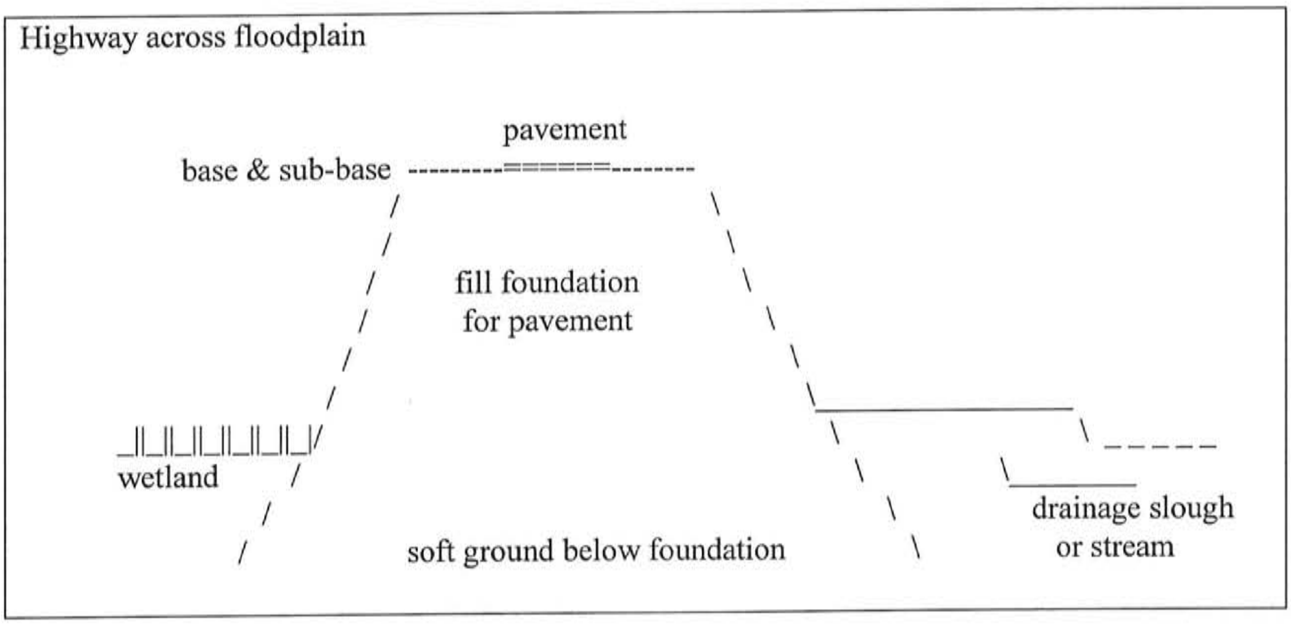

Figure 3.1: Highway Fill Cross Section with Soft Foundation that Extends the Structural Zone Beyond the Toe of the Fill [***This is not the final sketch but shows the ideas***]

3.1 THREATS TO HIGHWAY FOUNDATIONS

If the outer margin of a load-bearing foundation is threatened with damage, the result may be to reduce the overall integrity of the foundation and thus to threaten the pavement itself. If a potential threat is perceived, no matter what the cause, it can be expected that the design will be adjusted accordingly, albeit at increased cost. For example, design modifications can shift the alignment, reduce the lateral extent of the highway structural zone, support the highway differently, or provide other measures to nullify the threat where it may be expected to occur (e.g., inclusion of placed rock or riprap at the outer edge of the foundation in a zone threatened by slippage or stream erosion).

3.2 STRUCTURAL MEASURES AT WATER CROSSINGS

Highway crossings of streams require some form of 'bridge' to span the water. The simplest, a culvert, is not considered in this paper as it has been discussed by two of the authors in other ODOT work. For conventional bridges, the abutments and piers are the structural elements that interact with streams. Such interaction must be addressed through design. Abutments support the ends of a bridge whereas piers offer intermediate structural support at one or more points along the span. Bridges may be designed to 'free-span' the water or may have one or more sets of piers. In considering bridge type, the location and spacing of the abutments is an important cost consideration. When the main design focus is on the structure and control of its cost, rather than on the stream environment, abutments are likely to be closer together and to encroach on both stream banks or even on the water's edge. Fill sections may also be required across the adjacent floodplain approaches to elevate the bridge above floodwaters and allow vertical adjustments in roadbed elevation between the bridge deck and main highway. The extent of lateral encroachment of bridge abutments into the stream is usually limited by the need to provide an ample waterway under the bridge to pass the design flood. The amount of approach fill is usually limited by cost and by the requirement not to aggravate flooding upstream of the highway route.

3.3 STRUCTURAL INFLUENCE OF STREAMS ON HIGHWAYS

Streams dictate many highway features. The design of a new highway or bridge is affected in such ways as highway alignment, roadbed cut-and-fill sections, erosion protection, drainage discharge, bridge type, pier and abutment size and spacing, and associated structural elements. Streams continue to influence highways and bridges long after these structures are built. This influence is primary structural (since alignment issues were resolved during the original design). Bridge abutments and piers must be protected from local scour that could otherwise undermine and weaken the needed structural support. The foundations of roadways along streams must be protected from local damage that could otherwise lead to movement of the foundation and damage to or loss of pavement.

3.3.1 Conventional Riprap Applications

The conventional technique to deal with all of these stream influences on highways is to design (new highways) or add (existing highways) zones of riprap with quarry rock that is large enough and sufficiently abundant to nullify any erosion risks from the stream current. Rock size is a matter of the nature of the particular stream and its velocities and debris load. Rock amount is often more subjective and depends greatly on how the stream's stability or instability is evaluated. If the stream is assumed to be stable, it may be used in limited amounts to address only immediate problems, then, if the stream turns out to be less stable, additional riprap may be added as channel conditions change over time (e.g., stream meandering). If the stream is assumed to be changeable, large amounts of riprap may be used so as to address all present or potential changes of stream course -- much of this riprap may be passive rather than serving an active purpose of protecting the roadway from stream attack. For such changeable streams, a spot inspection is only a "snapshot in time" as to stream-roadway interaction but will give the observer a sense that there is more riprap than needed, whereas a photographic history of the site may reveal that riprap was needed at some time at most locations where placed. (It is just such locations where vegetated riprap may be both desirable and successful – discussed later.)

