EARTH RETENTION USING VEGETATION

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ABSTRACT

Vegetation and biotechnical methods can solve certain types of earth retention problems more effectively than traditional geotechnical approaches. Vegetation methods can be applied to water erosion, stream bank protection, shallow slope stabilization and slope failure rehabilitation problems. Vegetation methods are well-suited to remote and/or inaccessible sites with variable soil conditions, where simple, flexible, cost-effective solutions which do not involve special equipment, materials or labour, are required.

The benefits of vegetation derive principally from its hydrological and physical effects. These effects include rainfall interception, evapotranspiration, changes to surface runoff volumes and velocities, infiltration and groundwater levels, anchoring, arching, and buttressing, and soil reinforcing. The effects can be magnified using biotechnical forms such as wattles, brushlayers and live fascine drains, constructed from live vegetation.

Successful use of vegetation in all of its forms requires an appreciation of its characteristics, and these differ fundamentally from those of inert geotechnical materials. Important aspects of vegetation include plant form and root system, response to the environment, life cycle, variability, reliability, and plant community development. Changes in vegetation characteristics, such as those arising from forest harvesting, can have profound effects on erosion, slope instability and other problems.

This paper focuses on the forms, characteristics, physical effects, and applications of vegetation and biotechnical methods which are relevant to their use for earth retention problems, particularly erosion and shallow slope instability. A case history is presented in which vegetation methods were used to rehabilitate a large, remote slope failure with active erosion, mass wasting and sedimentation problems.

INTRODUCTION

Traditional geotechnical methods, such as anchors, retaining walls and shoring, have provided satisfactory solutions to earth retention problems for decades. They are well-suited to man-made works, easily accessible sites, and problems in which the values at risk, such as human life and private property, are extremely high. They produce immediate 'final' solutions in which excellent performance is all but guaranteed through the use of analytical design methods, materials with rigorous performance specifications, and appropriate factors of safety. To use traditional methods, however, subsurface investigations, quantitative design inputs, and specialized equipment, materials and labour, are often required.

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There are certain types of earth retention problems for which vegetation and/or biotechnical methods can be the most appropriate and cost effective. Vegetation methods can be applied to water erosion control, watercourse and shoreline protection, slope stabilization and slope failure rehabilitation, which are problems common in the construction, resource development and transportation industries, and may be of interest to geotechnical engineers. These problems typically have natural causes, involve large areas and occur in remote and/or inaccessible sites. They are often difficult to investigate, analyze and solve because of their location, scale or variability, or because design inputs are unknown. In addition, the solutions required often have modest performance requirements because inadequate performance, for example low forest productivity, temporary loss of access or disturbed habitat, can be tolerated until it is remedied. The benefits of vegetation and biotechnical methods include their simplicity, adaptability to variable site conditions, and lack of specialized labour, material or equipment. They are reliable, self-healing, self-sustaining, and create a natural aesthetic environment.

This paper focuses on the forms, characteristics, physical effects, and applications of vegetation and biotechnical methods which are relevant to their use for earth retention problems, particularly erosion and shallow slope instability. Characteristics of vegetation are examined first because it is necessary to understand plant types, their form and components, growth requirements and cycles, variability and reliability, in order to use vegetation effectively and successfully. The physical effects of vegetation, which are primarily hydrological and mechanical, are then examined in detail. Biotechnical forms are discussed and illustrated in the third section. The fourth section concerns vegetation applications and issues such as assessing the magnitude of vegetation effects. And the paper closes with a case history which illustrates the potential utility of vegetation and biotechnical methods.

CHARACTERISTICS OF VEGETATION

Vegetation is fundamentally different from materials commonly used by geotechnical engineers. It is alive and responds to its environment. It adapts to changing conditions with Darwinian single-mindedness, bent on succeeding and propagating. It naturally evolves towards a long-term, self-sustaining community, in contrast to inert materials which unavoidably deteriorate with time. Its properties and behaviour are more variable than man-made materials, however, these variations enable it to adapt to and survive a broad range of dynamic conditions.

