Research Report
Research Project WA-RD 491.1
Soil Bioengineering for Slopes

SOIL BIOENGINEERING FOR UPLAND SLOPE STABILIZATION

by

Lisa Lewis
Principal Investigator
USDA Forest Service
National Riparian Service Team
Bureau of Land Management Office
PO Box 550
Prineville, Oregon 97754

Sandra L. Salisbury
Landscape Designer
Washington State Department of Transportation
Roadside and Site Development Unit
PO Box 47329
Olympia, WA 98504-7329

Shannon Hagen
Research Assistant
Washington State Department of Transportation
Roadside and Site Development Unit
PO Box 47329
Olympia, WA 98504-7329

Washington State Transportation Center (TRAC)
University of Washington, Box 354802
University District Building
1107 NE 45th Street, Suite 535
Seattle, Washington 98105-4631

Washington State Department of Transportation
Technical Monitor
Mark Maurer, L.A., Roadside and Site Development Manager

February 2001

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. WA-RD 491.1	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE SOIL BIOENGINEERING FOR SLOPE STABILIZATION		5. REPORT DATE February 2001 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Lisa Lewis, Shannon Hagen, and Sandra Salisbury		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Lisa Lewis National Riparian Service Team USDA, Forest Service c/o Bureau of Land Management PO Box 550 Prineville, OR 97754		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Washington State Department of Transportation PO Box 47329 Olympia, Washington 98504-7370 Program Manager: Jim Schafer 360-705-7971		13. TYPE OF REPORT AND PERIOD COVERED Research Report 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with WSDOT, National Riparian Service Team (USDA Forest Service, Bureau of Land Management, Natural Resource Conservation Service), Washington State Department of Ecology, and the Washington Conservation Corps.

16. ABSTRACT

The objective of the study was to provide alternatives called soil bioengineering methods for slope and shallow rapid landslide stabilization along different roadside environments. Additional objectives were to educate WSDOT personnel in site selection, soil bioengineering techniques, and construction; to provide soil bioengineering decision-making skills. Three study sites were selected: based upon the following criteria: safety, visibility, accessibility, representation of disparate moisture conditions, climate, and erosion types, illustration of different techniques, availability of additional funding, and WSDOT input. Three different combinations of soil bioengineering techniques were used to stabilize upland slopes on the roadside. Results indicate soil bioengineering is an effective means of upland slope stabilization on erosional slopes and shallow rapid landslides and is practical and economical. Composted biosolids improved soil workability and enhanced the native plant community during the first year.

17. KEY WORDS Soil bioengineering, slope stabilization, erosion, erosion control, landslides, native plants, cribwall, fascine, branchpacking, brush layering, cordon, live cribwall, live gully repair, live staking, willow wall, biosolids, cost/benefit	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
None	None	96	

DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data represented herein. The contents do not necessarily reflect the official views or policies of the Washington State Transportation Commission, Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

RESEARCH OBJECTIVE

The purpose of this research project was to present viable soil bioengineering alternatives, or "living" approaches, to slope stabilization. This is not to argue that soil bioengineering is better than traditional engineering treatments, but to introduce the concept of soil bioengineering, to expand on the knowledge of the Washington State Department of Transportation (WSDOT) personnel, to provide additional alternatives, and to encourage integration of these two practices. Specifically, this report provides field personnel with examples of soil bioengineering restoration techniques intended primarily for upland roadside slope stabilization and revegetation. There are numerous soil bioengineering techniques, and multiple methods are often combined to stabilize one erosion feature. An additional goal of this project was to improve communication between disciplines within WSDOT.

PROJECT SITES

After a team field review of over 88 potential sites throughout most of Washington State, three project sites were selected by the Principal Investigator (PI). These sites were chosen on the basis of the following criteria:

- safety of the public and work crews (both road and slope-related safety issues were addressed)
- visibility and accessibility for educational opportunities
- representation of the disparate soil moisture conditions, climate, and erosion types common to Washington State
- illustration of soil bioengineering techniques that could be used on large erosion sites, small erosion sites, and combined soil bioengineering and traditional engineering treatments
- allocated dollars and the availability of additional funding
- recommendations by WSDOT personnel.

The three selected sites were located in three regions of Washington State:

- Chelan - North Central Region
- Lost Creek/Forks - Olympic Region
- Raymond - Southwest Region.

PROJECT EFFORT

A combination of WSDOT research, road maintenance, engineering, and environmental funding was used to conduct three large soil bioengineering projects from November 1999 through April 2000.

Challenges were encountered on all three sites and resulted in design changes and additional learning opportunities. Maintenance personnel were actively involved in excavation and construction on the Raymond site and in the selection of the heavy equipment contractor for the Chelan excavation. Six Washington Conservation Corps (WCC) crews, comprising 42 crew members, participated in the construction of the three soil bioengineering projects. The soil bioengineering work involved the following:

- willow wall construction
- willow walls with a brush layer base
- live cribwall construction
- cordon construction
- live fascine construction
- cedar bender board fencing
- planting diverse native vegetation
- seeding
- biosolid application on the Lost Creek and Chelan sites.

OUTCOMES

- Using multiple soil bioengineering techniques, three large upland slope stabilization projects were constructed.

- The PI and the research team presented the research findings to WSDOT personnel in January 2001. See Appendix A for research team members.

- The full research report is available on the Olympia Service Center (OSC) Roadside and Site Development Unit internet homepage at http://www.wsdot.wa.gov/eesc/cae/design/roadside/rm.htm.

- A Soil Bioengineering chapter was written for the *Roadside Manual,* and the *Design Manual* soil bioengineering chapter was updated.
- The Federal Highway Administration (FHWA) contracted the OSC Roadside and Site Development Unit to create bioengineering Plans, Specification, and Estimates for the Blaine Road project in southwestern Oregon.
- WSDOT obtained the right to use and reproduce all materials from Lewis, E.A., *Soil Bioengineering: An Alternative for Roadside Management: A Practical Guide*. United States Forest Service. San Dimas Technology and Development Center. San Dimas, California, 2000.
- Communication among disciplines within WSDOT was enhanced. Opportunities for improved communication have been highlighted in the report.
- Awareness of soil bioengineering as an option for roadside stabilization and erosion control was increased within WSDOT.
- Relations with the public were enhanced by the publication of four articles (two local newspapers, an in-house newsletter, and a nationally distributed magazine) about WSDOT's use of a natural method of erosion control.

INTRODUCTION

Soil bioengineering is the use of plant material, living or dead, to alleviate environmental problems such as shallow, rapid landslides and eroding slopes and stream banks. In bioengineering systems, plants are an important structural component. This approach to slope stabilization requires a true partnership among many disciplines, including soil scientists, hydrologists, botanists, engineering geologists, maintenance personnel, civil engineers, and landscape architects.

Soil bioengineering most often mimics nature by using locally available materials and a minimum of heavy equipment, and it can offer roadside managers an inexpensive way to resolve local environmental problems. These techniques can also be used in combination with traditional engineering techniques such as rock or concrete structures.

PROBLEM STATEMENT

Transportation systems provide access and allow utilization of land and resources. Development priorities usually emphasize access, safety, and economics. Environmental concerns involve operational and maintenance problems such as surface erosion, plugged drainage structures, and mass failures.

Transportation systems provide tremendous opportunities and, if properly located on the landscape with well designed drainage features, can remain stable for years with negligible effects to adjoining areas. However, roads are often linked to increased rates of erosion and the accumulation of adverse environmental effects on both aquatic and terrestrial resources. This has become even more apparent during major winter storm events in recent years.

This is not new information to road managers. Road maintenance personnel, for example, face a huge task in maintaining roads under their jurisdiction. Major winter storms that have resulted in significant increases in road landslides and impacts to adjoining resources have compounded the road manager’s challenge.

The Washington State Department of Transportation (WSDOT) has been using soil bioengineering methods since the 1980s. Its early focus was on stream bank stabilization. In 1995 a soil bioengineering task force was formed to study opportunities for the application of soil bioengineering methods along state roadways, and the work group agreed that the time had come for WSDOT to consolidate various soil bioengineering efforts currently under way in the department. From this work, a chapter on soil bioengineering was written for WSDOT's *Design Manual*--a document used by all roadway design engineers working for and with WSDOT. This report documents the planning, design, and construction of three soil bioengineering projects on upland slopes in the roadside.

RESEARCH OBJECTIVES

The objectives for this study were as follows:

- provide viable alternatives, called soil bioengineering or "living" approaches, for slope and shallow, rapid landslide stabilization along different roadside environments
- educate WSDOT personnel in site selection and evaluation, and soil bioengineering techniques, including construction, monitoring, and maintenance
- provide soil bioengineering decision making skills.

This report documents the project process and its outcomes.

METHODS

SITE SELECTION

The researchers wanted the project to include a combination of fill slope and cut slope erosional features. The criteria for selection were as follows:

- safety of the public and work crews (road and slope related safety issues were addressed)
- visibility and accessibility for educational opportunities
- representation of the disparate soil moisture conditions, climate, and erosion types common to Washington State
- illustration of techniques that could be used on large erosion sites, small erosion sites, and combined soil bioengineering and traditional engineering treatments
- allocated dollars and the availability of additional funding
- input from WSDOT personnel.

From June 16 through 18, 1999, the research team analyzed the potential of 82 sites. Later in June the PI made additional site visits to slopes on SR 101, SR 14, and SR 3 to view sites requested by maintenance. No fill slope areas met all the site selection criteria.

Although the original plan had been to work on several smaller sites, because of the difficulty of working on many sites over long distances in a limited amount of time, the PI decided to use several techniques on each of the selected sites. The final selection comprised two west-side sites and one site east of the Cascade Mountains. Two of the sites, Raymond and Chelan, are considered large sites. The Lost Creek site, near Forks, was selected because it had a rock apron at the base.

CHELAN

Located at Mile Post 8.22 on State Route 971, above Lake Chelan, this 630-foot-long by 70-feet-high, north-facing slope has been a chronic source of surface erosion and ditch maintenance needs.

Geology and Soils

Soils on site are composed of glacial deposits and volcanic ash overlying granitic bedrock. The glacial deposits are composed of sand, gravel, cobbles, and boulders. The weathering of the granite bedrock into rocks, fragments, and mineral components is called grus; in particular, the feldspar minerals weather rapidly to a fine or "ashy" size. There is evidence, as seen in Figure 1, of chronic surface erosion with rilling and associated accumulated debris in the ditch line.

Figure 1. SR 971, Mile Post 8.22 vicinity, June 1999

Climate and Moisture

During the June 1999 site visit, the soil was moist. This is a north-facing slope that receives no direct sunshine from fall through spring.

This area receives an average of 10.9 inches of precipitation per year. Snow depth in January is approximately 5 inches. Average maximum temperature is 85ºF, which occurs during July. Average minimum temperature is 22.2ºF in January. Further climate data can be found at: http://www.wrcc.dri.edu/cgi-bin/ cliMAIN.pl?wachel

Existing Vegetation

Existing vegetation was sparse on the slope face. It consisted of a bitterbrush (*Purshia tridentata*) and ponderosa pine (*Pinus ponderosa*) community and one willow (*salix exigua*). See Appendix H. This vegetation was located on portions of the slope that were at an angle of repose of 1.5(V):1(H). Where the slope was steeper, no vegetation grew.

The slope above the vertical lip had an established ponderosa pine community. The vegetation, especially the mature trees, growing on the edge are at risk because of continual erosion (see Figure 2).

Figure 2. Vegetation community on stable soils

Opportunities and Constraints

This site had some moisture, combined with a favorable slope aspect, high public visibility, and a large bank of volunteer plants on the slope above. The adjacent landowners were willing to grant WSDOT a construction easement, allowing an excavator to flatten the slope angle and increase stabilization of the site.

The team's engineering geologist said that, traditionally, she would not have recommended additional work beyond reducing slope steepness. A flatter slope angle would help reduce surface erosion and provide favorable ground to establish vegetation. As with traditional engineering methods, soil bioengineering also requires "re-working" the slope profile, but in addition it incorporates vegetative treatments to accelerate site recovery while providing a more permanent solution to the erosion problem.

The constraints were the large amount of excavation necessary to lay the slope back to 1 ½ :1 and the small amount of moisture in the soil during the summer. Because of the relatively dry conditions, traditional soil bioengineering techniques were altered.

Design Solution

After consultations with fellow scientists and lumber experts, the PI's solution was to use cedar bender board fencing. The consensus was that the slope would benefit from terracing, but traditional soil bioengineering plant species, such as willow, would not be appropriate for these site conditions. As a result, cedar bender board fencing was used as an alternative to willow walls to reduce the length and steepness of the slope and to create stable planting platforms for easier establishment of native (dry climate) vegetation.

Redwood or cedar bender board fencing is essentially a fence supported on a short layer of shrub or tree stems. Specifically, it is a short retaining wall built of redwood or cedar bender fencing with a stem layered base. The PI's original bender board fencing detail and specifications are found in Figure 3:

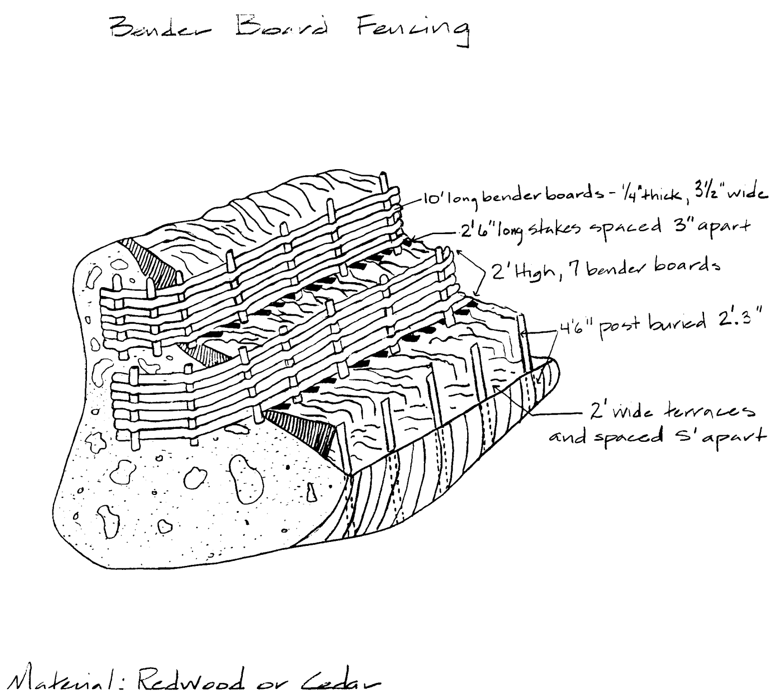

Figure 3. Bender board fencing

Construction

- North Central Region (NCR) Maintenance and the Environmental Office surveyed, staked, and created a topographic map of the site.
- NCR Real Estate Services contacted the landowners and obtained a construction easement for work through April 30, 2000.
- NCR Maintenance opted to use a contractor to excavate the vertical lip of the slope. The contractor removed approximately 11,000 cubic yards of material.
- NCR Maintenance provided traffic control during the 5.5 days of excavation.
- The crew constructed ten terraces with bender-board fencing. Figure 4 shows the terraces at the end of the season, on January 13, 1999.