4.0 THE NATURE AND EXTENT OF A STREAM

A river is not just the channel in which the dry-season base-level streamflow occurs. Nor should it be regarded only from the limited perspective of a physical zone of moving water and the immediate banks and bed that contain such flow. Instead, a stream has both aquatic and riparian zones (extending beyond the tops of the banks) that interact in a normally functioning river setting. When common floods are also considered, the stream corridor becomes a widely inclusive zone of space beyond the low-flow stream that includes adjacent low floodplains. Thus, from a broader perspective (Figures 4.1 and 4.2), streams consist of many elements that depend on flowing water at some time. These include: (a) the various segments of banks that contain low, intermediate and high flows, (b) the bed with its varying morphological features, (c) the low over-bank floodplain terraces that frequently are inundated by common floods, (d) the rock and soil materials present at and within these physical boundaries, (e) the various species and sizes of vegetation that grow along and within these physical boundaries, and (f) the biological ecosystem of plant and animal species present. Furthermore, important hydraulic and habitat aspects of streams are determined in terms of the variable water depths, velocities, flow directions, and flow patterns that occur over space and time.

Schematic example

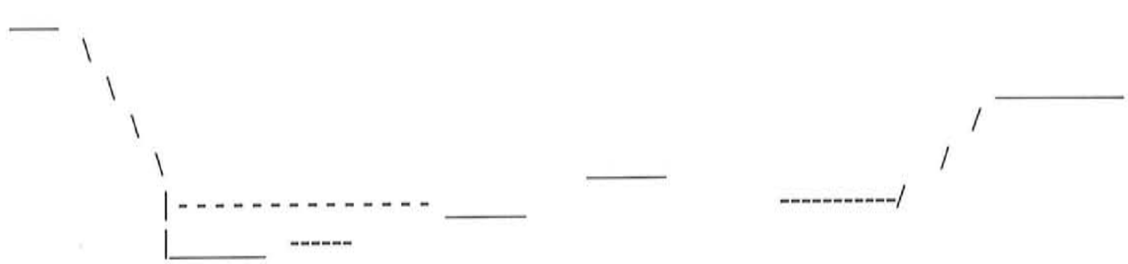

Figure 4.1: Illustration of Stream and Riparian Zones, Showing some Components of Each ***[Not final – to replace]***

Example: Plan-view of Willamette River upstream of Harrisburg

high valley floor

floodplain

Harrisburg relic main channel gravel pit

riprap bank RR

highway multiple channels and bars bridges

bridge (shifting over time)

natural bank highway

causeway low riprapped bank

floodplain highway floodplain farming

farming fill

higher valley floor

Figure 4.2: Illustration of a large river with multiple riparian zones and floodplain terraces *[Not final -- to replace]*

4.1 STRUCTURAL NATURE OF STREAM COMPONENTS

These stream components can be viewed as structural in the same way that we looked at the highway. The stream bed and banks are as important structurally to the stream as fill slopes and foundations are to the highway. Beyond the stream banks, the vegetation, including forbs and sedges, woody brush species, and trees, is important structurally to the riparian zone and the stream as well. The importance of the structural interaction of the riparian zone with the stream cannot be over emphasized. Brush and trees in riparian zones provide the primary roughness that resists stream currents at the margins of the main channel. The lower flow velocities occurring in riparian zones allow sediment to deposit, both during high flows and on the falling limbs of flood hydrographs. In this way, a well-vegetated riparian zone works to provide limited resistance to the normal erosive forces of a river, maintain soil for plant growth, and provide stability to the overall system.

4.2 STREAM CONDITIONS RESPOND TO CHANGING DISCHARGES

Streams change greatly in response to changes of water discharge. Highway protection planning should reflect awareness of such change. At each location within the channel and along the banks the water depths and velocities change over time, affecting local flow strengths, shear stresses, and flow directions. In turn, these affect overall water flow patterns, bank erosion, bed scour, sediment transport, sediment deposition, debris transport, and debris stranding. At high flows, riparian and bar vegetation are stressed by moving water, sediment, and debris. At low flows, such vegetation may instead be stressed by insufficient root-zone moisture. Wet seasons and dry seasons create different conditions that affect the overall stability and behavior of a stream. Sustained storm runoff adds time for erosion and channel-shaping processes to act and may increase the overall changes. Sustained periods with adequate water but without stressful floods may give time for plant species to grow and reinforce the stability of banks and bars.

4.3 RIVERS ARE DYNAMIC

Rivers are dynamic systems where erosion and deposition are normal processes. From a highway perspective, the best time to recognize and deal with this is in project planning and design. Without such awareness, subsequent maintenance and emergency measures may be quite costly. Erosion and deposition occur irregularly over time and are local in extent. Erosion is mainly associated with wet season flows and snowmelt floods but may also occur locally as steep banks dry out and unravel. Erosion and deposition lead to the movement of bank lines and channels. Over centuries, these processes have formed wide floodplains for many rivers. Over decades or less, they have led to startling changes in local conditions at places where humans observe such changes, such as at bridges and water intakes. Meandering results when erosion and deposition are widespread, such as through the accumulation and interaction of many local erosion events, and occurs where some floodplain exists. Elsewhere, lateral changes may be restricted by bedrock, cemented gravel, and hardpan soils. Meander changes are likely to be most evident during the larger, less common floods. Avulsive changes (abrupt, extreme, and often unpredictable events that typically involve the cut-off of a meander loop) are most likely to occur at times of major floods. Meandering and avulsive changes are probably the greatest concerns for highway maintenance, causing new and unexpected threats as well as emergencies for roadways and bridges.

4.3.1 Streams Change in Position Over Time

Dynamic streams change their specific positions on the landscape over time. This typically involves changes in lateral position (i.e., changes seen on a map), but may also involve changes of vertical features (i.e., changes seen in cross-section and profile views). Lateral changes are usually associated with erosion and deposition. They are likely to be quite local at any given instant but may have cumulative effects over time that lead to meandering in floodplains or to shifts from side to side between restraining banks and hillsides in narrower zones such as canyons or mountain gaps. Vertical changes involve local down-cutting through erosion and scour processes and local buildup through deposition and sedimentation processes. Sustained down-cutting and buildup lead, respectively, to bed elevation degradation or bed elevation aggradation.