It is necessary to understand some basic characteristics of vegetation in order to appreciate its functions and behaviour, and factors which influence its use. Characteristics relevant to vegetation and biotechnical uses include plant form and root system, plant requirements, growth and propagation, relationships between plants, soil and climate, and variability and reliability. Vegetation costs are also relevant to engineering uses.

Vegetation is comprised of plants. Although there are many plant forms, these can be simplified into three classes: trees, shrubs, and grasses and herbs. From a biotechnical perspective, the most relevant characteristics of trees are their large range of forms, large root, leaf and crown sizes, long life spans, leaf cycles which range from continuously leafed to seasonally bare, and root patterns which range from shallow and branching to deep and concentrated (e.g. tap roots). Shrubs are smaller, grow and propagate more rapidly, and have a shorter life span than trees. They are typically densely branched and woody above the ground. An important characteristic of grasses and herbs is that they can grow rapidly, produce dense subsurface masses of stems that reinforce soils, and create a continuous dense ground cover.

Root systems are closely linked to the biotechnical functions of plants, for example groundwater lowering, soil reinforcement, and buttressing. The primary vegetative functions of roots, namely water absorption, nutrient collection and anchorage, vary with root form, depth, strength and size. Root form can range from masses of very fine fibres, to branched systems, to deep tap roots. In terms of plant classes, grasses and herbs typically have the majority of their roots within about 50mm to 400mm of the ground surface, and shrubs and trees within the top 3m. These typical values will be influenced by the groundwater regime and soil density. Shallow groundwater promotes shallow, spreading roots while well-drained soils promote branching and deep rooting. Dense soils naturally impede rooting, resulting in reduced root depths. Root tensile strength, which strongly influences soil reinforcement, can vary with plant species, root size and age, site conditions and annual cycles of growth and decay. Root size and growth patterns can be influenced by physical stress, for example unstable soils: on inclined slopes, uphill roots will often be thicker and these can have a strong anchoring effect.

The physical effects of vegetation, described in detail later on, are affected by cycles. There is a yearly cycle during which plants grow, reproduce, die-back and become dormant. And there is a longer plant life cycle. Plant response to cycle stages varies widely depending on plant form, species, age, health, site conditions, the severity of the changes and other factors. The range of responses is bounded by annual plants which die completely after one year and ancient conifers which respond to seasonal changes with negligible leaf loss. With each cycle the above-ground plant biomasses changes, with a minimum during the dormant stage, usually winter. Biomass levels affect rainfall interception, windthrow potential, and soil reinforcement. Other vegetation functions, such as groundwater lowering due to evapotranspiration and self-healing of damage are usually also at a minimum during dormancy.

Another aspect of vegetation that distinguishes it from inert engineering materials is that plants and their communities are dynamic. They respond to external factors, such as climatic changes, harvesting and fires, and to internal changes, such as natural evolution towards maturity. Evolution affects both vegetation and soils. For example, the organic content of soil will increase due to nutrient cycling and porosity and permeability can increase due to plant roots and soil animals. Plant and community dynamics can also affect vegetation aesthetics and maintenance requirements.

Plants have different requirements than geotechnical materials - light, heat, nutrients, water and support being the most obvious - and these are largely determined by soil conditions and climate. Soil-related factors include physical and chemical characteristics such as rooting potential, soil density, fertility, and moisture content. Climate-related factors include temperature, precipitation, growing season and plant exposure. These requirements and factors are relevant when selecting vegetation for a site, specifying installation details for biotechnical works, predicting productivity, propagation or performance, and establishing a vegetation management plan.