The following species were planted within WSDOT right-of-way:

Service berry (*Amelanchier alnifolia*)	155
Snow berry (*Symphoricarpos albus*)	155
Blue Elderberry (*Sambucus cerulea*)	350
Mock Orange (*Philadelphus lewisii*)	160
Basin Big Sage (*Purshia tridentata*)	450
Antelope Bitterbrush (*Artemis tridentata tridentata*)	450
Rubber Rabbit Brush (*Chrysothamnus nauseosus*)	450
Ponderosa Pine (*Pinus ponderosa*)	950
Squaw currant (*Ribes cereum*)	190
Antelope Bitterbrush (*Purshia tridenta*)	200

The crew finished the planting and constructing of the 1,875 feet of terraces by April 13, 2000. Construction was complete by April 28, 2000.

Biosolid Application

In addition to reshaping the slope to 1 ½ to 1 and constructing bender board fencing terraces, the PI recommended biosolid application to increase soil moisture holding capacity and improve soil nutrient levels. The objective was to accelerate native plant establishment and provide long-term site recovery. GroCo compost was blown onto two-thirds of the slope on December 22, 1999. The prescription was for a very fine layer, of approximately 3/4 inch, to cover the slope. The prescription also required incorporation of the biosolids into the soil immediately upon application. This was not done until the terraces were constructed, and only in the terrace itself. The crew reported that constructing the terraces and pounding in the rebar was much easier after the application of the compost.

Figure 4. End of season - January 13, 2000

LOST CREEK, SR 101, MP 174

Site Geology

Thick glacial deposits that include lacustrine silts/clays and outwash silty sands and gravels are the dominant soils within the project limits. These deposits, left by the alpine glaciers that originated in the Olympic Mountains during the Pleistocene, include a thick sequence of laminated and massive silts and clays, similar to those identified along the present day coastline at the mouth of the Hoh River. These clays are thought to have been deposited in a glacial lake that formed from the stagnation of the Hoh River glacial lobe. Underlying the lacustrine deposits is a sequence of over-consolidated advanced outwash consisting of silty sands and sandy silts with gravels and glacial tills.

Climate And Moisture

This northwestern Washington site on the Olympic Peninsula receives an average of 119.5 inches of precipitation per year. Snowfall averages 13.6 inches per year between

December and April, with the greatest average depth of 5.6 inches in January. Average maximum temperature is 72.4º F in August, and average minimum temperature is 33.5º F in January. Further climate information can be found at: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?wafork

Existing Vegetation

Existing vegetation consisted of a cover of annual rye grass that had been seeded to prevent erosion.

Opportunities and Constraints

This site was part of a much larger road project. The project area had soil conditions that presented different challenges than those of the Chelan and Raymond project sites. For example, heavy marine clay soil on site, naturally dense material, had been further compacted by heavy equipment use during roadway construction.

This west facing, 180-feet-long by 86-feet-high slope has ample rainfall. A source of willows was nearby to aid in constructing the willow walls and brush layers.

The slope had rills and gullies and a shallow, rapid landslide with a head scarp near the top of the cut slope. The dense and heavily compacted marine clay presented challenges to all involved, especially the crews. Before the start of the research project, the geological engineer and project manager had placed a rock apron at the base of the slope to counter-weight the slope and to prevent further movement.

Two parallel lines of hay bales had been placed on the slope, approximately along the contours. These had apparently slipped, and the resulting downward slope of the bales was channeling surface water to the end of the hay bale row. In addition, water was seeping from between the bales, and concentrated water flows resulted in small rill and gully formations.

Design Solution

The Lost Creek project was divided into three sub-sites: 1, 3, and 5. Locations of these sites are shown in Figure 5.

The original design had techniques for all three sites. The original prescription for Lost Creek follows:

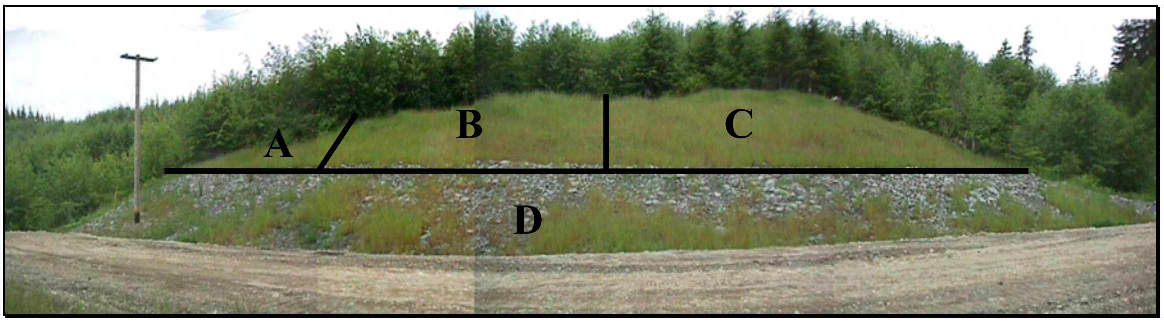

Figure 6. Site 1

Site 1 - Section A

Grasses had been effective at stabilizing surface erosion. To maintain surface stability and to prevent shallow rapid landsliding, trees (20%) and shrubs (80%) would be planted at a minimum of 4-foot x 4-foot spacing.

Benefit: root development increases soil strength and slope stability.

Site 1 - Section B

Grass had minimized surface erosion. To maintain stability and prevent further surface erosion and shallow, rapid landsliding, planting "islands" would be created by constructing willow fences. The dimensions would be 10 ft long and 2 ft high or 5 ft to 6 ft long and 2 ft high. Willows 3 ft to 4 ft long would be used for stakes to support the fencing. Once the fence had been constructed, the area behind the *willow fence* would be filled with soil (preferably a silt loam). Shrubs and small trees (i.e. dogwood) would be planted within these terraces.

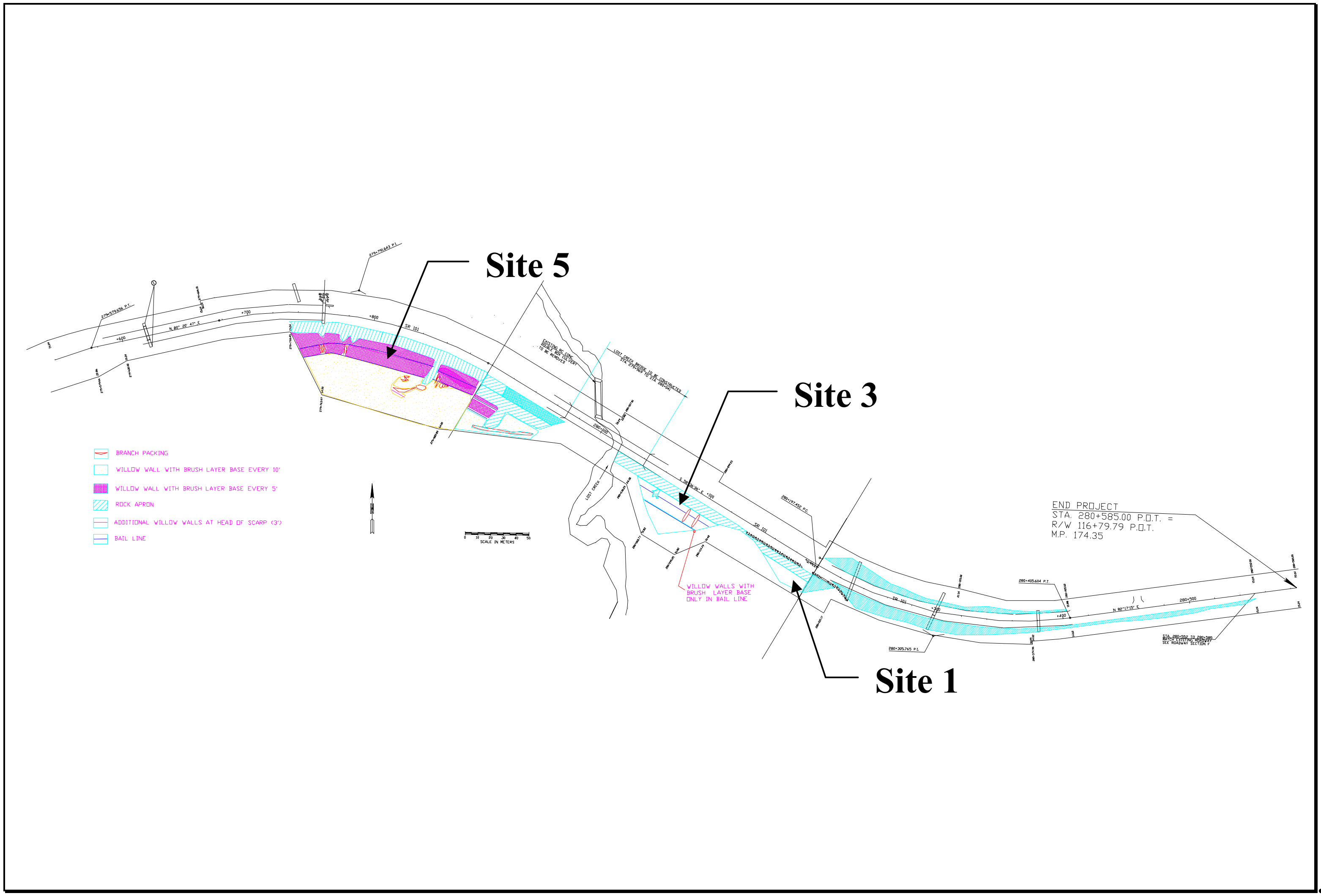

Figure 5. Lost Creek Project Areas

Benefits:

- reduce slope angle
- reduce surface erosion (rills and gullies)
- trap sediments
- capture and utilize both surface and subsurface water
- root development increases soil strength and slope stability.

Site 1 - Section C

Section C had experienced the highest level of surface erosion. This erosion was caused by overland flow and insufficient plant cover and root development. To maintain stability, inhibit additional surface erosion, and prevent shallow rapid landslides, planting "islands" would be created by constructing a *willow fence* and *willow fences with a brush layer base*. The *willow fence with a brush layer base* would be located above the rocked gullies. Once the fence had been constructed, the area behind the *willow fence with a brush layer base* would be filled with soil (preferably a silt loam). Shrubs and small trees (i.e. dogwood) would be planted within these terraces.

Benefits:

- reduce slope angle
- reduce surface erosion (rills and gullies)
- trap sediments
- capture and utilize both surface and subsurface water
- root development increases soil strength and slope stability
- slow water movement through sand layer
- *willow fence with a brush layer base* provides additional slope protection for critical areas above gullies.

Trees and shrubs would be planted throughout Sections A, B, and C.

Site 1 - Section D

To mitigate erosion, a rock apron had been placed at base of the slope. To complement the buttressing effect, live stakes would be installed in the rock apron. Stems 1.5 in. to 3 in. in diameter and 2 ft to 3 ft long would be used. These would be spaced 2 ft to 3 ft apart and tamped into the ground at right angles to the slope. Four-fifths of the stem should be installed into the soil.

Benefit: root systems form a mat that strengthens the soil and removes excess slope moisture.

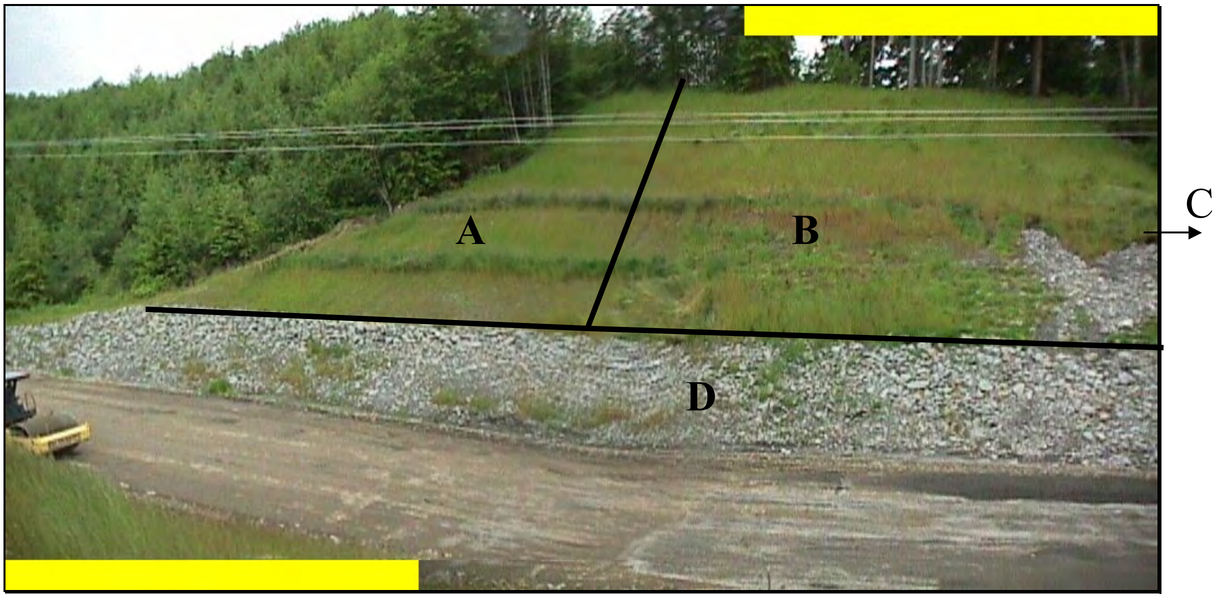

Figure 7. Site 3

Site 3 - Section A

Grasses had been effective at stabilizing surface erosion. To maintain surface stability and to prevent shallow rapid landsliding, all hay bales would be removed and trapped silts raked smooth. In addition, trees (30%) and shrubs (70%) would be planted throughout Section A. *Predominantly (90+%) shrubs would be used in terraced areas behind the willow fence*

Benefit: root development increases soil strength and slope stability.