4.3.2 Channel Vulnerability to Stream Changes

Because highways and bridges are static in position, they are quite vulnerable to many channel changes of the types just described. Direct erosive attack may occur due to changing channel flow directions or by deflected flows from new bars and debris. Sharper channel bends may result in deeper local scour that undermines banks, piers, and abutments. Widened channels may become less efficient in transporting sediment, leading to bar formation, local bed aggradation, accumulated debris, and the deflection of flows toward banks that support a roadway or bridge abutment.

4.3.3 Specific Changes are Unpredictable

Analysis of river processes and associated data allows general estimates to be made of the types of future stream changes to be anticipated, at least for short periods into the future. However, streams are subject to many unpredictable types of events along their lengths and within their drainage basins. Changes at one location set up influences elsewhere, while changes elsewhere are doing the same thing. The result is a highly "non-linear" (almost chaotic) system with multiple, overlapping, and cumulative impacts. Major floods in different years may have triggered changes that, in later years, partially cancel or partially reinforce each other. These make it virtually impossible to predict when a specific event may occur or whether a specific event will occur during a specified time interval of years. Hindcasting methods may be used (but for the reasons just given are often not reliable) to estimate when a future change might be expected if all conditions remain the same in the future as was the case over the past (quite an assumption). Instead, major occurrences like big floods and extended droughts are likely to be 'triggering' mechanisms to set in motion new trends of events (e.g., aggravated erosion that leads to meandering and bed aggradation; or loss of vegetative cover that affects bank erodibility until plants recover or recolonize a damaged zone). A large flood or landslide might set in motion processes that last for a decade or more. Given this lack of predictability, highway design and maintenance are perhaps best served through use of preventative measures that focus on the most likely kinds of changes, based on review of historical maps and photographs and on field investigations that extend well beyond highway right-of-ways.

4.3.4 Specific Consequences of Changes at Banks are also Unpredictable)

Several specific consequences of channel change are important at stream bank zones. These include the flow alignment along the bank (whether parallel to or attacking the bank) and the shear strength related to flow velocity and flow depth. If the plan-view features of a channel change over time due to various events, the flow patterns at banks will also change. Some banks will become subject to greater erosive forces, whereas others will become depositional zones. Over additional years, these circumstances may reverse one or several times. Such variable changes must be considered as part of preventative highway management.

4.4 STREAM STABILITY

Stream stability must be defined in terms of the inherently dynamic nature of streams. It cannot be defined in terms of absolute stability, which requires a lack of change and implies that bank lines remain fixed in location over time. Instead, it is commonly defined as a condition wherein processes (rather than boundaries) are stable. It is also commonly defined in terms of dynamic equilibrium, whereby conditions 'balance' about some average condition over time but change during shorter periods. For example, with dynamic equilibrium the sediment moves through a river reach in long-term balance of inputs and outputs, but the transport rates change as water discharge changes and the 'sources' and 'sinks' within the reach become altered through bank erosion and bar formation. Furthermore, major disturbances like meander cutoffs may place the system out of balance for several years -- but over a longer period of years these events are balanced out if the system is in dynamic equilibrium. Such a system may be thought of as stable over the long period but subject to instabilities in shorter periods. Large floods, debris jams, hillslope failures, large-scale gravel extraction, bank revetting, channel meandering, and significant changes of watershed condition all may affect stream stability. Many streams seek to adjust back toward former states; but others instead adjust to the newly imposed conditions or constraints and seek a new dynamic equilibrium. Thus, depending on the extent of boundary involved, riprapping the banks of a stream for highway protection may impose a modest boundary forcing-condition that affects nearby stream dynamics. This is more likely to occur at constricting bridge crossings than for streamside roadways.

5.0 NATURAL EROSION PROTECTION AT STREAM BANKS

Since erosion protection will be required in many highway situations, it is appropriate to comment briefly on the ability of natural elements of stream riparian zones to provide erosion protection functions. As has been indicated, streams move laterally across their floodplains over time. Evidence of such movement is clear from geologic features and vegetation patterns. Natural features such as rock outcrops, cemented gravel or soil deposits, and erratic boulders provide quite durable erosion resistance, akin to that provided by riprap. Natural vegetation also limits the rate of lateral channel movement, but does not eliminate it. Evidence of this can be seen in many eroding stream banks that are fully within riparian zones that have significant components of forb, woody shrub, and tree vegetation. The structural integrity provided by tree and shrub root systems commonly limits the attack of flowing water to that of undermining the root systems. This creates a number of positive components of fish habitat. The exact character of the interaction of the stream with riparian tree and shrub root systems is quite varied. Together, the local riparian soil, the rooting habit of the trees and shrubs, and the flood regime of the stream make for an extensive array of possibilities. However, the erosion resistance provided by tree and shrub root systems produces only a temporary delay in lateral movement of the stream channel. Undermining ultimately results in collapse of the stream bank. These dynamics of water, soil and vegetation are part of the proper functioning condition of a stream. The addition of the tree or shrub into the aquatic zone as wood, adds a positive element of fish habitat.

5.1 ROLE OF BANK EROSION AS NATURAL HABITAT BENEFIT

Bank erosion and lateral channel movement are required in order to create overhanging banks and introduce large wood into a channel by undermining riparian trees and shrubs. Ultimately, this may become incompatible with the structural integrity of a highway that is adjacent to a stream. However, when tree growth has become substantial, the root structure may be adequate to maintain the bank line against further retreat. Such stable bank-lines that are steep and even overhanging may provide significant habitat benefits for aquatic species.

5.2 LIMITATIONS TO NATURAL VEGETATIVE PROTECTION

The success of vegetation in protecting stream banks is a question of the scale and nature of disturbances, as well as the alignment of the flows to the bank. Riparian vegetation is likely to have the longest "permanence" for small streams, diminishing in longevity as streams become larger and carry bigger floods. Even in large rivers, vegetative protection may be appreciable when the flows are aligned parallel to the banks. But when large flows are directed toward a vegetated bank, due to changes of channel alignment or flow deflection (e.g., from bar growth or debris accumulation), there is increased risk that the base of the vegetated bank may be undercut or scoured. At such points in time, the vegetative protection is likely to become reduced or perhaps eventually lost. Once the bank-slope vegetation is lost, together with its root system, further bank erosion of weak soils may begin to undercut bank-top vegetation and perhaps affect the structural zone of an adjacent highway.