Plant propagation, like growth, is inapplicable to man-made materials, however, it is an essential aspect of vegetation methods and leads to long-term sustainability. Natural propagation occurs by seed and spore production and vegetatively through runners. Biotechnical works usually involve sowing, planting nursery raised plants, or planting cuttings. During the establishment period of vegetation, which is the time immediately following the germination of seeds or the transplanting of relocated stock, the risk of failure is high and water is critical to success. This fragile state must be recognized for vegetation solutions.

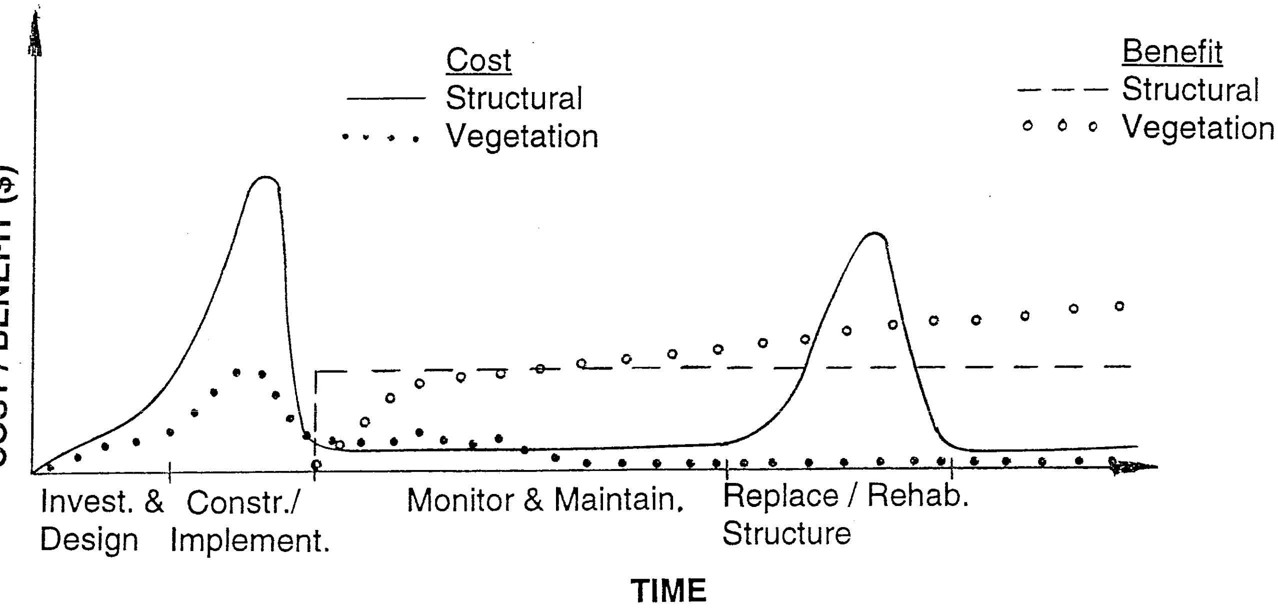
Vegetation is a living material, inherently variable and responsive to its environment. Because it is natural and not manufactured, neither its composition nor its behaviour can be closely specified. Its performance can, however, be reasonably well predicted because of collective knowledge about and experience with plant behaviour. Variability, usually viewed as detrimental in geotechnical solutions, provides diversity and allows a range of site conditions to be accommodated. The living aspect of vegetation, and its responsiveness to the environment, are assets that enable it to recover from damage, and expand its influence through growth and propagation.

There are methods available both for estimating and reducing the variability, and for increasing the reliability, of vegetation. Variations can occur in response to external changes such as weather cycles and episodic events such as fires. Weather changes can, for example, affect root strengths and patterns, plant biomass, and even plant survival in severe cases. Although climatic conditions cannot be controlled, meteorological data can be used to estimate variations, and preventative measures can be implemented to enhance performance during adverse conditions. Similarly, preventative measures can be taken to reduce the occurrence, or mitigate the effects of fires, windthrow, grazing, vandalism, pollution and disease. Appropriate measures can include controlled superficial burns, constructing fire breaks and wind protection, using unpalatable plants to deter grazing, installing fencing, planting pollution-tolerant species and using pest control. Preventative measures and quality control in vegetation solutions perform the same roles as corrosion prevention and construction inspection in geotechnical engineering, namely to minimize variability and maximize performance.