Starting above the rock apron, a continuous row of *willow fence* would be constructed. The dimensions would be a continuous length and 2-ft height. Willows 3 ft to 4 ft long willows would be used for stakes to support the fencing. Once the fence had been constructed, the area behind the *willow fence* would be filled with soil (preferably a silt loam).

Shrubs and small trees (i.e., dogwood) would be planted within these terraces.

Benefits:

- reduce slope angle
- reduce surface erosion (rills and gullies)
- trap sediments
- capture and utilizes both surface and subsurface water
- root development increases soil strength and slope stability.

Site 3 - Section B

Grasses had been effective at stabilizing the surface erosion of upper B section. Below this upper section, however, grasses had had a minimal effect in preventing erosion. Within Site 3, Section B had experienced the highest level of surface erosion (rills and gullies). This erosion was caused by overland flow and insufficient plant cover and root development. To maintain stability, inhibit additional surface erosion, and prevent shallow rapid landsliding, all hay bales would be removed and trapped silts raked smooth. In addition, trees (40%) and shrubs (60%) would be planted.

Benefit: root development increases soil strength and slope stability.

Starting above the rock apron, a continuous row of a *willow fence with a brush layer base* would be constructed. The dimensions would be a continuous length and 2-ft height. Willows 3 ft to 4 ft long would be used for stakes to support the fencing. Four-fifths of the length of the brush layering willows should be buried within the terrace. Once the fence has been constructed, any excess should be trimmed; *the more stem exposed to air, the more moisture is lost for critical root development.* Also, once the fence had been constructed, the area behind the *willow fence with a brush layer base* and *willow fence* would be filled with soil (preferably a silt loam). Shrubs and small trees (i.e. dogwood) would be planted within these terraces.

Benefits:

- reduce slope angle
- reduce surface erosion (rills and gullies)
- trap sediments
- capture and utilize both surface and subsurface water
- root development increases soil strength and slope stability
- *a willow fence with a brush layer base* provides additional slope protection.

“Live gully repairs” would be constructed in all gullies except the one already filled with rock. Willow stems 1 in. to 2 in. in diameter and length, determined by the depth of the gully, would be used.

Live stakes would be installed in the rocked gully. Stems 1.5 in. to 2.5 in. in diameter and 2 ft to 3 ft long would be used. The would be spaced 2 ft to 3 ft apart and tamped into the ground at right angles to the slope. Four-fifths of the stem should be installed into soil.

Benefit: root systems form a mat that strengthens the soil and removes excess slope moisture.

Trees (30%) and shrubs (70%) would be planted throughout Section B (excluding the rocked gully). *Predominantly (90+%) shrubs would be used in the terraced areas behind the willow fence with a brush layer base and the willow fence*

<u>*Site 3 - Section C*</u>

Grasses had effective at stabilizing the surface erosion of upper C section. However, saturated soils had led to a small shallow, rapid landslide located in the center of Section C. To inhibit the area from enlarging and stabilize the feature, all hay bales would be removed and trapped silts raked smooth.

"Branch packing" would be installed in the shallow rapid landslide. Willow stems ½ in. to 2 in. in diameter would be used.

Benefits:

- reconstruction of slope by refilling localized slump
- retard runoff
- reduce surface erosion (rills and gullies)
- capture and utilize both surface and subsurface water
- root developmen, increassd soil strength and slope stability.

Starting at the rock apron, continuous rows of *willow fence with a brush layer base* would be constructed. The dimensions would be continuous length and 2-ft height on both sides of the branch packing area. Willows 3 ft to 4 ft long would be used for stakes to support the fencing. Four-fifths of the length of the brush layering willows should be buried within the terrace. Once the fence had been constructed, any excess would be trimmed; *the more stem exposed to air, the more moisture is lost for critical root development.* Also, once the fence has been constructed, the area behind the *willow fence with a brush layer base* and *willow fence* would be filled with soil (preferably a silt loam). Shrubs and small trees (i.e. dogwood) would be planted within these terraces.

Benefits:

- reduce slope angle
- reduce surface erosion (rills and gullies)
- trap sediments
- capture and utilize both surface and subsurface water
- root development increases soil strength and slope stability
- *willow fence with a brush layer base* provides additional slope protection.

Site 3 - Section D

Live stakes would be installed in the rock apron. Stems 1.5 in. to 3 in. in diameter and 2 ft to 3 ft long would be used. These would be spacd 2 ft to 3 ft apart and tamped into the ground at right angles to the slope. Four-fifths of the stem should be installed into soil.

Benefit: root systems form a mat that strengthens the soil and removes excess slope moisture.

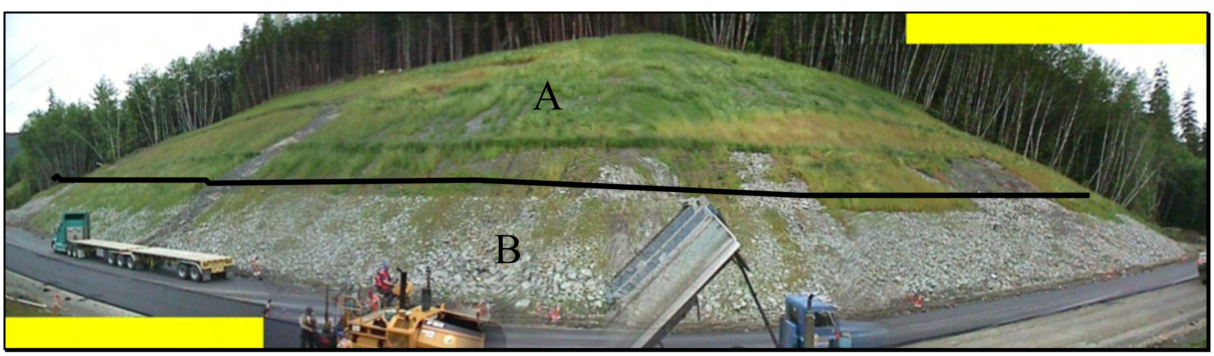

Figure 8. Site 5 before treatment

Site 5 - Section A

Grass had minimized surface erosion. Within Site 5, Section A had experienced the highest level of surface erosion. This erosion was caused by high rainfall and subsequent saturated soils, which led to excess overland flow and draining hay bales. Plant cover and root development were insufficient to maintain slope stability. To inhibit additional surface erosion and shallow rapid landsliding, all hay bales would be removed and trapped silts raked smooth. In addition, planting "islands" would be created by constructing a *willow fence with a brush layer base*. Once the fence had been constructed, the area behind the *willow fence with a brush layer base* would be filled with soil (preferably a silt loam). Shrubs and small trees (i.e. dogwood) would be planted within these terraces.

Benefits:

- reduce slope angle
- reduce surface erosion (rills and gullies)
- trap sediments
- capture and utilizes both surface and subsurface water
- root development increases soil strength and slope stability
- slow water movement through sand layer
- *willow fence with a brush layer base* provides additional slope protection for critical areas above gullies.

"Branchpacking" in the shallow, rapid landslide would be installed. Willow stems ½ in. to 2 in. in diameter would be used.

Benefits:

- reconstruction of slope by refilling localized slump
- retard runoff
- reduce surface erosion (rills and gullies)
- capture and utilizes both surface and subsurface water
- root development, increased soil strength and slope stability.

Trees and shrubs would be planted throughout Section A.

Site 5 - Section B

Live stakes would be installed in the rock apron. Stems 1.5 in. to 3 in. in diameter and 2 ft to 3 ft long would be used. These would be spaced 2 ft to 3 ft apart and tamped into the ground at right angles to the slope. Four-fifths of the stem should be installed into soil.

Benefits: root systems form a mat that strengthens the soil and removes excess slope moisture.

Construction

Construction began on Site 3 on October 25, 1999, with one vrew on willow wall construction. The vrew began using branch packing for one gully according to the original design.

Construction on Site 5 began on November 9, 1999, with the uppermost willow wall. The original intention was to use a winch to bring fill dirt up to the top of the slope. However, the crew supervisor had safety concerns with that method and decided to hand-carry buckets of soil up the slope. The crew had successfully used that method on Site 3 for two weeks.

Because of the amount of surface water received by the gullies on Site 3, the original branch packing design washed out. Additional willow walls were constructed at the head of this gully, and the branch packing design was changed to the design seen in Figure 9.

Figure 9. Branch packing parallel to contours

The crew supervisor designed a winch system for Site 5. This system was very slow, and the amount of time projected to complete the work on Site 5 was beyond the scope of the soil bioengineering research project. Because of the size of Site 5 and its complexity and the problems associated with running two projects on the same slope at the same time, Site 5 was dropped from the research project.

Construction concluded on Site 3 on January 27, 2000. Native vegetation was planted on Site 3 the week of January 24th. Figure 10 shows the site immediately after construction.

Figure 10. Site 3 immediately after construction

The following plants were planted at the Forks site:

Mix A	%Mix	# plants
Alnus crispa (Sitka Alder)	3	16.5
Oemleria cerasiformis (Indian-plum)	5	27.5
Mahonia nervosa (Oregon Grape)	6	33
Cornus sericea (Red-osier Dogwood)	14	77
Rubus spectabilis (Salmonberry)	12	66
Amelanchier alnifolia (Serviceberry)	12	66
Salix sitchensis (Sitka Willow)	14	77
Symphoricarpos alba (Snowberry)	12	66
Rubus parviflorus (Thimbleberry)	12	66
Rhamnus purshiana (Cascara)	4	22
Rosa nootkana (Nootka Rose)	4	22
*Physocarpus capitatus (*Pacific Ninebark)	2	11
Totals	**100**	**550**

Mix B	%Mix	# plants
Alnus crispa (Sitka Alder)	18	99
Oemleria cerasiformis (Indian-plum)	5	27.5
Mahonia nervosa (Oregon Grape)	5	27.5
Cornus sericea (Red-osier Dogwood)	7	38.5
Rubus spectabilis (Salmonberry)	9	49.5
Amelanchier alnifolia (Serviceberry)	4	22
Salix sitchensis (Sitka Willow)	4	22
Symphoricarpos alba (Snowberry)	23	126.5
Rubus parviflorus (Thimbleberry)	4	22
Rhamnus purshiana (Cascara)	4	22
Rosa nootkana (Nootka Rose)	3	16.5
Totals	**86**	**473**

MIX C	%Mix	# plants
Thuja plicata (Western Red Cedar)	25	15
Pseudotsuga menziesii (Douglas Fir)	25	15
Tsuga heterophylla (Western Hemlock)	25	15
Picea sitchensis (Sitka Spruce)	25	15
Totals	**100**	**60**

RAYMOND, SR 101, MP 60.35

Geology and Soils

Soils on this 591-feet-long by 112-feet-high east-facing slope are composed of weathered marine sedimentary rocks. Small shallow, rapid landslides have occurred where these weathered clay layers left slope sections exposed to water movement. With excess surface and subsurface moisture, these layers slipped and moved downhill into the ditch. To manage stormwater runoff, maintenance activities required these plugged ditch lines to be cleared. In doing so, the base of the shallow rapid landslide was undercut, leaving a portion of the area with an exposed vertical face. During the year, the slope would “adjust,” move again into the ditch line, leaving a larger head scarp exposed to surface and subsurface water movement (see Figure 11).

Figure 11. Area of instability

<u>Climate and Moisture</u>

This southwestern Washington site receives an average of 85 inches of precipitation per year. January is the only month that generally receives snow, with an average of 0.4 inches. Average maximum temperature is 72.9º F in August, and average minimum temperature is 32.5º F in December. Further climate information can be found at: http://www.wrcc.dri.edu/cgi-bin/cliMAIN.pl?waraym

<u>Existing Vegetation</u>

On-site vegetation consisted of a very young community of Douglas fir, red alder, salal, palmate coltsfoot, common horsetail, and sword fern, with a good grass cover. A mature Douglas fir, western red cedar, and western hemlock community lived at the top of the slope, which provides ample seed source for plant recruitment. Tree seedlings had been cut from the hillside on a regular basis; however, WSDOT area maintenance personnel had not been involved in any tree removal at that site.

<u>Opportunities And Constraints</u>

This large slope, located on an outside curve just north of the city of Raymond, is highly visible and receives ample rain throughout the year. The local climate and soils have supported a diverse plant community. Trees and shrubs were needed to stabilize the slope but were being cut on a regular basis.

This was a good candidate for a soil bioengineering project because the erosion process of the site involved surface erosion and a shallow rapid landslide, which both fall under the parameters of soil bioengineering techniques.

<u>Design Solution</u>

The Raymond Soil Bioengineering Design, December 28, 1999, is shown in Figure 12.