6.0 THE HIGHWAY / RIVER INTERFACE

Stability in a natural stream system is not the same as we envision for the structural elements of a highway. As described in detail earlier, stability of a stream system means stability of processes, not a static stream channel. Streams are dynamic, shifting positions within their floodplains over time. It is exactly this natural lateral migration, which occurs through the process of bank erosion, that highway erosion protection seeks to prevent.

6.1 EROSION THREATS CHANGE OVER TIME

Lateral stream changes that occur over time affect the relative alignment between a stream and adjacent roadway or crossing bridge. This may increase bank erosion near the highway embankment or bridge abutment if changing flow directions cause increased angles of attack on the banks over time. Lateral stream changes may be accompanied by vertical stream changes, either by local down-cutting or deposition. In turn, these may alter the nature of scour threats over time at the bases of abutments and piers, along the bases of stream banks, and at the toes of road fills. Such conditions provide a critical reminder that those stream conditions observed at the time of design survey work are not necessarily going to remain the same over the service life of the roadway or bridge.

6.2 HIGHWAY STABILITY MAY REQUIRE BANK STABILIZATION

Clearly, in order to maintain the structural integrity of the highway, normal stream bank erosion that threatens or encroaches on the structural influence zone of the highway must be prevented. By the time encroachment occurs, the choices for taking effective action are diminished. There is a need to provide critical protection to meet existing conditions during design and a further need to provide initiation of long-term protection to address likely or possible future changes.

6.3 EARLY TIMING TO ACT POSITIVELY TO EROSION THREAT

The moment when a highway structural zone and a river structural zone first intersect is not likely to be known. The reason is simple. Both structural zones are much wider than the casual observer realizes. It is when the structural zones first intersect that we have the greatest flexibility to affect a positive outcome that will prevent encroachment of the river on the highway and yet preserve important elements of the river structural zone. But, is it possible to preserve all elements of both systems? Quite simply, No! In that case, what can we do? We can work to design an interface that preserves much, even if not all, of the values of both structural zones.

6.4 KEEPING THE RIPARIAN ZONE INTACT

The value to a highway system of having a healthy growth of riparian vegetation present is that it acts as a natural means of erosion protection, slowing down the erosion process even if not stopping it. This allows highway protection and habitat benefit to occur simultaneously. A key element in the design of a highway / river interface is to stop lateral movement of the stream when there is still a riparian zone between the two. In this way, the positive functions of the riparian zone -- exclusive of those involving erosion -- can continue. Once a stream bank structural zone intersects the highway structural zone, most of the flexibility in designing a solution and most of the value in the structural zone of the stream may become lost. Further, the probability of success of the vegetative components of a design likely varies as a function of the space available between the highway and stream (Figure 6.1).

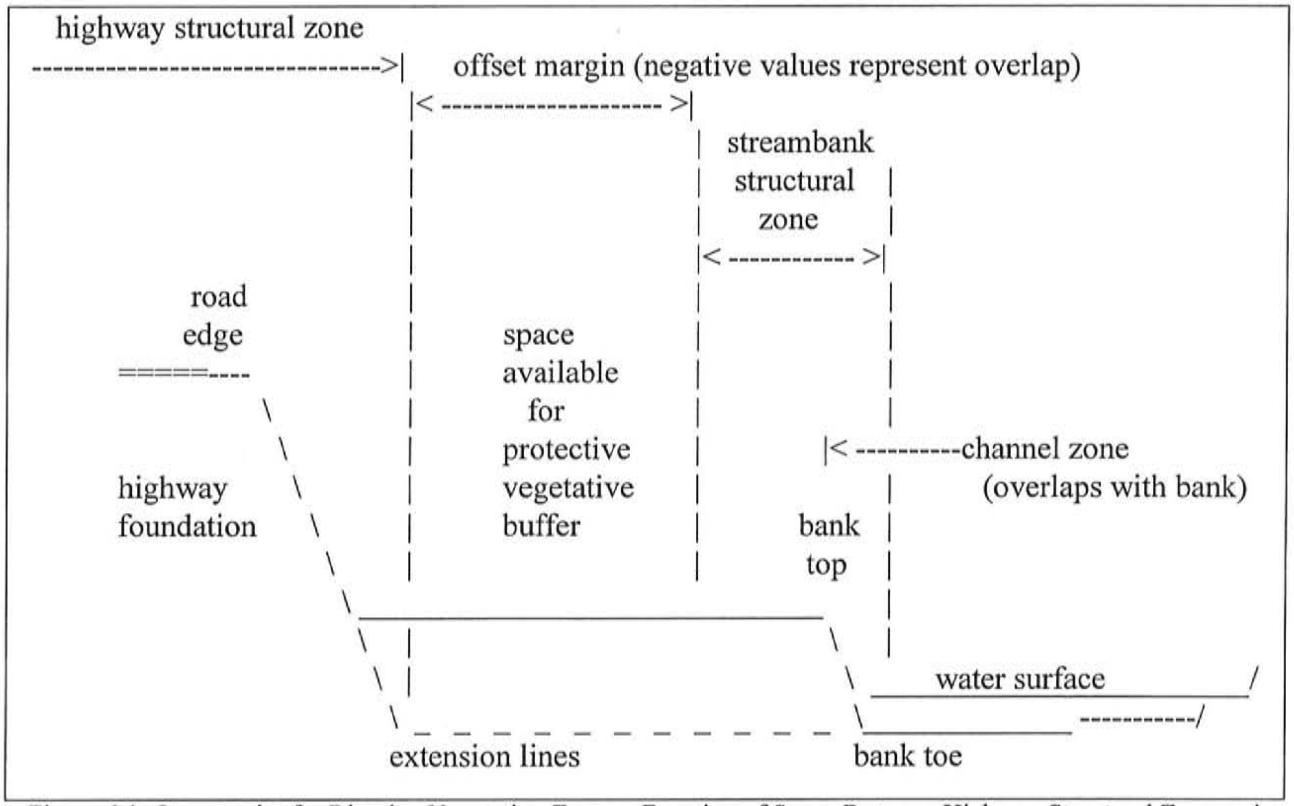

Figure 6.1: Opportunity for Riparian Vegetation Zone as Function of Space Between Highway Structural Zone and Streambank Structural Zone. *[Not final – to replace]*

6.5 METHODS FOR KEEPING PART OF THE RIPARIAN ZONE INTACT

The stream structural zone adjacent to or overlapping a roadway structural zone may be protected in several ways. Each tends to compromise the integrity of a fully-functioning zone for one of the two competing uses – as an ecologically productive stream bank structural zone and as a least-cost highway structural zone. For purposes of discussion, this may be illustrated by six techniques (Figures 6.2 and 6.3), beyond which several variations or combinations are also possible.