The value of vegetation will depend upon its lifecycle costs and benefits. Initial costs will be associated with a site investigation, design, and implementation, and these costs can be estimated fairly accurately. Subsequent costs can include monitoring, management and repair; these costs are more difficult to estimate in advance because they will be governed by vegetation performance. The direct benefits of vegetation used for earth retention accrue because erosion, mass wasting and/or sedimentation is reduced or eliminated. Indirect benefits can include improved water quality, wildlife and aquatic habitat, and aesthetics, increased forest productivity and property values, and enhanced recreational opportunities. Earthwork and land take costs can also be decreased. A proper comparison of vegetation and structural solutions requires that all values, including the less tangible ones, be assessed.

Lifecycle cost and benefit profiles for vegetation and structural solutions can differ substantially. Figure 1 schematically illustrates potential differences for a slope stabilized using either vegetation or a combination of slope grading and a structural toe wall. The cost curve for the structural solution reflects higher initial costs for investigation, design and construction, increasing maintenance costs with time, and a finite service life which requires either substantial rehabilitation or replacement of the structure. The structural benefits, which would be largely functional, have been assumed constant over time. In comparison, the vegetation approach would probably have lower initial costs, but periodic maintenance and repair could be incurred in the short to medium term. Once the vegetation was fully established, maintenance costs would likely be nil. The service life of the vegetation would be practically infinite, eliminating any need for replacement. The benefits of vegetation would likely develop more slowly initially, however, they would increase continually as aesthetics, habitat, productivity and other values improved.

Figure 1 - Example Lifecycle Cost and Benefit Profiles for Vegetation and Structural Earth Retention Solutions



PHYSICAL EFFECTS OF VEGETATION

The principal effects of vegetation, in its many varied forms, are hydrological and mechanical. Hydrologically, vegetation provides a protective barrier between the atmosphere and the soil. It can intercept or impede rain, change surface runoff volumes and velocities, alter infiltration rates and amount, and affect both subsurface flows and the groundwater level. Mechanically, vegetation can alter the stability of soils and slopes through mechanisms such as reinforcing, arching, buttressing, surcharging and wind loading. These effects are discussed below.

Vegetation can reduce the impacts of rainfall. For example, leaves and stems can intercept rainfall and allow it either to evaporate or to form leaf-drips and continue to the ground. The degree of interception depends upon the extent of vegetative cover. The amount of rain reaching the ground is governed both by the extent of the cover and by rainfall intensity. For example, light rainfalls on well-covered areas can result in little rain at the ground surface, while most of the rain during long, intense storms will reach the ground. In a mature forest in a temperate climate approximately 30 percent of intercepted water is evaporated on an annual basis. The remaining rainfall forms leaf-drips or stem flows which usually have lower impacts on the ground surface than direct rainfall. Leaf-drip from grasses and low shrubs are usually insignificant.

Vegetation can also reduce surface runoff volumes and velocities. Higher surface roughness caused by roots can reduce runoff velocities, increase infiltration and decrease runoff volumes on vegetated versus bare surfaces. Higher infiltration is largely restricted to the near-surface zone where roots and root holes locally increase permeability. Even small reductions in runoff velocity are important because the erosion potential of water varies exponentially with velocity. Vegetation coverage must be uniform, however, because patchy coverage can concentrate water and result in localized erosion that can be worse than if soils were bare.