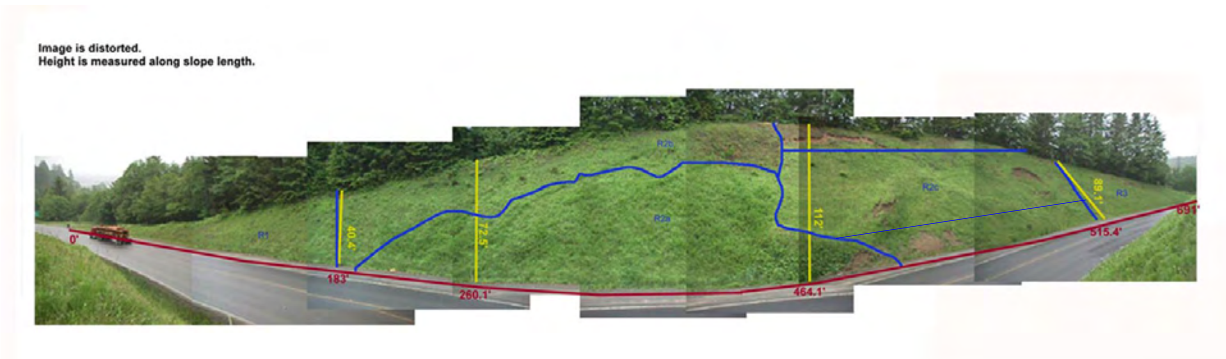

Figure 12. Raymond research site with sub-areas

<u>Areas R1 and R3</u>

The primary focus was aesthetic.

- A recommended mix of vegetation would be planted. Bender board fencing would be installed to complement the existing bronze animal sculptures by local artists. Rather than excavating a terrace behind the fencing (contrary to usual installation), fill would be added to create a planting platform.
- Cordons would be constructed.

<u>Area R2</u>

The primary focus was stabilization.

R2a: The area would be planted with an approved mix of water-loving vegetation.

R2b: The area would be planted with an approved mix of vegetation.

R2c: The area would receive soil bioengineering. Starting at 6 ft above the cribwall at the slope base, a brush layer 5 ft deep would be constructed across the slope. A willow wall with a brush layer base would be constructed across the slope above the brush layer. These two treatments would be alternated at a maximum of 10-ft intervals up to 75 ft. At 75 ft above the cribwall, willow walls at would be constructed at 10-ft intervals. The goal of these treatments was to provide slope stability and easy access to planting areas.

R2d: A live cribwall would be constructed at the base of the slope. The total length of the cribwall would be 183 ft to 515.4 ft (as seen from width markings on photo). From 260.1 ft to 515.4 ft, a cribwall 6 ft high x 6 ft wide x 255.3 ft long would be constructed. For 77 ft on either end, a cribwall 5 ft high x 5 ft wide would be constructed. Then for 10 ft on either end, a cribwall 4 ft high x 4 ft wide would be constructed. The ends would be flanged to blend in with the slope and to eliminate any potential "snagging" safety concerns.

<u>Construction</u>

Construction began with region maintenance personnel using heavy equipment and two WCC crews using hand equipment on February 1, 2000. They began by excavating at the northern end of the site and installing the first cordon. Figure 13 shows the cordon construction after the bottom two logs had been placed in the terrace parallel to the slope.

Figure 13. Cordon construction

Figure 14 was taken on February 10, 2000. It shows cribwall construction at the end of the first week of construction.

Figure 14. End of first week of construction.

During site preparation for the base of the cribwall, the heavy equipment operator removed a portion of the slope toe. The fresh cut was left unsupported overnight, and when excavation resumed the next morning, the slope moved (Figure 15). The slope was oversteepened in the adversely oriented bedrock, causing failure of the bedrock and colluvial soils overlying the bedrock. In different material this might not have happened, and if the site had not been excavated and left exposed overnight, this slope movement might have been prevented. For future projects, on sites of this size and with propensity for large movement it is recommended that a slope stability analysis be a part of project design.

The modular cribwall frames were constructed off-site by February 28, 2000. They were installed in two vertical sections so that willow branches could be installed between the lifts, and soil could be added and compacted with the excavator bucket.

Installation can be seen in Figure 16. Each 15-ft cribwall framed section was cabled to the adjacent unit and to the ones above and below it.

Figure 15. Slope failure

Figure 16. Installation of modular live cribwall sections

The live cribwall and cordon construction was completed with these changes on March 2, 2000. The crews finished the Raymond project, with willow wall construction further up the slope and with plantings and straw mulch application, on March 28, 2000. Figure 17 shows the willow walls constructed above the live cribwalls. Figure 18 shows the entire project after completion.

The following species were planted on this site:

Twinberry (*Lonicera involucrata*)	50
Salmonberry (*Rubus spectabilis*)	100
Sword fern (*Polystichum munitum*)	50
Snowberry (*Symphoricarpos albus*)	100
Salal (*Gaultheria shallon*)	50
Scouler's Willow (*Salix scouleriana*)	50
Red Osier Dogwood (*Cornus sericea*)	100
Sitka Alder (*Alnus sitchensis*)	100
Ninebark (*Physocarpos capitus or pacifica*)	50

Figure 17. Live cribwall and willow walls

Figure 18. Completed soil bioengineering research site

FINDINGS AND DISCUSSION

As with most construction projects, each of the three research sites presented complications and unique challenges that resulted in modifications to the original plans.

CHELAN

Construction on the Chelan project site began November 4, 1999, and concluded April 19, 2000. The original design had to be changed because of harder than expected sub soil. The principle design changes included substitution of rebar for wood stakes as the upright members of the bender board fencing units and the lowering of the fencing height from 2 ft to 1 ft.

In addition, the crew did not rake the biosolids into the parent material as instructed. However, this oversight presented an opportunity to compare three areas within the site. For example, the control area received no biosolid application, a second area received a biosolid application that was not raked in, and the third area received a biosolid application that was raked in. During the first season, the principle grass species growing in the control area was fescue. Within the area where compost was raked in, rye was the principle grass species the first summer. On the west end of the site, where compost was left on the surface, fescue was also the principle species, and it was more vigorous than the area without compost. During the first summer, trees grew at the same rate throughout the project slope. Shrub growth appeared to correlate to shading, with more growth where shading occurred.

By the end of June 2000 the bender board appeared to have stabilized the surface erosion, and grass was growing on all terraces. However, where the composted biosolids had been applied, the annual rye was thicker, greener, and withstanding drought conditions better than the control section without compost, as seen in the Figure 19.

The following observations were made:

- Trend: improvement.
- There was slight evidence of continued surface erosion in unvegetated areas.
- The site supported 43 percent vegetative cover.

Figure 19. Grass communities differ with biosolids

- The survivability of woody vegetation planted at the brush layer base of each terrace varied with position on the slope. This finding was possibly related to soil moisture availability, thawing and refreezing, or installation date. Of the plants installed at the base of the structures,
  - Terraces 1-5 demonstrated 40 percent survival
  - Terrace 6 demonstrated 75 percent survival
  - Terrace 7 demonstrated 70 percent survival
  - Terrace 8 demonstrated 75 percent survival
  - Terrace 9 demonstrated 60 percent survival
  - Terrace 10 demonstrated 80 percent survival.
- Native woody vegetation planted on top of the terraces showed variable survivability:
  - uniform groundcover of native plants – 15 percent overall.
  - uniform survival of native plants – 70 percent overall.
  - uniform survival of native *Ponderosa Pine* sp. – 90 percent overall.
  - no difference in the first 6 months in survival of woody vegetation between areas with and without compost.
  - marked increase in the vigor of horizontally planted vegetation when compost was added.

As of October 2000, trees planted on the landowners' property were green, as seen from below, and the grass and trees in soil disturbed by a bobcat were growing.

Long-term monitoring will allow WSDOT to determine long-term slope stability and to further understand the relationship between native plants, native soil, and biosolids. The status of this site in July 2000 is shown in Figure 20.

Figure 20. Chelan, July 20, 2000

Table 1 summarizes the costs for the Chelan project:

Table 1. Chelan costs

Item	***Cost***
Total WCC Crew Time (10.5 weeks)	$26,250.00
Total Materials Cost	$ 3,945.24
Vegetation Costs	$ 2,640.80
Biosolid Application	$ 1,329.00
RA'S Salary and Per Diem	$ 5,522.00
Contractor/Excavation Costs	$ 7,296.10
Total Cost for Project	$46,983.14
Cost per Square Foot	$ 1.96

LOST CREEK

Construction on the Lost Creek project began October 25, 1999, and concluded December 27, 1999. The original design was altered because heavy rains caused springs to flow from areas in the slope, which drained directly through the conventional brush layers placed perpendicular to the slope contour, as seen in Figure 21.

Figure 21. Brushlayers failed when placed perpendicular to the slope.

The design was changed so that the brush layers were laid parallel with the slope contour to better manage surface flow. This is shown in Figure 22.

In addition, mineral soils were used in place of specified topsoil, and compost was prematurely applied to the project site. Finally, the geotechnical engineer and the PI recommended removing Site 5 from the research project because of a reactivated deep-seated rotational failure. With this and other problems, the site exceeded the scope and time frame of the research project.

As of July 2000, the head scarp was stabilizing with grasses, shrubs, trees, and willow structures. The top photo in Figure 23 shows the site six months after construction. The lower photo shows the site before construction.

Figure 22. Branch packing parallel to slope contours.

Figure 23. Site 3 Before and after soil bioengineering

- Trend: improvement to stability.
- There was no evidence of mass movement or gully erosion.
- The site supported 95 percent vegetative cover.
- Brushlayer survivability:
  - brushlayer structures – 80 percent show new growth
  - willow wall structures – 40 percent show new growth.
- Survivability of vegetation on terraces:
  - uniform survival above rock apron – 70 percent overall
  - uniform survival within the rock apron – 40 percent overall.

Table 2 provides costs for the Lost Creek project.

Table 2. Lost Creek costs

Item	*Cost*
Total WCC Crew Time (8 weeks)	$20,000.00
Total Materials Cost	$ 210.82
Vegetation Costs	$ 1,131.64
Biosolid Application	$ 3,200.00
RA Salary and Per Diem	$ 3,712.00
Geotechnical Rock Apron	$15,020.00
Total Cost for Project	$30,774.46
Cost per Square Foot	$ 3.55

RAYMOND

Construction on the Raymond project began January 31, 2000, and concluded March 23, 2000. The original design was altered because underlying sheets of bedrock failed when the toe was removed and left overnight without support. The principal design change was the off-site construction of the log cribwalls and their installation as modular 15-ft units. The slope was excavated in 15-ft sections, the cribwall units placed, cribwall units cabled to the adjoining unit, willow stakes placed, and the cribwall backfilled in approximately 2 hours per unit. This change allowed the project to continue with minimum crew exposure to the unstable slope condition and with minimum time for the undercut slope to strain without a stabilized toe.

The design also had to be changed because the delivered logs were larger than those specified in the drawings. Rebar was used to link the logs instead of ¼-in. by 8-in.-long spikes. Cables were used to link the cribwall sections that had been constructed off site. Spaces between the logs were larger than originally designed and allowed for greater soil exposure than was intended in the original design. The larger logs, however, did result in the use of fewer logs.

The following are the results as of summer 2000.

- Trend: improvement to stability.
- There was no evidence of mass movement or surface erosion.
- The site supported 95 percent vegetative cover.
- Structure survivability:
  - cribwall structure - 90 percent new growth
  - willow wall structures – 30 percent show new growth
- fascines – 10 percent show new growth.
- Native woody vegetation survivability:
  - nursery stock – 80 percent survival
  - woody vegetation cuttings – 80 percent show new growth
  - no difference in survival between nursery stock and cuttings of the same species.

Table 3 summarizes the time and materials costs for the Raymond project:

Table 3. Raymond costs

Item	*Cost*
Total WCC Crew Time (10 weeks)	$25,000.00
Total Materials Costs	$ 5,996.32
Heavy Equipment Rental	$ 7,296.08
Vegetation Costs	$ 1,820.00
RA's Salary and Per Diem	$ 4,212.00
SWR Costs	$ 185.25

Total Cost for Project	$44,509.65
Cost per Square Foot	$ 1.59

COST/BENEFIT ANALYSIS[1]

PURPOSE

The benefit/cost analysis had the following objectives:

- assist decision-makers in justifying the promotion of soil bioengineering as a cost-saving and environmentally friendly alternative for surface erosion and shallow rapid landslide stabilization
- evaluate cost-efficiency and help select the best alternative from traditional engineering treatments, soil bioengineering, or their combinations
- educate WSDOT personnel, other land managers, and the public about the integration, economic efficiency, and environmental values of soil bioengineering.

Soil bioengineering as an alternative to roadside management offers, but is not limited to, the following benefits:

- increased practicability
  - useful on sensitive or steep sites
  - installed in construction slow seasons
  - long-term soil stability
- cost savings
  - reduce/eliminate maintenance
  - treat erosion earlier and avoid costly solutions
  - use indigenous plant species
- improved environment
  - less soil disturbance to the site and adjoining areas
  - improved air and water quality
  - improved landscape and habitat values.

METHODOLOGY

Cost Assessment

For the analysis, soil bioengineering treatment costs were the actual costs for achieving the designed functions. Hypothetical traditional treatments costs were

---

[1] Research analyst: George Xu, Ph.D. WSDOT Environmental Economist

estimated on the basis of phone interviews with WSDOT personnel. They were asked what treatments would be used on the three sites if the department had chosen to treat those slopes traditionally. Costs for those treatments were estimated by using the bid tabs of nearby projects.

For the Chelan site, the traditional engineering treatment would have been to excavate the slope back to a 1 ½(H) to 1(V) angle (Moses) and to apply a hydroseed mix with tackifier to control surface erosion. (Tveten, Belmont, and Salisbury)

The traditional engineering treatment for Lost Creekwould have involved treating surface water runoff by collecting runoff at the base of the slope in a quarry spall-lined ditch, then moving it under the road in a culvert and into a detention pond to allow sedimentation. (Witecki, Tveten, Salisbury) The fine, compacted soils on the site resisted infiltration, and large amounts of overland flow contributed to sedimentation problems during and after road construction. (Lewis) A rock apron was installed on this site to prevent slope movement before the research project. Its cost was included in the estimated cost for the non-soil bioengineering treatment.