1. Separate lower-bank riprap and upper-bank vegetation zones.
2. Vegetated step between separate lower-bank riprap and upper-bank vegetation zones.
3. Like 2 but with the addition of vegetation pockets in the riprap.
4. Bank-toe spur dikes.
5. Like 4 but with the addition of vegetation pockets in the spur dikes.
6. An upstream structure, as in 1 to 5 above, that redirects flow away from sensitive areas.

```
1st technique              2nd and 3rd techniques          4th, 5th, & 6th techniques
  Divided bank slope       Stepped, divided bank slope     Spur dikes at base of bank
                           Without/with vegetated riprap   Without/with vegetation

      top of bank

      _____                _____                           _____
           \ vegetation         \                               \
            \ zone               \                               \
             \                    \______ step                    \
             \ \ riprap                  \ \                       \
              \ \ zone                    \ \                    __\______
               \ \__ toe                   \ \__ toe             \ riprap spur \
                \  \___                     \  \___              \___________\___
                    stream bed                     bed                          bed
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Figure 6.2: Sectional Views of Six Techniques to Keep Riparian Zones Intact. (Does not show vegetation pockets).
[To be completed and improved]

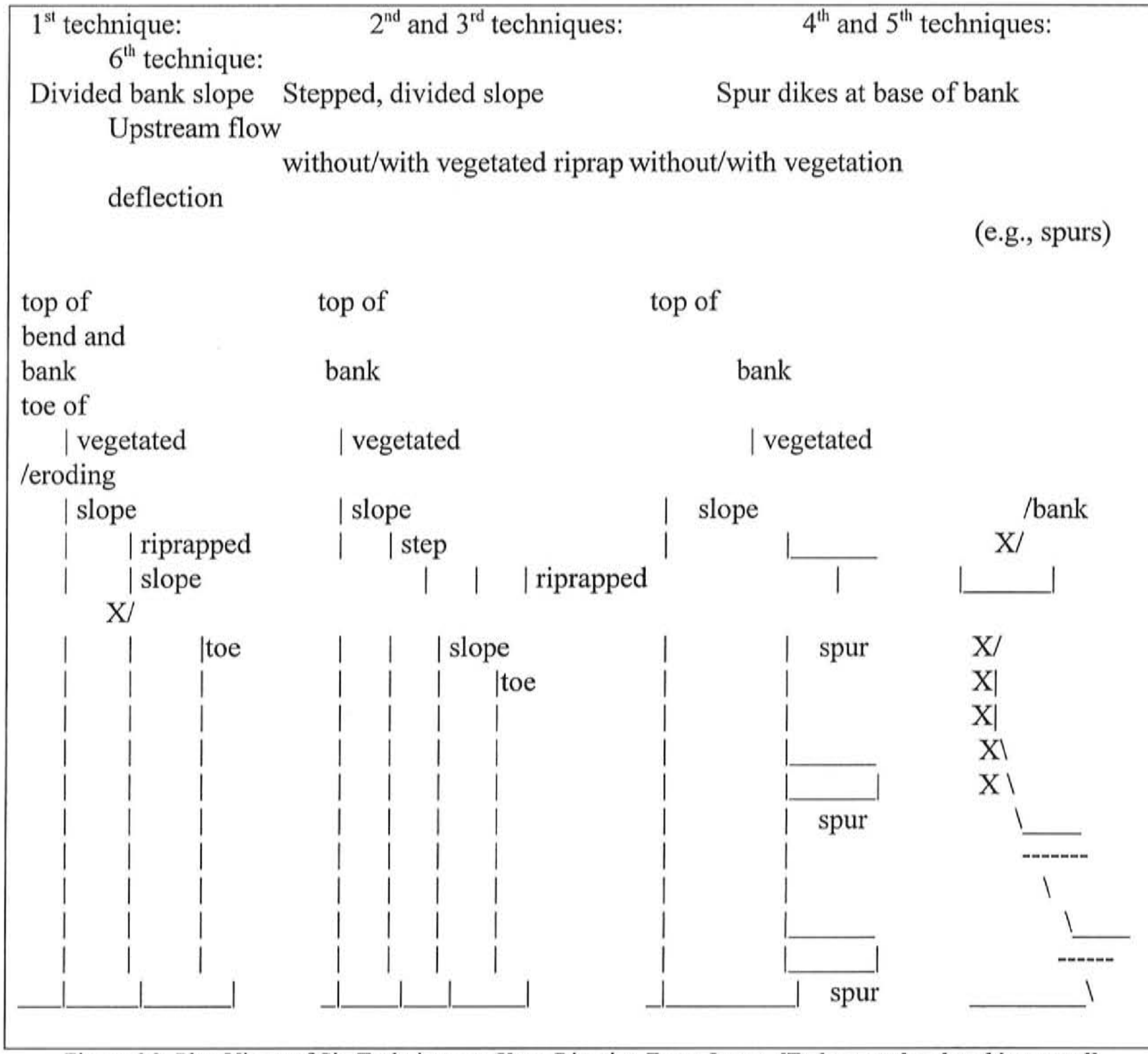

Figure 6.3: Plan Views of Six Techniques to Keep Riparian Zones Intact. ***[To be completed and improved]***

6.5.1 Discussion of Methods

The first technique limits riprap to only the lower bank, protects the toe of the highway structural zone with riprap, and relies on vegetation to protect much of the slope. The second adds a horizontal step or bench where vegetation may be able to thrive as dense protection to retard velocities against the upper vegetated bank slope. The third adds pockets of planted or retained vegetation within the riprap zone, closer to the low-flow water table. The fourth and fifth techniques change the method of protection from a 'hardened continuous toe line' of riprap protection to a 'spaced, hardened toe deflector' set of short spurs (groins) extending outward from the bank, either without or with pockets of vegetation. A single deflector may suffice to realign flows in a small stream, but multiple deflectors are more effective and are needed for general protection on large streams. Flow patterns develop along banks with eddies that could allow some near-shore deposition but may also cause local bank scour unless closely spaced. Controlled scour may be useful for maintaining aquatic habitat features while protecting a highway from further channel changes. Spur dike techniques may also be supplemented with stepped banks (not listed above). The sixth technique provides a small upstream modification to reduce or eliminate the need for larger modifications at sensitive locations. Upstream features may influence flow patterns in positive ways to protect a given bank while maintaining general habitat diversity.

6.6 POTENTIAL CLASSES OF PROJECT OPPORTUNITIES

Given these concepts, we can begin to look at the current state of affairs by classifying potential project opportunity categories. Three classes come to mind.

6.6.1 Emergency Situations where Erosion of the Toe of the Highway Fill Has Occurred

These cases, which include most of the riprap work currently done by ODOT, leave little flexibility or opportunity for establishing a riparian zone. During emergencies, riprap must be placed quickly to avoid further damage, leaving little time for planning any inclusion of vegetation. Opportunities exist for establishment of vegetation within conventional riprap, but the likelihood of establishing a sustaining natural riparian shrub and tree community is probably low in the absence of adequate soil, unless special care is taken to maintain a natural zone above or within the riprap. Moving the highway or the stream may have appeal, but moving either does not come without significant cost and moving a stream, albeit within the bounds of its formerly occupied channel, does not come without significant uncertainty. Preparation of 'generic' plans for emergency work, that include vegetation re-establishment and that represent several 'typical' high-risk sites, may be effective at less cost and with less uncertainty.

6.6.2 Distressed Situations where Lateral Migration of the Stream has Reduced the Effective Width of the Riparian Zone and/or where the Stream has Encroached on the Highway Structural Zone

Two possibilities define the range of options in these cases, (1) the highway structure can be modified to reduce the lateral extent of the highway structural zone, or (2) the geometry or the erosion resistance of the eroding bank of the stream can be modified. In either case, the design can range from a delaying tactic to a relatively permanent solution to the erosion problem. Cost as well as environmental and ecological factors can be considered in arriving at a solution.

6.6.3 Opportunities where Highway Protection Can Work to the Maximum Extent in Harmony with the Stream

These cases are truly opportunities where the maximum benefit to the riparian and aquatic zones can be obtained. Note however, that some means of erosion protection will be required to keep a case 3 opportunity from becoming a case 2 distressed situation.

7.0 DESIGN APPLICATIONS

The three classes of highway/stream interaction outlined above, combined with the likely result that ODOT will want to develop a design to stabilize lateral erosion, give rise to a range in riparian/aquatic function outcomes. As indicated above, all functions of riparian and aquatic zones cannot be preserved. Table 7.1 on the following page outlines the functions that can be designed into a project related to these three classes, as well as additional highway considerations to address bridge crossings. Individual projects will vary, of course, but the listing in Table 7.1 illustrates the general trend in function that is likely to result from the range in project types.

7.1 THE TIME FUNCTION IN EROSION CONTROL