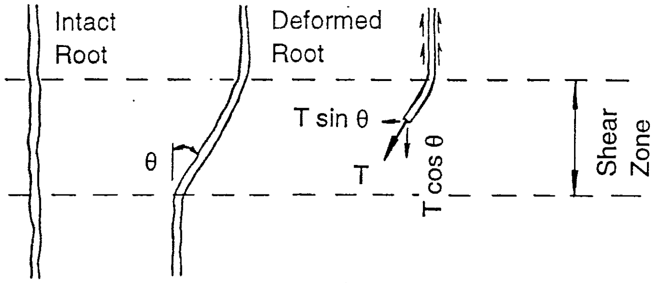
Vegetation can also affect subsurface water conditions. The principal agent is evapotranspiration which removes water from the soil and liberates it through plant surfaces to the atmosphere. This lowers the groundwater level, decreases the unit weight of unsaturated soils, and increases soil suction in unsaturated soils. These effects have been confirmed qualitatively to benefit slope stability, however their magnitudes have not been quantified. Their influence will vary with plant water requirements and groundwater flux, and will be at a minimum but not negligible during periods of high precipitation and low metabolic activity.

The mechanical effects of vegetation are, perhaps, more readily appreciable by geotechnical engineers than are hydrological effects. Mechanical effects include matting, reinforcing, anchoring, arching and buttressing, surcharging and wind loading. These effects are, by and large, dominated by the action of roots.

Surface mat effects arise where densely intertwined roots form a continuous, coherent mat with considerable in-plane strength. Continuity and coherence can be very effective in reducing erosion, for example along a stream bank. The in-plane strength is often effective in reducing soil creep on slopes. Mat effects are greatest in near-surface soils because roots tend to become less dense and more uniformly oriented, typically vertically, with depth. As this occurs, mat effects diminish and root reinforcing increases.

Root reinforcing is similar to soil reinforcing using geosynthetics except that nature has been using it a little longer. Roots and soil form a composite material in which the roots provide tensile resistance, increase confining stress, and redistribute load from areas of high stress to areas of lower stress. The effects are greatest where roots smaller than about 20mm diameter cross shear zones in the soil. Larger roots tend to be more effective as anchors than as reinforcing; anchoring is discussed later on. Figure 2 illustrates the reinforcing mechanism. Root distortion via shearing generates tensile stresses and these can be resolved into forces parallel to and normal to the shear zone. The parallel force component directly resists displacement while the normal force component increases the confining stress on the shearing soil, thereby increasing its frictional strength.

Figure 2 - Root Forces
(after Wu et al., 1979)



The magnitude of root reinforcing depends primarily upon the properties of the roots, with minor influences from the soil and geometry. The key root properties are tensile strength, tensile modulus, root concentration, length, roughness and shape. Individual live roots from trees and shrubs have been tested in tension by various researchers and the measured strengths range from 5 to 68MPa (25 to 35MPa being typical). Root strength is known to vary, however, according to root size and age, plant health and species, and site conditions. In the case of dead roots, tensile strength decreases with time due to decay, which is an important factor for the post-harvesting stability of forest slopes. The tensile modulus of a root affects the rate of stress transfer during shearing. The most effective roots have moduli which contribute to the peak strength of the soil. Root concentration describes the amount of roots which are reinforcing the soil. The final three root characteristics, namely length, roughness and shape, all relate to pull-out resistance. In order to develop tensile stresses and reinforcing effects, roots must be adequately imbedded in soil outside of the shear zone. The required length will depend upon the bond strength between the root and the soil, and the root shape, with rough irregularly shaped roots providing the most effective imbedment.

Given the large number of properties and related factors which influence root reinforcing, a simple means is required to express the overall effect of reinforcing on soil strength. Some research has been carried out aimed at quantifying the properties and factors above, however, it is incomplete. Further, it is impractical to attempt to investigate or measure these individual properties routinely in the field. A more pragmatic approach is to examine the cumulative effect of root reinforcing on soil shear strength and express it as root cohesion, an amount in addition to soil cohesion. Values for root cohesion for various types of vegetation and forest communities have been estimated, through direct shear tests and back analysis of failures, by O'Loughlin (1974a), Burroughs and Thomas (1977), Sidle and Swanston (1982), Buchanan and Savigny (1990),and others. Selected values for root cohesion are presented in Table 1.