For the Raymond site, the traditional engineering treatment would have been to construct a rock buttress similar to one directly across the highway from the project location. Note that typically, a soil stability analysis would be needed to determine the size (mass) of a rock buttress. (Moses) Without this study, the size of the proposed buttress was estimated the same volume as that of the constructed cribwall. Note also that in this example, the purpose of the rock buttress was only to add a vertical component to the slope by which the toe of the slope could be elevated to reduce overall steepness and to provide support for eroding materials. A bench would have to be excavated for placement of the rock buttress.

Benefit Assessment

Soil bioengineering was evaluated as an alternative investment option in this benefit cost analysis. Soil bioengineering projects were designed to produce the same roadside stabilization effects as their traditional alternatives. Therefore, the cost saving resulting from adoption of soil bioengineering projects was evaluated as a net benefit.

The benefit of stabilization was assessed by using the same cost pricing method for both soil bioengineering and traditional alternatives.

Environmental benefits generated by the projects were assessed by using the benefit transfer approach that is a common method in environmental economic assessment when time and resources are limited. Environmental benefits were derived on the basis of the results and findings of similar studies (Sotir 2001; EPA 1998, California Department of Transportation 1998; McPherson & Simpson 1999), and transferred values were adjusted according to the changes of key factors.

Trees remove pollutants from the atmosphere and also eliminate or reduce the source of pollution. Pollutants deposited and particulates intercepted include ozone, NO_2, and PM_{10}. Air pollutant uptake benefits were assessed on the basis of the number of trees planted, growth rate and canopy cover information, unit value of pollutant uptake, and effectiveness. Effectiveness was determined by evaluating source elimination and pollutant uptake effects.

Stormwater runoff reduction benefits were assessed by using the runoff coefficients of different land covers, the local hydrograph, sediment treatment requirements, and the unit value of stormwater treated.

The assessment of carbon sequestration benefits was based on the assumption that 80 percent of carbon will be released at the end of the life cycle (removal of trees) and the unit value of carbon sequestration derived by other studies.

Many other environmental and aesthetic values are associated with soil bioengineering treatments. They were not assessed because of either intangibility or time constraints.

Comparability

Three key factors were considered to ensure the comparability of both benefits and costs. They were effectiveness, life cycle, and discounting.

1. Effectiveness

The benefit of soil bioengineering alternatives should be adjusted in terms of effectiveness. Soil bioengineering techniques are assumed to have the same effective as traditional engineering methods when used on appropriate sites for roadside stabilization and the treatment of runoff. However, since soil bioengineering uses living plants, it has benefits that rock and cement do not have. For example, plants can provide air pollutant uptake and carbon sequestration. Plants also provide visual benefits such as distraction screening, guidance and navigation enhancement, and aesthetic pleasure. When we applied benefit transfer to evaluate environmental benefits, the effectiveness for related functions was assessed on the basis of the different conditions between the original study sites and the sites of this study.

Table 4 shows the assumptions of effectiveness used in this study.

Table 4. Effectiveness assumptions

Effectiveness Assumptions Used in This Study				
	Roadside Stabilization	Runoff Treatment	Air Pollutant Uptake	CO_2 Sequestration
Chelan	100%	100%	34%	100%
Raymond	100%			
Forks	100%	50%	9%	100%

Benefits for runoff treatment, air pollutant uptake, and CO_2 sequestration for the Raymond site are not shown. Because the slope was previously vegetated, those functions were already taking place and no improvement was assumed.

Air pollutant uptake effectiveness for soil bioengineering treatments were determined by two factors: seriousness of air pollution and air pollutant-taking capacity of the alternative.

Data sources for the effectiveness analysis included Sotir (2001), EPA (1998), California Department of Transportation (1998), and McPherson and Simpson (1999).

2. Life Cycle Analysis

Life cycle analysis was used to adjust the life cycle costs of both thetraditional and soil bioengineering alternatives. The initial investment for a soil bioengineering project can be higher than a traditional engineering technique, especially if no structure or heavy riprap is involved. However, the project life is historically longer with a living system, such as soil bioengineering. Therefor,e the annualized life cycle cost is lower with soil bioengineering, since those systems can work at least 50 years. (Sotir 2001, Schiechtl 1980) Life cycle costs for soil bioengineering techniques were analyzed using a cycle of 30 years. A 20-year life cycle was used for traditional alternatives for roadside management.

3. Discounting

Discounting was used to make benefit and cost streams over the project life comparable. In other words, it made the benefits of different times comparable. The discounting rate used in the analysis was 4 percent.

DATA SOURCES

The following were the major data sources used in this analysis:

- actual costs
- estimated costs using historic data
- Environmental Protection Agency (EPA)
- USDA Forest Service
- California Department of Transportation
- experts' opinions.

FINDINGS

Costs

The costs for the three sites are summarized in the tables 5 and 6:

Table 5. Costs of "traditional" treatments

Summarized Costs of Traditional Treatments	Chelan	Raymond	Forks	Sum
Capital Cost	$ 12,451	$ 130,910	$ 45,130	$ 188,491
O&M	$ 2,990	$ -	$ 22,745	$ 25,734
Total Cost	$ 15,441	$ 130,910	$ 67,875	$ 214,225
Annualized Cost for Life Cycle	$ 772	$ 6,546	$ 3,394	$ 10,711

Table 6. Soil bioengineering treatment costs

Summarized Costs of Soil Bioengineering Treatments	Chelan	Raymond	Forks	Sum
Capital Cost	$ 46,983	$ 44,510	$ 30,774	$ 122,267
O&M	$	$	$	$
Total Cost	$ 46,983	$ 44,510	$ 30,774	$ 122,267
Annualized Cost for Life Cycle	$ 1,566	$ 1,484	$ 1,026	$ 4,076

Benefit Composition

The benefits were broken into the categories seen in Figure 24 (RM stands for Roadside Maintenance). Cost savings were the dominant source of the benefits provided by soil bioengineering projects in comparison to traditional alternatives.

Cost Savings

The initial construction costs for the three soil bioengineering research sites are shown in Figure 25 as they compare to the traditional engineering treatment that would have been used if WSDOT had chosen to stabilize those slopes. Annualized cost, which includes maintenance savings, between soil bioengineering and traditional engineering showed that all three projects were cost effective.

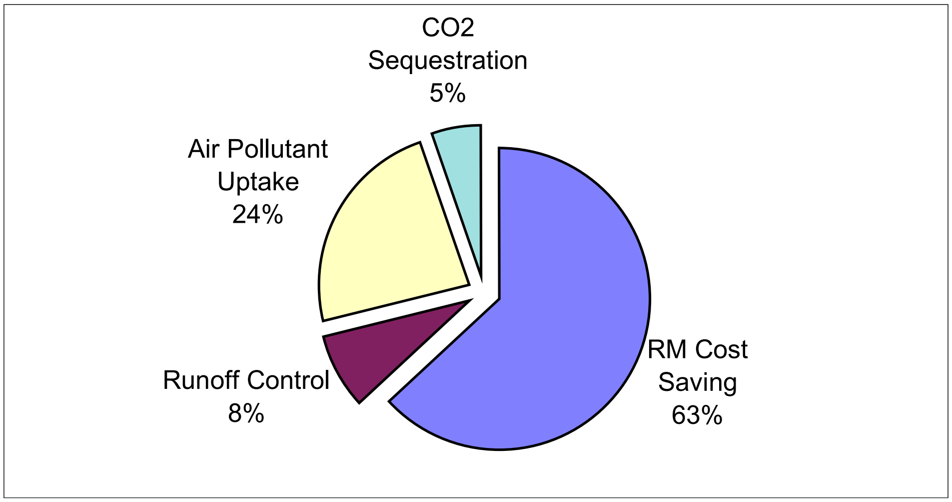

Figure 24. Benefit composition

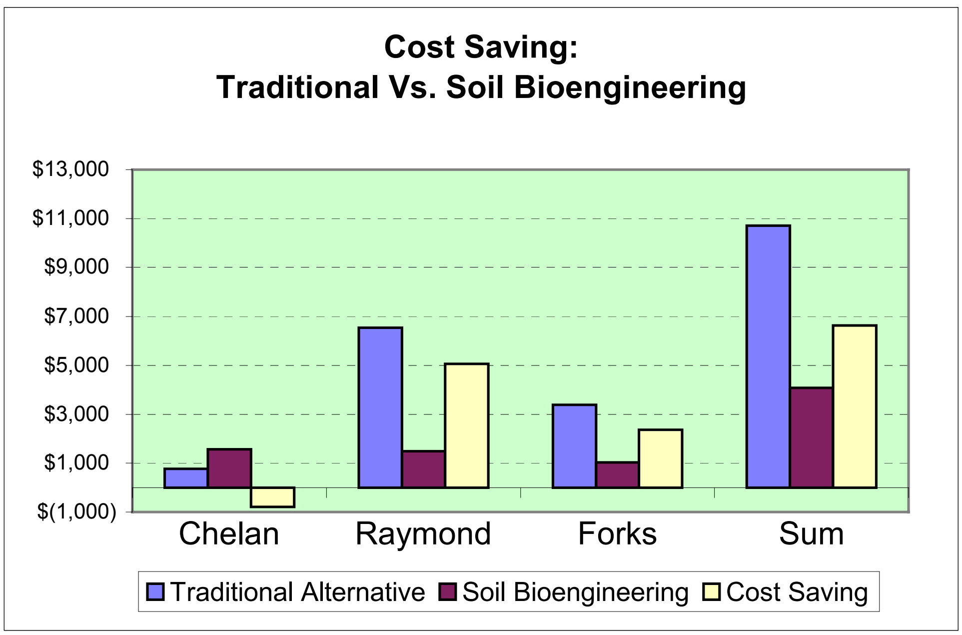

Figure 25. Initial construction cost saving

Benefits

Table 7 summarizes the benefits of the soil bioengineering project.

Table 7. Assessed benefits of soil bioengineering alternatives

Assessed Benefits: Soil Bioengineering Alternatives						
	CHELAN		**RAYMOND**		**FORKS**	
	Life Cycle Benefit	**Annualized Benefit**	**Life Cycle Benefit**	**Annualized Benefit**	**Life Cycle Benefit**	**Annualized Benefit**
Total Benefit:	$67,499	$2,250	$133,404	$4,447	$85,622	$2,854
Stabilization	$15,441	$515	$133,404	$4,447	$67,872	$2,262
Runoff Control	$1,638	$55			$13,338	$445
Air Pollutant Uptake	$43,837	$1,461			$1,020	$34
CO2 Sequestration	$6,583	$219			$3,391	$113
Total Costs:	$46,983	$1,566	$44,510	$1,484	$30,774	$1,026
Net Benefit:	$20,516	$684	$88,895	$2,963	$54,847	$1,828
B/C Ratio	1.44	1.44	3.00	3.00	2.78	2.78

B/C Ratio

The benefit to cost ratio is a means of comparing the dollar figure of benefits derived in relation to the cost of a project. The benefit/cost figures include annualized maintenance cost savings. For each dollar spent on the soil bioengineering projects, $1.44 benefit was generated at the Chelan site, $3 at the Raymond site and $2.78 at the Forks site.

In comparison with the traditional treatments, for each dollar invested in roadside stabilization using the soil bioengineering alternative, $1.01 more benefit was generated than would have been with the traditional alternative ($2.41 – $1.40 = $1.01).

Table 8. Benefit/cost ratio

B/C Ratio	CHELAN	RAYMOND	FORKS	Average
Soil Bioengineering	1.44	3.00	2.78	2.41
Traditional Alternative	1.95	1.00	1.26	1.40

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions are based on experience acquired during the design and construction phases of this project.

1. Soil bioengineering can be constructed and used successfully on WSDOT projects. As of the writing of this report, all three project sites are revegetating and appear stable. They demonstrate viable alternatives for stabilizing upland slopes.

2. When technically feasible, soil bioengineering alternatives can be adopted to produce equal or better economic and environmental results than the traditional geotechnical solutions alone. The average benefit to cost ratio in this study was 2.41, demonstrating that soil bioengineering is a favorable economic alternative in roadside management.

3. Incorporated ("raked in") composted Class A biosolids used on the Chelan site correlated with enhanced grass growth. The addition of composted Class A biosolids increased soil workability and influenced the grass community composition.

4. On project areas with a potential for mass wasting, such as sections of both the Lost Creek and Raymond sites, an engineering slope stability analysis should be performed. This was done on the Lost Creek site.

5. Woody vegetation planted as 10-inch plugs had a higher survival rate than the bare root plants at the Chelan site. Purchasing plugs or containerized plants in Central and Eastern Washington may increase survival rates.

6. The creation of terraces at the Chelan site allowed for enhanced plant growth. Little vegetation is now growing on the steep areas between the terraces. This is similar to the on-site conditions before the project. While the initial costs of soil bioengineering are higher than the costs of slope flattening and hydroseeding (the "traditional" approach), more vegetation establishes with soil bioengineering. This allows for more long-term environmental benefits, such as air and water quality improvements.

7. Communication and education are important components of any "new" technology.

8. An interdisciplinary team, continuously involved in the project, is critical for success.

RECOMMENDATIONS

- Further monitoring is recommended to analyze the long-term stability of these slopes. This monitoring must include observations by local maintenance personnel and will be carried out by the Olympia Service Center Roadside and Site Development Office.
- Composted biosolids created with a carbon-to-nitrogen ratio formula can be applied on other projects to reduce weed competition, reduce soil erosion, and enhance native plant growth. It is critical to incorporate (rake in) these biosolids as they are applied.
- The long-term survival and vigor of plants in the control and composted biosolids areas of the Chelan site should be studied to determine the residual benefits of biosolids application.
- Further research into the cost/benefit ratio of soil bioengineering techniques should be carried out in areas with other climates and soils.
- Research projects should have one project manager. That person, preferably the PI, should be in charge of authorizing all expenses and tracking the budget. The PI should do a thorough cost estimate before beginning work. Additional dollars should be budgeted for contingencies.
- Further study is needed to analyze the shear stress of different plant root masses under varying slope angles, moisture conditions, and soil types. Currently, this type of research is under way in the United Kingdom. Results of that work can be found at http://www.highways.gov.uk/info/techinf/randd/compen/8a.htm#1
- This type of work should be translated to local ecosystems (soils and plant types).
- Persons or agencies wishing to use this technology should do so with a team of experts and should begin with small erosional features on small slopes before working on large slopes.
- The plants and soil bioengineering techniques used must be specific to each site.