Addressing the time function in erosion problems is clearly a significant and new challenge. To design an erosion protection scheme that either slows or stops lateral channel movement while a significant riparian zone still exists requires understanding of which sites will experience the greatest lateral channel movement over the current highway's service life. Given that evaluation, then the necessary projects should be undertaken. In some cases, anticipating channel migration may be relatively easy, while in others it will no doubt be quite difficult. In general, re-evaluation and new decisions will be required periodically. The problem is further complicated because the location of an existing highway (and perhaps its use) will often remain fixed well beyond the physical service life cycle determined from economic analysis. Channel changes will continue indefinitely into the future. The problem is compounded even further by the present legal mandate for protection of endangered species without regard for cost.

Table 7.1: Design Applications to Address Highway and Stream Structural Zones and Functions

PROJECT CLASS	HIGHWAY DESIGN ELEMENTS	MAINTENANCE OVER LIFETIME	RIPARIAN-AQUATIC FUNCTION INCLUDED IN DESIGN
Emergency Toe Erosion	Steep-slope riprap	Limited	Limited
	Stepped-slope with lower slope riprap	Vegetation maintenance	Inter-planting above lowest slope for shade
	Highway-fill retaining structure with gentle slope and riprap	Vegetation maintenance	Planting in and above riprap for shade, stability
	Highway-fill retaining structure with terraced riprap	Vegetation maintenance	Planting in and above riprap for shade, stability
Distressed Highway Structural Zone	Low-level riprap in stream at bank toe	Limited or vegetation maintenance	Not applicable or incorporate vegetation in riprap
	Current deflectors	Limited or vegetation maintenance	Not applicable or incorporate vegetation in riprap
	Highway-fill retaining structure to reduce highway encroachment and thus increase effective width of riparian zone	Bank inspections; Vegetation maintenance	Soil addition and planting in newly available space
Long-Term Protection Opportunities	Low-level riprap in stream at bank toe	Vegetation maintenance	Planting in and above riprap for shade, stability
	Increased riparian zone width with plantings	Vegetation maintenance	Diverse plantings for shade, stability
	Flood flow current control to encourage sediment deposition	Bank inspections; Vegetation maintenance	May eventually provide planting opportunity
Bridge Abutments	Least interference with wide range of flows	Local wrap-around riprap in scour hole zone	Nearby limited-height plantings for root structure and shade
	Upstream guidance structure integrated with bank	Bank inspections; Vegetation maintenance	Vegetated for long-term growth, with strategic riprap for stability
Bridge Piers	Deep footings below anticipated scour depth, considering past/future channel conditions and positions	Local riprap in scour hole below level of pier footing	Not applicable.
Abutment Emergency	Not applicable	Riprap in scour hole to retard scour / deflect flows	Not applicable.
Pier Emergency	Not applicable.	Riprap in scour hole to retard scour / deflect flows	Not applicable
Roadway Along Stream	Guided culvert flow with riprapped cascade or step-pool outflow path	Inspections	Not applicable
	Stepped-slope streambank; vegetated upper bank; step with dense-root frictional vegetation; vegetated riprap for lower bank	Vegetation maintenance	Planting in and above riprap for shade, stability
Roadway Back-Set From Stream	Buried riprap spurs as future protection	Inspections and vegetation maintenance	Reliance on mixed vegetation, selected based on ground position above low water

8.0 CHOICE OF RIPARIAN VEGETATION

Riverine riparian zones are three-dimensional ecological transition zones between aquatic and upland ecosystems. They have distinct vegetation and soil characteristics and may encompass sharp gradients of environmental factors, ecological processes and plant communities. In general, the gradients are not as sharp in western Oregon, producing broader riparian zones compared with streams of similar size east of the Cascades.

8.1 IDENTIFICATION OF CANDIDATE VEGETATION SPECIES

8.1.1 Use of Literature to Identify Candidate Species

A literature review was used to identify and characterize those common tree and shrub species that would be suitable candidates for riparian plantings in ODOT streamside stabilization projects. A set of tables was produced, one for each ODOT management region, that describe the riparian species found in that region. The species lists are not exhaustive; also, the less common species are not included. (The tables appear in a separate vegetation document, Hibbs and Kauffman, May 17, 2000, along with details about their construction and use.)

8.1.2 Use of Eco-Regions Matching ODOT Management Regions

Eco-regions selected to match the five ODOT management regions were used for identifying and grouping suitable riparian vegetation: 1) Portland Metro Area; 2) Northwest Oregon; 3) Southwest Oregon; 4) Central Oregon and 5) Eastern Oregon. The boundary between eco-region 4 and the three eco-regions lying to the west approximately follows the crest of the high Cascades. At the northern and particularly the southern ends, this boundary deviates from the Cascade crest. For the purpose of matching vegetation to eco-region, this boundary was assumed to follow the Cascade crest through its length.

8.1.3 Oregon Natural Vegetation Zones and Types

Each of ODOT's five eco-regions encompasses several natural vegetation zones. These zones are characterized by different combinations of dominant tree and shrub species. Vegetation zones established in the literature provided a suitable scale for the research, identification, and compilation of the dominant riparian trees and shrubs, which were then reduced to suitable candidates for each eco-region. In grouping species from different vegetation zones into a single, large-scale ODOT eco-region, invariably some species are grouped together which do not naturally occur together. Vegetation Classification Tables in the vegetation document were designed to present information useful in determining plant associations appropriate to different riparian sites. The common riparian woody vegetation was listed in table-form for each ODOT eco-region. Ecological characteristics were provided for each species to assist in matching species to specific project sites. Physiological characteristics pertinent to establishment and streambank stabilization were also evaluated.

8.2 VEGETATION SELECTION STRATEGY

8.2.1 First Steps in Vegetation Selection Strategy