Table 1 - Values of Root Cohesion

Investigators	Vegetation and Soils	C_r (kPa)
Swanston, 1970	Conifers on till, Alaska	3.4 - 4.4
O'Loughlin, 1974a	Conifers on till, B.C.	1.0 - 3.0
Burroughs and Thomas, 1977	Conifers on mtn. soils, Oregon and Idaho	3.1 - 17.5
Wu et al., 1979	Conifers on till, Alaska	5.9
O'Loughlin and Zeimer, 1982	Mixed conifers on shallow till, New Zeal.	3.3
Sidle and Swanston, 1982	Brush and conifers on stony mtn. soils	2.2
Buchanan and Savigny, 1990	Mixed forests on mtn. soils, Washington	1.65 - 2.87

Anchoring, arching and buttressing are three root-related effects which have parallels in geotechnical engineering. Anchoring occurs when deep tap roots penetrate either stable soils or cracks in stable bedrock beneath surficial soils. An anchored root wad, which is a mass of anchored roots and the soil within, can act like a pile and buttress soils directly up slope. If the spacing between root wads is not too large, then the soil between buttresses will arch and be supported by the anchored root wads, similar to the behaviour of soils behind closely spaced piles. The effects of root anchoring, arching and buttressing on stable slopes can be quantified if values for tree spacing, root wad size, depth to bedrock, slope angle, earth pressure coefficients and several other parameters, can be measured or estimated. It is more common, however, to assess the effects either by back-analysis of failures or by qualitative observations. These effects can be vitally important when changes to existing mature vegetation are proposed, such as forest harvesting on marginally stable, densely vegetated slopes.

Surcharging and wind loading are two additional mechanical effects. Surcharging, caused by the weight of vegetation, can influence slope stability beneficially or adversely, depending on vegetation height, density and distribution. A well-stocked coniferous forest with 40m high trees can apply a surcharge of 0.6kPa, and harvesting activities can dramatically alter the distribution of vegetation. In general, however, the effects of surcharge on slope stability are small compared with other influences. Wind loading can also have beneficial or adverse effects on stability, although only the adverse effects leave traces. A downhill wind on shallow-rooted trees can promote planar surficial failure. An uphill wind on deep-rooted trees can cause a destabilizing moment. And wind in any direction can 'throw' unsheltered trees, resulting in exposed soils and increased infiltration.

The foregoing discussions reveal many hydrological and mechanical effects which can be caused by vegetation. Effects related to soil erosion and slope stability are summarized in Table 2. Individual effects, and their collective effect, will vary with vegetation type, age and health, soil characteristics, site conditions, climate and other factors. Using vegetation effectively, to solve earth retention or other types of problems, requires knowledge of plant, soil and climate relationships, and experience with vegetation performance over a range of conditions.

Table 2 - Summary of Vegetation Effects

Hydrological Effects	Mechanical Effects
Interception • reduces rainfall reaching ground • reduces rainfall impact energy	*Matting* • reduces erosion due to soil restraint • reduces surficial creep
Surface Water • reduces velocity due to surface roughness • reduces volume due to infiltration • increases erosion locally if veg. uneven	*Root Reinforcing* • reduces erosion due to soil restraint • increases soil strength
	Anchoring, Arching and Buttressing • increases soil stability
Subsurface Water • lowers groundwater due to transpiration • increases soil suction due to transpiration • increases infiltration due to roots & holes	*Surcharging* • changes soil stability (±)
	Wind Loading • changes soil stability (±)

BIOTECHNICAL FORMS AND TECHNIQUES

In addition to the vegetation discussed above, there are biotechnical forms and techniques which use live stems and branches to create biological structures. They are constructed by inserting, driving, or burying stems and branches into the ground in particular arrangements. They concentrate the functions of vegetation, namely soil retention, root reinforcing, and water control. They are stronger, more robust and more effective than vegetation alone because they meld structural and biological attributes. Biotechnical forms are often used locally to solve particularly difficult cases of raveling, sloughing, surface erosion, gullying and/or poor drainage.