LIMITATIONS OF THE STUDY

- Project funding was limited to deal with the extent of the unexpected problems encountered at each site. In addition, all three sites were large and complicated, and funding levels limited the scope of the numerous soil bioengineering techniques the team could have used to stabilize the sites.
- The benefit-cost study was limited by funding and time. Further study into the benefit/cost ratios of soil bioengineering methods in varying ecosystems is needed, especially for Eastern Washington.

- When changes were necessary, it was difficult for the PI, because of her location in Oregon, to be physically present. However, the use of digital cameras, digital photographs, and frequent conference calls kept the project moving forward without interruption.

OUTCOMES

The following outcomes were directly associated with this project:

- Three large upland slope stabilization projects were constructed.
- The research report was published on the OSC Roadside and Site Development Unit Internet homepage at http://www.wsdot.wa.gov/eesc/cae/design/roadside/rm.htm.
- WSDOT personnel were trained in the selection of soil bioengineering sites and in the design and construction of soil bioengineering techniques.
- The Federal Highway Administration contracted the OSC Roadside and Site Development Unit to analyze slopes in southwestern Oregon for the possible design of soil bioengineering treatments.
- Regional offices within WSDOT have shown an interest in using soil bioengineering on specific roadside sites.
- A chapter on soil bioengineering has been written for the department's *Roadside Manual*.
- A workshop was conducted by the Principal Investigator and the research team for WSDOT personnel.
- WSDOT obtained the right to use and reproduce all materials from Lewis, E.A., *Soil Bioengineering: An Alternative for Roadside Management: A Practical Guide*. United States Forest Service. San Dimas Technology and Development Center. San Dimas, California, 2000.
- The value of using soil amendments to enhance plant survival was demonstrated.
- Communication skills, for example use of interdisciplinary team process, were highlighted and enhanced.
- Project management skills were highlighted and awareness enhanced.
- Partnerships were formed that will carry into the future.
- Awareness of soil bioengineering as an option for roadside stabilization and erosion

control was increased within WSDOT.

- Relations with the public were enhanced by the publication of four articles (two local newspapers, an in-house newsletter, and a nationally distributed magazine) about WSDOT's use of a natural method of erosion control.

ACKNOWLEDGMENTS

The authors express their appreciation to the personnel of the Washington State Department of Transportation who provided information and help with all the various aspects of this project. Special thanks go to the USDA Forest Service for funding of the Principal Investigator's time and travel and to the Entiat Ranger Station for its logistical support. The authors would like to recognize the contribution of the Washington State Department of Ecology's donation of Washington Conservation Crew time to this project. The authors gratefully acknowledge the support of WSDOT's Research Office, the Environmental and Engineering Service Center, and the Field Operations Service and Support Center. The author's wish to thank Dr. George Xu for his work on the benefit/cost analysis.

The Chelan project would not have been possible without the granting of a construction easement by the adjacent landowners, Art and Susan Douglas. The authors are very grateful for their contribution to this project. Mark Cullington, formerly of the Department of Ecology, provided guidance and calculations for the application of composted biosolids, and we are most grateful for his contributions. Thanks go to McCully Orchards for providing apple stakes for the Chelan project. The authors appreciate the research of Kevin Finney on the history of soil bioengineering.

The authors wish to thank the City of Raymond and the Willapa Port Authority for allowing us to take willow cuttings from their lands for the Raymond project. The authors wish to thank the Rayonier Timber company for allowing us to taking willow cuttings from their land for the Forks project. We appreciate the help of the Jefferson County Extension Service, the Natural Resource Conservation Service, and the National Park Service for their help with plant selections adaptable to marine clay. We appreciate the opportunity to coordinate with the Hoh Tribe on the Forks project. Finally, this project could not have been completed without the active participation of maintenance personnel in the North Central, Olympic, and Southwest regions.

BIBLIOGRAPHY

SOIL BIOENGINEERING METHODS

Bache, D. H. and I. A. MacAskill. *Vegetation in Civil and Landscape Engineering.* London: Granada. 1984.

Barker, D. H. editor. *Vegetation and slopes: Stabilization, protection, and ecology.* New York: Thomas Telford Publishing Company. 1995.

Bennett, Francis W. "Methods of Quickly Vegetating Soils of Low Productivity." *Construction Activities*. Washington, D.C.: U.S. Environmental Protection Agency. 1975.

Chandler, R. J. *Slope Stability Engineering*. Institution of Civil Engineers. New York: Thomas Telford Publishing Company. 1991.

Chatwin, S., D. Howes, and D. Swantson. *A Guide for Management of Landslide Prone Terrain in the Pacific Northwest*. Second edition. Ministry of Forests. Victoria, BC: Crown Publications. 1994.

Christensen, M. and J. Jacobovitch. *Revegetation Projects: Everything You Wanted to Know About Live Staking*. Unpublished report for King County Dept. of Public Works, Surface Water Management Div. Seattle, WA. 1992.

Coppin, N. J. and I.G. Richards. *Use of Vegetation in Civil Engineering*. London: Butterworths. 1990.

Finney, Kevin P. *BioEngineering Solutions, A Tool for Education*. Submitted in partial fulfillment of the degree of Master of Landscape Architecture, University of Oregon. 1993.

Gray, Donald H. and Robbin B. Sotir. *Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control*. New York: John Wiley & Sons, Inc. 1996.

Donald H. Gray and Andrew T. Leiser. *Biotechnical Slope Protection and Erosion Control.* New York: VanNostrand Reinhold Co. 1982.

Gray, Donald H., Andrew T. Leiser, and C. A. White. "Combined Vegetative Structural Slope Stabilization. *Civil Engineering,* 50(1) January 1980: pp. 82-85.

Greenway, D.R. "Vegetation and Slope Stability - Chapter 6." *Slope Stability*. John Wiley and Sons Ltd. 1987.

Johnson, A.W. and J.M. Stypula. eds. *Guidelines for Bank Stabilization Projects In the Riverine Environments of King County*. King County Department of Public Works, Surface Water Management Division, Seattle, WA. 1993.

Kraebel, C.J. *Willow Cuttings for Erosion Control.* Technical Note No. 1, USDA, California Forest Experiment Station, Berkeley, California. 1933.

------*Erosion Control on Mountain Roads*, U.S.D.A. Circular No. 380, USDA, Washington D.C. 1936.

Larson, F.E. and W.E. Guse. *Propagating Deciduous and Evergreen Shrubs, Trees, and Vines with Stem Cuttings*. Pacific Northwest Coop. Ext. Pub. PNW152. 1981.

Leiser, Andrew T., J.J. Nussbaum, Kay, Burgess, Paul, Jack, and W. Thornhill. *Revegetation of Disturbed Soils in the Tahoe Basin*. Final Report: CA-DOT-TL-7036-1-75-25. California Department of Transportation, Sacramento, California. 1974.

Lewis, E.A. *Soil Bioengineering: An alternative for Roadside Management: A Practical Guide*. United States Forest Service. San Dimas Technology and Development Center. San Dimas, California. 2000.

Maleike, R. and R.L. Hummel. *Planting Landscape Plants*. Washington State University Cooperative Extension Publication EB1505. 1988.

David F, Polster. "Soil Bioengineering for Steep/Unstable Slopes and Riparian Restoration." *Watershed Restoration Technical Bulletin: Streamline*. Victoria, British Columbia: B.C. Ministry of Environment. Vol. 4, No. 4.

..... *Soil Bioengineering for Forest Land Reclamation and Stabilization*. British Columbia Ministry of Forests. 1998.

Schiechtl, Hugo and R. Stern. *Ground Bioengineering Techniques for Slope Protection and Erosion Control*. Blackwell Science Publications, 1997. ISBN: 0-632-04061-0

Schiechtl, Hugo. *Bioengineering for Land Reclamation and Conservation.* Edmonton: University of Alberta Press. 1980.

State of Alaska website on streambank stabilization http://www.state.ak.us/adfg/habitat/geninfo/webpage/techniques.htm

Turner & Schuster, eds. *Landslides Investigation and Mitigation, Special Report,* Transportation Research Board. 1996.

U.S. Army Corps of Engineers. *Bioengineering for Streambank Erosion Control - Report 1, Guidelines.* Technical Report EL-97-8. Can be found through the following link: http://www.wes.army.mil/el/wetlands/wlpubs.html

USDA Natural Resource Conservation Service. Chapter 16, "Streambank and Shoreline Protection," *Engineering Field Handbook*. United States Department of Agriculture, 1996.

USDA Natural Resource Conservation Service. Chapter 18, "Soil Bioengineering for Upland Slope Protection and Erosion Reduction," *Engineering Field Handbook*. United States Department of Agriculture, 1992.

Weaver, W.E. and M.A. Madej. "Erosion Control Techniques Used in Redwood National Park." In: T.R.H. Davies and A.J. Pearce, eds. *Erosion and Sediment Transport in Pacific Rim Steeplands*. Washington D.C. Int'l Assoc. Hydrological Sciences: 640-654. IAHS-AISH Pub. 132. 1981.

Westmacott, Richard. “The Rediscovered Arts of Twilling and Wattling.” *Landscape Architecture*. 75(4): 95-98. 1985.

White, Charles A. and A.L. Franks. *Demonstration of Erosion and Sediment Control Technology*; Lake Tahoe Region of California, EPA-600/2-78-208, Municipal Environmental Research Laboratory, Office of Research and Development, US Environmental Protection Agency, Cincinnati, Ohio. 1978.

Ziemer, R.R. “Roots and the Stability of Forested Slopes.” In: T.R.H. Davies and A.J. Pearce, eds. *Erosion and Sediment Transport in Pacific Rim Steeplands*. 1981.

BENEFIT/COST ANALYSIS

California Department of Transportation. 1998. Cost of Stormwater Treatment for California Urbanized Areas.

EPA. 1999. Economic Analysis of the Final Phase II Stormwater Rule. Office of Water. EPA 833-R-99-002.

E. Gregory McPherson and James R. Simpson. *Carbon Dioxide Reduction Through Urban Forestry: Guidelines for Professional and Volunteer Tree Planters.* Berkeley, California. USDA Forest Service. 1999.

Robbin Sotir. Phone conversation. January 2001.

http://wcufre.ucdavis.edu/benefit-.htm

SOIL BIOENGINEERING HISTORY

Brosius, Myra. *“The Restoration of an Urban Stream Using Geomorphic Relationships and Biotechnical Streambank Stabilization.”* MLA Thesis, University of Georgia. 1985.

Coppin, Nick J. and R. Stiles. “The Use of Vegetation in Slope Stabilization.” *Landscape Design with Plants*. Second Edition, ed. by Brian Clouston. Boca Raton, Florida: CRC Press. pp. 212-234. 1989.

Edlin, H.L. *Woodland Crafts in Britain*. London: B.T. Batsford Ltd. 1949.

Finney, K. *History of Soil Bioengineering*. Masters Thesis, University of Oregon. 1993.

Leys, Emil. “Wilhelm Hassenteufel 80 Years Old.” *Garten und Landschaft in China*. Vol. 4, Part 3. Cambridge: The University Press. 1978.

Schiechtl, Hugo. *Bioengineering for Land Reclamation and Conservation*. Edmonton, Canada: The University of Alberta Press. 1980.

Sotir, Robbin B. &Associates, A Brief History of Soil Bioengineering, unpublished and undated manuscript.

Stiles, Richard. “Engineering with Vegetation.” *Landscape Design.* (172): 57-61. 1988.

------ “Re-inventing the Wheel?” *Landscape Design*. (203): 1991.

Westmacott, Richard. “The Rediscovered Arts of Twilling and Wattling.” *Landscape Architecture*. 75(4): 95-98. 1985.

APPENDIX A: PROJECT PARTICIPANTS

Team Member	*Role*	*Representing*
Lisa Lewis	Team Leader & Principal Investigator	USDA Forest Service
Shannon Hagen	Research Assistant	WSDOT
Jim Schafer	Research Coordinator	WSDOT, Environmental Affairs Office
Mark Maurer, L.A.	Technical Support	WSDOT, OSC Roadside and Site Development Manager
Bob Barnes, L.A.	Technical Support	WSDOT, Olympic Region Landscape Architect
Lynn Moses	Technical Support	WSDOT, Materials Lab. Engineering Geologist
Sandy Salisbury	Technical Support, compiled this report	WSDOT, OSC Roadside and Site Development
Terri Dukes	Technical Support, Lost Creek site	WSDOT, Olympic Region Landscape Architecture
Carrie Sunstrom	Technical Support, wrote original grant application	WSDOT, Olympic Region Landscape Architecture
Ed Winkley	Technical Support, Lost Creek site	WSDOT, Olympic Region Landscape Architecture
Dan Corlett, L.A.	Technical Support, Raymond site	WSDOT, Southwest Region Landscape Architecture
Mike Whipple	Raymond site excavation & construction	WSDOT, Raymond Maintenance Supervisor

Team Member	*Role*	*Representing*
Sally Anderson, L.A.	Technical Support	WSDOT, Northwest Region Principal Landscape Architect
Ray Willard, L.A.	Technical Support	WSDOT, OSC Roadside Maintenance Landscape Architect.
Russ Rosenthal, PhD	Technical Support	WSDOT, State Horticulturist
Dave Rodin, L.A.	Technical Support, Raymond	WSDOT, Southwest Region Landscape Architectect
Claton Belmont	Technical Support, Chelan	WSDOT, North Central Region Environmental Manager
Jim Flack	Technical Support, Chelan	WSDOT, North Central Region Environmental Office
DeWayne Standerford	Technical Support, Chelan	WSDOT, North Central Region Maintenance Superintendent
Darrel Anderson	Technical Support, Chelan	WSDOT, North Central Region, Chelan Area Maintenance Supervisor
Dick Albin	Technical Support	WSDOT, OSC Design Office, Standards Engineer

APPENDIX B: DEFINITIONS

angle of repose the angle between the horizontal and the maximum slope that a soil assumes through natural processes.[2]

Approximate Angle of Repose for Soil Texture	
Very wet clay and silt	1V:3H
Wet clay and silt	1V:2H
Dry sand and gravel	1V:1¾
Dry clay	1V:1½
Moist sand	1V:1¼

ecosystem a complex of biological communities and the physical and chemical environment forming a functioning whole in nature. Wetlands, upland forests, lakes, and streams are examples of types of ecosystems.[3]

physiographic a geographic unit with discrete physical characteristics, such as elevation, aspect, and rainfall patterns.

rotational failure a slide that moves along a surface of rupture that is curved and concave.[4]

slope gradient the angle of the slope as expressed in a percentage.

soil bioengineering the use of live plant materials and engineering techniques to reinforce soil and stabilize slopes.

translational failure a slide mass that displaces along a planar or undulating surface of rupture and slides out over the original ground surface. Translational slides frequently grade into flows or spreads.