For a highway project intended to include riparian vegetation, the first step is determining the site elevation and identifying the species normally occurring at that elevation found in that eco-region. In addition to elevation range, the natural range of a species may be further restricted geographically within an eco-region. The Ecology-Associations category of the vegetation report broadly describes geographic distribution within an eco-region for each species. It should be noted that riparian interfaces produce complex and varied ecosystems. Hence guidance in vegetation selection requires field verification. A survey of nearby riparian zones is appropriate at each project site to assess local ecological conditions and associated plant communities. Since the tables in the vegetation report characterize only common woody species for generalized ecological conditions, a field survey is necessary for two reasons. First, the research sites from available literature represent only a sampling of the range of riparian communities found across the state. Second, in compiling the tables at the eco-region level, local community (site specific) detail was necessarily generalized.

8.2.2 Further Aspects of Vegetation Selection Strategy

Riparian zones are also complex at the site scale, with different plant communities suitable for different locations within the zone. For any project, the riparian zone needs to be delineated and subdivided into lateral levels (defined under Riparian Zone Levels in the vegetation document) as necessary for the specific site. At this point, plant species can be evaluated for use in respective Riparian Zone Levels. First, the Riparian Zone Level category provides a general guide for each species. Further information relevant to matching species to locations within the riparian zone are provided in the Wetland Indicator Status, Shade Tolerance, Flood Tolerance and Drought Tolerance categories of the vegetation report. Additional ecological requirements and common plant associations may be described in the Ecology-Associations category of the vegetation document. Site-specific variables that influence riparian communities include hydrology, substrate, microclimate, aspect, slope and valley constraint.

8.2.3 Selection for a Specific Site

For any specific streambank location, the Tables in the vegetation document indicate that many plant species can grow at the site. Not all of these species can be grown successfully together; some will out-compete others. An inspection of nearby riparian plant communities will indicate which combinations are most likely to work.

8.2.4 Root system

Since a main purpose of vegetation plantings is streambank stabilization, a category describing rooting characteristics pertinent to plant stability and soil binding is provided in the vegetation document. Furthermore, riparian zones are dynamic, subjecting plants to stresses affecting survivability. Growth response to damage and disturbance is described in the tables for each species. Since reproduction is important to long-term community function, key sexual and vegetative reproduction characteristics are also described.

9.0 CONCLUDING REMARKS AND RECOMMENDATIONS

To accommodate concerns about stream bank management and effects on aquatic habitat quality, many new and diverse approaches are being tried in various parts of the country. These approaches are sometimes based on science and sometimes only on common beliefs. Many of the observations that form the bases for these approaches were made in different locations (sometimes in different eco-regions) than the location of the application site. It becomes very uncertain, therefore, if the sought-after habitat management goals were really achieved. Thus, there is a pressing need to assess the actual outputs of these expensive projects.

9.1 LITERATURE REVIEW

The literature reviewed to date appears to be representative of the total literature on the subject of vegetated riprap. Direct literature is quite limited but related literature is extensive.

9.2 MORE JUDGMENT NEEDED IN USE OF RIPRAP

Highway protection from stream erosion must be determined based on sound judgment and careful risk assessment. Such protection cannot be treated as a risk-taking activity to accommodate and take a "backseat" to other objectives, such as aquatic/riparian habitat. However, it appears that there may be many instances of excessive use of riprap. If true, this suggests that the choice to use riprap is not always supported with analyses of how much riprap is essential and where it must be placed. It may be speculated that often these decisions are not made during design, where there is the opportunity for careful planning, but rather during field operations with less thought to overall implications. Regardless of such aspects, it seems plausible that the exclusive use of riprap may be criticized at many specific locations.

9.3 A RANGE OF CHOICES

Roadway bank protection is not an "all or nothing" choice. At the one extreme of protection, one may opt to use riprap exclusively and extensively. At the other extreme of protection, one may consider the need to move the road away from the stream. As example of the latter extreme, a highway in a narrow stream corridor may be damaged many times by repeated floods or debris flows and extensive riprap may not be sufficient to protect against loss of local roadway segments. Ultimately, it may be prudent to relocate portions of such routes out of the stream corridor. Yet in contrast to such tight stream-corridor highway routes, there are many places where only local riprap protection may be needed. A bridge crossing usually involves only localized interaction and protection needs. If the bridge span is adequate, the technical measures (and their impacts) should be quite local. They may be of two types: scour/erosion protection for abutments and approach-flow alignment control to prevent channel changes from leading to greater future protection needs.

9.4 VEGETATED RIPRAP IS NOT ALWAYS A CLEAR CHOICE

Similarly, at a streambank roadway or bridge crossing, the decision on whether or not to use vegetated riprap is not a clear and decisive yes or no. Riprap with living vegetation may be found in many places where both the rock and the vegetation appear to be sound. In the normal range of stream conditions, there are many possibilities between the extremes of no-use and extensive-use. The difficult problem is to determine the guidelines for such choices.

9.5 USE OF VEGETATED RIPRAP DURING CONSTRUCTION

It appears that vegetation may be safely incorporated into riprap projects at the time of project construction. By doing this as part of original design, the riprap and vegetation can be planned for joint service and appropriate measures can be taken to protect the riprap so as to accommodate vegetation growth.