The most common biotechnical forms used for earth retention are livestakes, wattles, brushlayers and live fascine drains, although many additional forms exist for other purposes. The various forms have several common characteristics. Cuttings for the forms, commonly taken from willows because of their excellent handling, rooting and growth characteristics, can often be found near to the site and obtained at low cost. Few non-vegetation materials are required and none is specialized. Similarly, no heavy or specialized equipment is required. The techniques are labour intensive, which may be socially beneficial, and the construction skills required can readily be taught to workers. All of the biotechnical forms become more effective with time due to growth. Finally, growth produces additional materials for biotechnical structures or for repairs, if required.

Livestakes

Livestakes are the least intense biotechnical form. They consist of poles or cuttings from live trees or shrubs which are pushed or driven vertically into the slope at points, usually to form a 'button' pattern (Figure 3). Once installed, the cuttings root and sprout and these growths help stabilize surficial soils, bridge local weaknesses, and improve conditions for neighbouring vegetation. They are a quick and effective means of binding and reinforcing surficial soils and they provide greater stability than vegetation alone. Their effect on surface water movement is minimal because they cover little of the ground surface.

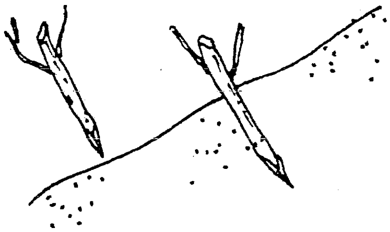


Figure 3 - Livestakes
(after Coppin et al., 1990)

Wattles

Wattles are linear forms which consist of bundles of live woody plant stems installed in shallow trenches, typically along contours (Figure 4). Cuttings are formed and tied into cigar-shaped bundles 20 to 30cm in diameter and then staked into shallow trenches using either live or manufactured stakes. Soil is then pulled down, worked into the interstices, and placed over the wattles as cover. This serves to protect the wattles and prevent undermining. A small amount of wattle is left exposed to impede surface water. As the wattles root and sprout, the soil is reinforced, surface soils are retained, surface water is significantly impeded, eroded sediments are trapped, and moist zones favourable for other vegetation are created. Wattles can be used to

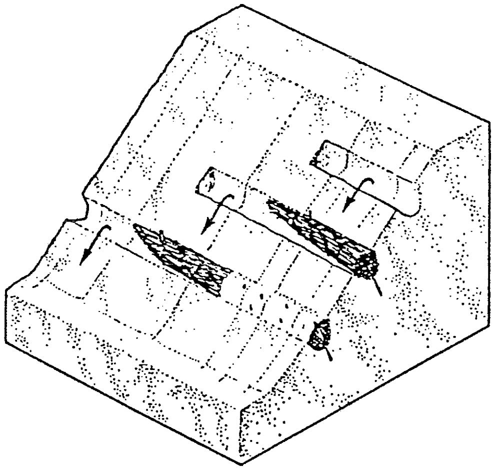


Figure 4 - Wattles
(after Coppin et al., 1990)

stabilize soils exposed by raveling and surficial sloughing, repair and protect gullies, segment long steep slopes into short lengths, reinforce seepage zones and reduce piping.

Brushlayers

Brushlayers are linear at the ground surface but have a planar form set into the slope (Figure 5), similar to mechanically reinforced slopes. Like wattles, brushlayers are constructed of live woody materials which are usually installed along slope contours. The materials may consist of either cut stems and branches from trees or shrubs, or rooted plants. They can be set in trenches cut into native slopes and then backfilled, or layered between lifts in fill slopes. A portion of the stems is left protruding to impede surface water. As the stems become established and sprout, root reinforcing, soil binding and surface water interference all increase.