---

[2] Robert W. Zolomij. "Vehicular Circulation." *Handbook of Landscape Architecture Construction.* 1975. p. 66.
[3] Transportation Research Board. "Report 379: Guidelines for the Development of Wetland Replacement Areas. Washington D.C.. National Academy Press. 1996. p. 72.
[4] Turner & Schuster, eds, 1996, *Landslides Investigation and Mitigation, Special Report, Transportation Research Board,* pp. 56-57.

APPENDIX C: LITERATURE REVIEW

Much like the practices of medicine, engineering, and architecture, soil bioengineering developed historically as discrete techniques designed to solve specific problems. Knowledge of these techniques was part of the body of folk wisdom accumulated long ago and passed orally from generation to generation. In the last two centuries, this knowledge has been compiled and codified, and finally in fairly recent times, has been taught formally and practiced as a profession.

The system of technologies that is called soil bioengineering today can be traced to the ancient peoples of Asia and Europe. Chinese historians recorded use of soil bioengineering techniques for dike repair as early as 28 BC. (Needham, 1971, p. 331) Early visitors to China told of river banks and dikes stabilized with large baskets woven of willow, hemp, or bamboo and filled with rocks. In Europe, Celtic and Illyrian villagers developed techniques of weaving willow branches together to create fences and walls. Later, Romans used fascines, bundles of willow poles, for hydroconstruction.

By the 16th century, soil bioengineering techniques were being used and codified throughout Europe, from the Alps to the Baltic Sea and west to the British Isles. One of the earliest surviving written accounts of the use of soil bioengineering techniques, a publication by Woltmann from 1791, illustrated the use of live stakes for vegetating and stabilizing stream banks. (Stiles, 1991, p.ii) About the same time, other early bioengineers working in Austria were developing live siltation construction techniques, planting rows of brushy cuttings in waterways for trapping sediment and reshaping channels.

After the Industrial Revolution, much of the development and documentation of soil bioengineering techniques took place in the mountainous areas of Austria and southern Germany. Extensive logging of the forests in the region resulted in increased environmental problems, much like what is found in parts of the western U.S. today. Problems such as extreme slope erosion, frequent landslides and avalanches, and severe stream bank degradation required repair. By the turn of the century, European bioengineers had begun to study traditional techniques and to publish their work. Today's soil bioengineering profession would develop from these compilations.

The biggest boost to development of new soil bioengineering techniques in Europe came as a result of political developments during the 1930s. Financial restrictions of pre-war years in Germany and Austria favored the use of low cost, local materials and traditional construction methods for public works projects. Construction of the German Autobahn system, during this time, involved extensive applications of soil bioengineering technologies. The use of indigenous materials and traditional methods was also consistent with spreading nationalist ideology. In 1936, Hitler established a research institute in Munich charged with developing soil bioengineering techniques for road construction. (Stiles, 1988, p. 59) Although this development work was lost, a Livonian forester named Arthur von Kruedener, the head of the institute, continued to work in the field and is known in central Europe as the father of soil bioengineering.

At the same time the Germans were establishing their research institute, some of the most important early soil bioengineering work in the United States was being done in California. Charles Kraebel, working for the US Forest Service, was developing his "contour wattling" techniques for stabilizing road cuts. Kraebel used a combination of soil bioengineering techniques including live stakes, live fascines, and vegetative transplants to stabilize degrading slopes in the National Forests of central and southern California. His unfortunate and confusing misuse of the term "wattle" to describe his live fascine system continues to be used today. Kraebel's work was well documented in USDA Circular #380, published in 1936. Two years later the Natural Resource Conservation Service (NRCS), formally known as the Soil Conservation Service, began a study of bluff stabilization techniques along the shores of Lake Michigan. That agency's work, which included use of live fascines, brush dams, and live stakes, was published in 1938. (Gray and Leiser, 1982, p. 188)

During the post-war period, many European bioengineers returned to studying, developing, and evaluating new techniques. In 1950, a committee of bioengineers from Germany, Austria, and Switzerland was formed to standardize emerging technologies, which became part of the German national system of construction specifications, the DIN. (Robbin B. Sotir & Associates, n.d.)

Arthor von Kruedener's book, *Ingenieurbiologie* (Engineering biology), was published in 1951, and it was the mistranslation of the German title that provided the English term used today. The term "bioengineering" has caused some confusion and has proven problematic for researchers, who find, in this country, that it is most often thought to refer to an area of medical research.

German and Austrian soil bioengineers continued to perfect their techniques and to publish their work through the 1950s and '60s. This was an important step in launching a more structural approach, laying the foundation for development of the professional field of soil bioengineering. In the United States, two important projects were carried out in the 1970s. These are the Trials of Bioengineering Techniques in the Lake Tahoe Basin designed by Leiser and others (1974), and Revegetation Work in Redwood National Park (Reed and Hektner, 1981, Weaver,et al., 1987). Both studies have been well documented and provide important information about the application of soil bioengineering techniques in the western United States.

In 1980, Hugo Schiechtl's *Bioengineering for Land Reclamation and Conservation* was published in Canada. It presents, for the first time in English, work of many important European soil bioengineers, including Lorenz, Hassenteufel, Hoffman, Courtorier, and Schiechtl himself. The book made the technologies and the history of their development and applications accessible to the English speaking world. In 1997, another Schiechtl book was published, *Ground Bioengineering Techniques for Slope Protection and Erosion Control*. To date, his writings remain the most important works on bioengineering in the English language.

With subsequent publications, including Gray and Leiser's *Biotechnical Slope Protection and Erosion Control* in the United States and the British Construction Industry Research, Sotir and Gray's *Soil Bioengineering for Upland Slope Protection and Erosion Reduction* in the Natural Resource and Conservation Service's Engineering Field Handbook, Gray and Sotir's *Biotechnical and Soil Bioengineering Slope Stabilization*, and the Information Association's *Use of Vegetation in Civil Engineering,* bioengineering technologies are better known in the engineering profession. However, resistance to the techniques still exists in this country.

Soil bioengineering approaches most often use locally available materials and a minimum of heavy equipment and can offer local people an inexpensive way to resolve local environmental problems. The public's increased "green" consciousness often makes soil bioengineering solutions more acceptable than traditional engineering approaches.

Despite, and maybe because of, the differences in approach and philosophy between soil bioengineering and other engineering methods of addressing environmental problems, soil bioengineering technologies are especially appropriate today. The scale and range of environmental problems require consideration of new technologies even when, as illustrated earlier, they are in fact centuries old.

APPENDIX D: CHECKLIST FOR EVALUATING EROSION SITES

Name of Erosion Site: ____
Date: _______________ **Road Number or Name:** _______________________
Milepost Number: ____
Name of Observer(s): ____

Yes	*No*	**N/A**	
			1. Overland water flow is not contributing to accelerated erosion (i.e., formation of rills and gullies)
			2. Upland watershed is not contributing to site degradation
			3. Diverse composition of vegetation
			4. Site is comprised of those plants, or plant communities, with root masses capable of preventing further erosion
			5. Plants exhibit high vigor
			6. Adequate vegetative cover present to protect slopes and dissipate overland water flow
			7. Erosion site is revegetating with native vegetation
			8. Erosion site shows no sign of additional soil movement
			9. Ditch line has no evidence of fresh soil deposits

Remarks

Summary Determination

Stabilization Rating:

Stable
Stability - At risk
Not Stable
Unknown

Trend for Stability - At Risk:

Upward
Downward
Not Apparent

Photograph or Sketch

APPENDIX E: MONITORING FORM

Soil Bioengineering Project

Date:_________________ Preparer(s):_____________ Site Name:_____________
SR ___________________ Road Mp:_______________

Geographic Features

Elevation:____________________Slope%______________ Aspect:___________
Soils:________________________Erosion Source:_________________________
Shade (H-M-L):_______________Dimensions:_______L x______W x______D
Ground Cover:_____%Vegetation_______%Soil____%Rock

Vegetation Information

Trees		Shrubs		Herbaceous	Grasses
Evergrn	Decid	Evergrn	Decid		

Species Noted:____
____
____

Noxious Weeds:____
____

Treatment Information

Treatment Date` Description Success/Vigor (H-M-L)

_________ ____ _____
_________ ____ _____
_________ ____ _____
_________ ____ _____
_________ ____ _____
_________ ____ _____
_________ ____ _____
_________ ____ _____

Overall Condition

Current Condition:	Improving	No Change	Worsening

Narrative

Maintenance Needed?	High Priority	Low Priority	Not Needed

Site Sketch

(Please include groundcover, structures, plants and any erosion evidence)

APPENDIX F
METHODS: FURTHER DETAILS

SITE SELECTION

WSDOT Engineering Geologists, in the Olympia Service Center (OSC) Materials Laboratory, keep a record of erosional slopes. These data were provided to the Research Team. The eastern half of the state was not considered for this project because the team wanted slopes closer to Olympia for easier logistics in construction and monitoring.

E-mails were sent in March 1999 to four of the regional Materials Engineers (Olympic, Southwest, North Central, South Central) to seek their help in locating erosional slopes within quarry and pit sites, or on the highway. They were also asked whether any maintenance areas had erosional slopes that might be included in this project. At this time the PI thought that 50 bioengineering sites might be available statewide for use in the research project, if they all were less than ¼ acre in size and had erosional features. The slopes identified by the regional Materials Engineers and Maintenance personnel were compiled into a list of potential sites. Some slopes were also nominated by the Olympic Region LA.

On June 15, 1999, the PI and members of the research team made site visits to problem slopes along over 350 miles of Highway 101 around the Olympic Peninsula. The special stops included three major landslides on SR 101 (MP 321, MP 322, and MP 326) that were clearly not soil bioengineering candidates for this project

From June 16 through June 18, 1999, the PI and research team members traveled over 1,500 miles to evaluate additional sites suggested by the regional Materials Engineers. See Figure F-1 for site visit routes:

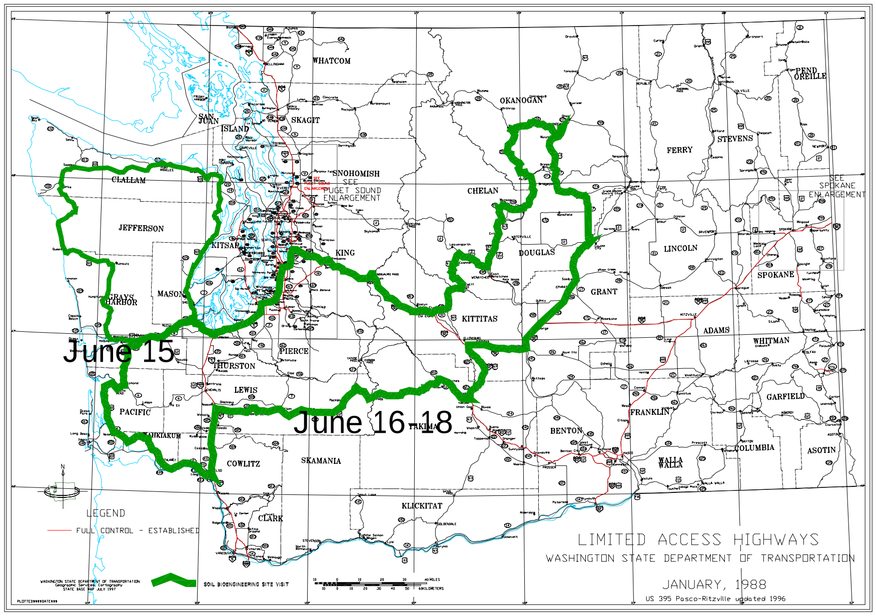

Figure F-5. Screening Site Visit Route

From June 16 through 18, 1999, the team reviewed 82 sites, analyzing their potential use. Later in June the PI made additional site visits to slopes on SR 101, SR 14, and SR 3 to view sites requested by Maintenance. The following criteria were used to select three sites from those candidates.

Site Selection Criteria

The PI took comments from all team members on site selection, but the final decision was hers. She wanted a combination of fill slope and cut slope erosional features represented in the research project. However, no fill slope areas met all the site selection criteria. The criteria for selection were as follows:

- safety of the public and work crews (road and slope related safety issues were addressed)
- visibility and accessibility for educational opportunities
- representation of the disparate soil moisture conditions, climate, and erosion types common to Washington State
- illustration of techniques that could be used on large erosion sites, small erosion sites, and combined soil bioengineering and traditional engineering treatments
- allocated dollars and the availability of additional funding

- input from WSDOT personnel.

Sites Selected

The team had originally intended to work on several smaller sites; however, because of the difficulty of working on so many sites over long distances in a limited time, the PI decided to use several techniques on each of the selected sites. Three sites were selected: two west-side sites and one site east of the Cascade Mountains. Two of the sites, Raymond and Chelan, are considered large sites. Because of the many storm damaged slopes in the state, the Engineering Geologists and Geotechnical Engineers were too busy to do a special project combining soil bioengineering with a traditional treatment. The Lost Creek site, near Forks, was selected because it had a rock apron at the base.