9.6 ADDING VEGETATION TO EXISTING RIPRAP

Allowing vegetation to grow in existing riprap requires greater caution. Because the riprap system was not designed with this in mind, damage may result. Inspections are needed to determine the condition of riprap as trunk growth occurs and diameters exceed 2-4 inches. In particular, rock displacements must be determined and any potential of such displacements to cause loss of riprap integrity must be assessed. The initial assessment is to decide if trunk and root growth are considered to be acceptable risks. The next assessment should address the potential for vegetation pull-out from water flow forces or wind forces.

9.7 INCLUSION OF VEGETATION DURING EMERGENCY WORK

Although difficult to consider under the stress of an emergency, vegetation should be addressed at the time that emergency protection work is being undertaken. Emergencies that result from expected-but-overlooked situations, such as channel meandering, should have included preventative measures in advance, with ample opportunity to integrate vegetation with 'hard fixes.' But unexpected emergencies may still provide opportunities. The abrupt change of channel alignment may have added fresh bar deposits in the widened channel. Analysis of channel morphology and stability in the reach may show that modest removal of part of such a bar should have only a immediate, short-term impact in most cases that 'trades off' with instead having a longer stretch of new riprapped bank. In the longer run, analysis may show that retention of such a bar and the associated erosion and riprap at the highway may have off-site repercussions on upstream and downstream channel adjustments. If so, the short-term immediate impacts may be more acceptable than longer-term chronic impacts. Given that some channel space may be recaptured at the eroded bank, local riprap protection is still likely to be essential. However, this may be designed to include vegetation. Given, further, that the work must be done quickly under the stress of an emergency, it may be most beneficial to have a set of 'off-the-shelf' solutions available for various circumstances. These could then be considered at a given emergency site at the time when engineers, biologists, maintenance personnel, and environmental staff first meet to discuss the emergency and its resolution.

9.8 SOME FIELD OBSERVATIONS

Examination of some revetments that have growing vegetation suggests that:

1. Riprap rock displacement does occur. Adjacent rocks are pushed up along the trunk.
2. Rock displacement does not diminish the riprap integrity when the tree is part of an extensive mass of vegetation growing in the riprap, since the flow resistance provided appears to diminish the local velocities at the vegetated riprap. This observation is supported by literature.
3. Isolated trees in riprap have not yet been observed, so judgment is reserved on such conditions.

9.9 ADDITIONAL INVESTIGATION IS NEEDED

While it is clear that erosion protection to effectively prevent lateral channel migration at the roadway structural zone is a necessary part of protecting Oregon's roadways, it is also clear that the means of providing erosion protection and at the same time maintaining a component of riparian function has not received the investigation that would be beneficial to meeting today's objectives. We suggest a number of study areas that should be helpful in expanding ODOT's ability to tailor erosion protection schemes to today's broader project requirements. In some cases, formal fundamental research may be necessary, while in other cases carefully controlled field trials may be in order.

9.9.1 Suggested investigation topics

The following list of suggestions can serve as a guide in directing future work, either for ODOT research or for operational projects.

1. Incorporating rootable and water-holding fines in conventional riprap to improve vegetation survival and growth.
2. Plant vegetation in conventional riprap at those zones where sedimentation now occurs.
3. Comparative study of the survival of different candidate plant species for planting riprap.
4. Further research along several fronts regarding riparian vegetation: (a) under-represented riparian communities and those in areas of most concern to ODOT should be adequately studied; (b) comparisons of community response to ecological processes and variables between project sites and natural systems should also be evaluated for developing future standards for measuring project success.
5. Study of the necessary "top elevation" for conventional riprap as a function of velocity, turbulence, and flow duration.
6. Comparative study of terraced versus sloping riprap in terms of hydraulic performance and planted vegetation success.
7. Comparative study of current deflectors that have a lesser effect on aquatic habitat than riprap, but are effective in preventing bank erosion.

8. Conduct more-detailed inspection of riprap where vegetation is now growing or has grown, to better understand its impacts, such as by looking for: a) downed trees, if any can be found, b) snapped trees, and c) for toppled trees with root wads and any hole that is formed in the riprap.
9. Examine riprap failures where vegetation is not a causative factor, to better characterize riprap failures.
10. Examine bank failures at solid banks where vegetation is present (omitting flow undercutting), to characterize bank failures when riprap is not present but vegetation may have a stabilizing or destabilizing role.
11. Develop 'generic' plans for inclusion of vegetation in emergency work at a variety of sites.
12. There may be some merit in conducting pull tests on vegetation, by pulling trees in the downstream direction to simulate drag from water flow, with comparison of results for brittle and flexible trunks.

9.10 DEVELOPMENT OF DESIGN GUIDELINES

Regarding design guidelines, the next step is to develop an outline of the design approach to follow, together with recognition of limitations and potential-risk methods that might be tried experimentally. Further, it is necessary to identify questions that should be asked in the field by maintenance personnel working with design/inspection teams. Procedures should be developed or suggestions made on ways to resolve the remaining unanswered questions. Biological guidance needs to be developed on how to integrate rock riprap and vegetation. At the onset, these may be educated guesses that lead to ideas for experimentation.

10.0 REFERENCES

List of references to be added by OSU research team.