CHELAN

Bender Board Fence Specifications

Tools needed

Hand pruners and clippers
Pulaski or hazel hoe
McLeod rake
Deadblow or rubber hammer
Pickaxe
Wood stakes

Stem-Layered Base

Begin the project at the base of the treatment area. Excavate a 24-in.-deep terrace along the slope contour and for the full width of the treatment area. The back of the terrace should be dug at an approximate 70-degree angle. To allow ample planting platforms, space terraces about 5 ft apart.

Lay 2 ft 6 in.-long stems and 2 ft 6 in.-long wood stakes (50/50 mix) 2 inches apart and for the full length of the terrace. The diameter can range from ½ in. to 2 in.

Approximately 6 in. will extend beyond the slope face. Every 1 ft, place plant material (plugs) within the terrace.

Bender Board Fencing Construction

Drive supporting 4 ft 6 in.-long (2 ft x 2 ft) stakes 2 ft 3 in. into the ground vertically, and spaced 2 ft apart.

Weave 10-ft-long bender boards through these stakes until the wall reaches a height of 2 ft. Once complete, the bender board fence wall should be at a 15-degree angle to the slope. Once the wall frame has been constructed, carefully rake enough soil into the terrace to cover the stem layered base.

Stand in the terrace and begin excavation of a second row. This process will allow soil from the second trench to cover the first bender board fencing row.

A goal should be to construct a 2:1 slope, or flatter, between the top of the bender board fence wall and the bottom of the one above.

Move upslope to the next terrace alignment and repeat the process.

Plant trees and shrubs on the terraces. For this project, the species mix was selected by the PI, research assistant, and WSDOT Landscape Architects. The location of installation was determined by the RA and Landscape Architect(s) at WSDOT. The PI reviewed the work to make sure placement met slope stability objectives.

Problems and Solutions During Construction

The contractor began working on Monday, November 1, 1999. His crew removed approximately 14 trees near the right-of-way line and then attempted to remove the vertical lip of the slope from above. Because of the large amount of volcanic ash and glacial materials, the top soil layer was soft and difficult to excavate. As a result, the front-end loader left deep track marks and began slipping near the slope edge and had to be pulled out by an excavator. The soil disturbance on their property upset the landowners. As a result, the contractor removed his machinery and began working from the base of the slope with an excavator.

Soil below the soft, top layer was composed of compacted glacial materials. These compacted materials were hard and required the contractor to use a bucket with teeth to scrape at the "rock-like" material. These conditions lengthened the excavation time beyond the anticipated three to four days.

The Washington Conservation Crew (WCC, hereinafter referred to as "the crew") arrived on Thursday afternoon, November 4, 1999, while the heavy equipment contractor was still working. However, the contractor had finished excavation on the west end of the site by that time. The crew spent Thursday setting up their materials. The research assistant (RA) used a laser level to stake level terraces. Beginning from the west, the crew began digging out the terraces with great difficulty. In addition, the crew could not start from the bottom of the slope because the excavator was working there. Therefore, they began with one of the middle terraces, working from the west end of the site. Because of the hardness of the soil, terrace construction took much more time than anticipated. Once the soil was broken up, however, it became a fine powder mixed with sand and rounded rocks. This mix of soil materials made walking on the slope difficult.

As the RA and the crew began trying to construct the bender board fencing as designed, they discovered they could not get the specified wooden stakes into the ground. The RA decided to try ½-in.-diameter rebar and to use the wood stakes as the brush layer base. In addition, the bender board material was much thinner and weaker than anticipated. This necessitated a change in the design. Plant plugs had been heeled-in within the right-of-way and were now frozen. To plant the plugs, the crew chief thawed the plugs and set them between the brush layer every 3 ft, where they froze again.

When the WSDOT Landscape Designer, hereinafter referred to as the Landscape Designer, arrived on Sunday, November 7, 1999, approximately 110 ft of bender board terrace, seven boards high, had been constructed, and approximately two-thirds of the slope had been excavated back to 1 ½ (H):1 (V).

On Monday, the heavy equipment contractor returned to finish the excavation on the eastern end of the site, and the crew continued constructing the level terrace. The Landscape Designer had the crew leave the terrace and had the excavator operator backfill the terrace with excavated material. The operator was very careful and worked to shake out boulders before he placed the soil behind the bender board fencing. Immediately after backfilling, the terrace looked good. However, three hours later sections of the terrace had warped out of alignment in a slow deformation. The Landscape Designer had the crew remove the soil down to a depth of less than 1 ft in an attempt to halt the bending of the rebar and the breaking of the bender board material. The crew also began repairing the damaged area, including the landowner's property. Repair work included raking, seeding, and planting.

The following species were planted on the landowner's property:

Service berry (*Amelanchier alnifolia*)	10
Snow berry (*Symphoricarpos albus*)	20
Blue Elderberry (*Sambucus cerulea*)	5
Mock Orange (*Philidelphus lewisii*)	5
Ponderosa Pine (*Pinus ponderosa*)	50
Squaw currant (*Ribes cereum*)	10
Native seed mix	10lbs

Even after attempting repairs on the bender board fence, the crew could still feel the brush layer on the base of the terrace moving and hear bender boards cracking. The crew leader did not feel that ½-in. rebar had enough strength to be driven into the soil without bending. The Landscape Designer consulted with the PI by phone, and a decision was made to halt crew work on the site at the end of the day on Monday, pending a site visit by the PI and WSDOT technical advisors. The Landscape Designer was also concerned by the large amount of rebar going into a soil bioengineering project.

The Contractor completed excavation of the slope face by noon on Tuesday, November 9th.

Further hand construction was delayed until after the first week in December, when the PI, the OSC Roadside and Site Development Manager, and Department of Ecology Soil Scientist Mark Cullington could examine the slope conditions. They made the on-site decision to continue using rebar to reinforce the terraces and to adjust bender board structures from 2 ft to a 1 ft height (three boards instead of six).

Construction resumed with a different crew in mid-December. The RA and the crew made an additional decision to discontinue weaving the bender board through the rebar because the bender board was breaking. The poor quality bender board was thin and had many knots. In addition, the gaps in the fencing, created by the weave, allowed soil to erode out from the bender board face. Instead, they had the soil hold the boards against the rebar. This adjustment also held the soil in place.

The Landscape Designer checked the site on March 15, 2000, to determine whether the soil had thawed and to check for disturbance to the site during winter. Without snow mixed into the soil, the soil had settled, allowing some of the boards to fall back onto the terrace. This can be seen in Figure F-2. With the addition of water, areas on the control section had liquefied and moved down slope. However, where compost had been applied, there was no visible movement of soil.

Figure F-6. Status before spring construction - March 15, 2000

Work resumed on April 6, 2000, with the original crew. This crew worked an eight-day shift. The crew completed the planting and constructing of the 1,875 feet of terraces by April 13, 2000.

The RA returned to the site during the last week in April to clean up unused rebar, bender board, and other remaining construction materials.

Biosolid Application

The PI recommended biosolid application to increase soil moisture holding capacity and improve soil nutrient levels. The objective was to accelerate native plant establishment and provide long-term site recovery.

Mark Cullington prescribed a Class A biosolid and fir-compost mixture for the slope to provide the soil and native plants with an ideal carbon to nitrogen ratio. Class A biosolids undergo an additional process to kill pathogens. The biosolid industry is highly regulated. Cullington developed the application formula in his Master's thesis in Soil Science at the University of Washington. In addition Cullington states that a high carbon to nitrogen ratio (C:N) suppresses weeds. The addition of Class A biosolids improves the moisture holding capacity of mineral soil and is especially beneficial in arid climates. (Cullington's worksheet is found as Appendix G).

GroCo compost was blown onto two-thirds of the slope on December 22, 1999. The prescription was for a very fine layer of approximately 3/4 in. to cover the slope. Because of the high moisture content of the compost and weight restrictions, the contractor could not haul all of the compost that he had anticipated. This high moisture content also caused the blower to lay on a thicker cover (but less than 2 in.), and therefore, he ran out of compost before covering the entire site. Because of cost and distance, the team decided to use the uncovered area as a control.

The prescription also required incorporation of the biosolids into the soil immediately upon application. This was not done until the terraces had been constructed, and only in the terrace itself. Because of the cemented soil conditions of the substrate, incorporation might add several weeks to the workload of the crew. Where soils were pliable, the crew did incorporate the soil amendments, and in the terraces, where the crew chipped off mineral soil with pickaxes to fill the terraces, the amendment was also incorporated.

The crew reported a large difference in the ability to construct the terraces and pound in the rebar after the application of the compost. The soil was much easier to work with after the compost application.

LOST CREEK, SR 101, MP 174

The Olympic Region Landscape Architect requested that the Lost Creek site be included in the soil bioengineering research project. The road construction project provided additional funding for roadside work on that site.

Regional Geology

The project area is in the Hoh River valley, on the western flanks of the Olympic Peninsula. The Hoh River is one of the major river valleys originating in the interior of the Olympic Mountains. Bedrock consists of interbedded sandstone and siltstone units that originally deposited in a marginally deep marine environment during the Tertiary period (5 to 35 million years ago). These deposits were subsequently tectonically folded and faulted.

The earliest and most extensive glacier occupied the Hoh valley during the mid- or late Pleistocene (20,000 to 750,000 years ago). The glacier flowed westward across a land base that extended beyond the present day coastline. Glacial deposits are found on Mount Hoh, north of the mouth of the river, at an elevation of 1,200 feet, indicating that the existing Hoh River valley was once filled with glacial deposits.

West of the project area, near the coast, massive and laminated clay deposits have been observed. These deposits suggest stagnation of the Hoh glacier, with the accompanying lake formation in the area occupied by the terminal lobe. This was the last glacier to reach this far west of the Hoh River Valley. Peat bogs north and east of the project area are associated with younger glacial lobes. Alpine glaciers are presently active on the slopes of Mount Olympus (7,950-ft elevation); the terminus of the Hoh Glacier was at an elevation of 3,940 ft in 1955.

Problems and Solutions During Construction

Construction on the Lost Creek site ran concurrently with construction on the Chelan site. The RA managed her time to be on both sites as much as possible during construction. Members of the research team helped on each site in the RA's absence. However, because of other projects, team members in Olympic Region were not able to be at the Lost Creek site at the same time as the RA to discuss ongoing work. This resulted in some communication problems and caused confusion and conflict with crew time and work assignments.

Because of the compost contractor's busy schedule, compost was applied to Site 3 before willow walls were constructed, causing erosion problems and slippery footing for the crew. Without the terraces in place, heavy rains washed some of the compost into the ditch and into Lost Creek.

Sandy, rocky waste soils were delivered to the site and accepted by the RA instead of the Class C topsoil specified by the PI. The steepness of the slope and the heavy materials that were to be transported up the slope were a source of problems. Various methods of bringing topsoil up this slope were suggested, but none was safe enough with the combination of slick clay, compost, and rain. The crews had to carry soil and rock up the slope by bucket to fill in gullies and construct the brush layers.

The original plan called for willow wall construction in the same general location as existing hay bales. However, the hay bale rows were not level and encouraged runoff, beginning from the center of the hay bale row and extending to the edges of each row. This resulted in erosion of material from behind the hay bales and at each end. After consultation with the PI, the crew was to begin at the highest point of the hay bale row and continue constructing the willow walls level with that highest point. The RA used a laser level to stake all terraces for the crews with pink flagging tape, as seen in F-3. At this point, the RA had to leave for Chelan. While she was gone, the crew did not follow her instructions and continued to construct the willow wall in the straw bale line. The Crew constructed two additional rows of willow wall that were also not level. The crew did not understand how to keep the terraces level on a convex surface. For example, Figure F-3 shows the marking tape where the wall should have been constructed above and behind the stakes the crew placed.

Heavier than normal rains during project construction led to increased surface and subsurface water movement, resulting in increased surface erosion. Because of water quality concerns, the Hoh Tribe and Washington Department of Fish and Wildlife (WDFW) shut the project down in December until this erosion and sediment runoff could be stopped and additional sediment control measures could be installed or improved.

Concurrent with the decision to stop work on Site 5, the head scarp on Site 5 began rapidly moving. This rotational failure moved 10 to 15 ft within a week. A WSDOT geotechnical engineer was brought in, and upon field review, placed this site on

WSDOT's list of major erosion sites to be considered for engineering solutions. This confirmed the PI's decision to discontinue soil bioengineering on Site 5.

Figure F-3. Site 3 - Stakes placed below level terrace marking tape

<u>RAYMOND, SR 101, MP 60.35</u>

<u>Problems and Solutions During Construction</u>

An e-mail from the RA on February 15, 2000 read as follows:

Some excitement here in Raymond this morning. About 80' into the 6X6 section of cribwall, an area approximately 70'W x 90' high began to slide as the excavator was removing the toe. It slid in one piece about 4' vertically in less than 30 seconds. I really hesitate to excavate any more of this area until we have a plan. I instructed the operator to continue to fill in the cribwall that has already been completed (to the right of the slide) as much as possible to counter weight the movement. The current cribwall is about 20' under the slide zone. Additional comments on the movement: the borders of the slide zone on the left is flaking away fairly normally (in response to the oversteepening and removal of the toe), but the one on the right seems to border a fracture area. The border on the right is almost vertical and the two areas are moving independently.

Soil bioengineering work was halted in the area of the slide until an interdisciplinary team of experts could visit the site. On February 16, 2000, the PI and research team and the region maintenance supervisor, Mike Whipple, held an interdisciplinary conference call to discuss all safety concerns and issues. The group developed preliminary alternatives to be considered for the following day's field review.

On February 17th, members of the research team visited the site with two WSDOT engineering geologists to determine the cause and to decide upon a course of action.

The research team recommended, and the PI approved, continued construction but with excavation of no more than 10 to 15 ft of the slope toe at any one time. It was also recommended that exposure of personnel to the slope be avoided or minimized. Mike Whipple, Maintenance Area Superintendent, devised a plan to construct the log cribwall frames off site and to install them on-site in modules. No crew members were allowed behind or inside the cribwalls at any time.

The Landscape Architect specified a mixture of cuttings and container plantings of the same species. These will be observed during the monitoring period to determine whether the cuttings thrive.