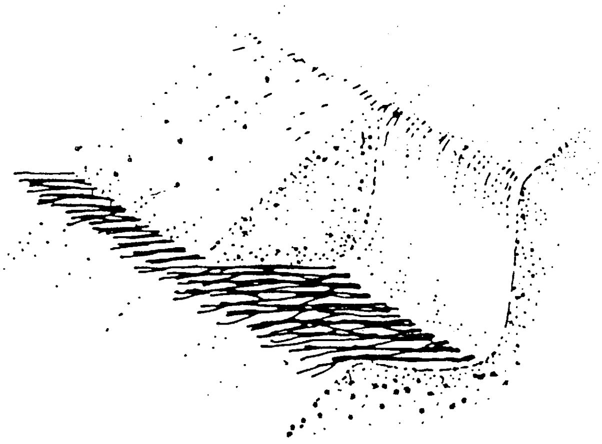


Figure 5 - Brushlayer
(after Coppin et al., 1990)

Although brushlayers and wattles are related, they differ in several important ways. Brushlayers provide greater resistance to shallow failures and stream bank erosion because they involve more stems and they are set more deeply into the slope. When installed into native slopes, they require more excavation and backfilling, but no bundling or tying. Brushlayers installed in fill slopes can be placed and buried efficiently using an excavator. Because brushlayers penetrate the slope they are better able to survive drying of surficial soils.

Brushlayers have many applications. They can be incorporated into fill slopes, and through a combination of mechanical strength and rooting, enable unusually steep slopes (1.5H:1V or steeper) to be formed. Erodible soils can be restrained, mobile sediments trapped and gully degradation controlled. Stream banks can be protected against erosion, undercutting, flow slides due to rapid draw down, and piping. Finally, active sites can be stabilized and seriously damaged sites rehabilitated.

Brushlayered slopes and mechanically reinforced slopes have important similarities and differences. Both involve imbedded inclusions which impart immediate strength. Mechanical reinforcement, such as geosynthetic material, is inherently strong. It is used in fill slopes, and these are typically constructed using heavy equipment and select backfill. Native materials may be disturbed during construction and a relatively large amount of fill is usually moved. After construction, mechanically reinforced slopes may require vegetation for protection and/or to improve aesthetics. Brushlayers are, in comparison, weaker but they can still significantly improve moderately steep slopes. Brushlayers become stronger as the cuttings root and sprout. They can be installed in cuts or fills, using local materials if available, without either heavy equipment or the need for select backfill. Commercial species can be planted when the brushlayers are constructed, thereby returning the site to productivity.

Live Fascine Drains

Live fascine drains and wattles have similar compositions and construction details, but very different functions. Like wattles, fascine drains (Figure 6) consist of long tied bundles of live woody materials staked and buried in shallow trenches. Unlike wattles, the bundles are oriented downslope across contours, and their primary function is drainage. The open but irregular cross-section of fascines creates a highly permeable drain which simultaneously conveys water but impedes it and thereby reduces its erosion potential.

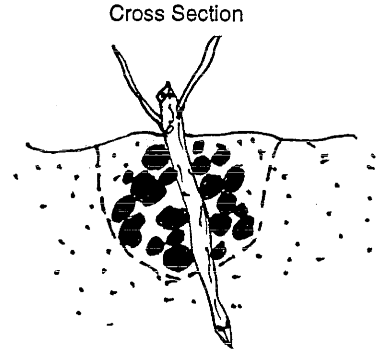


Figure 6 - Live Fascine Drain
(after Schiechtl, 1980)

Fascine drains are initially staked to the slope during installation, using livestakes if desired, to prevent movement and undermining. As roots develop, the drains attach themselves strongly to the slope and the roots armor the 'invert'. The advantages of fascine drains include flexibility, self-healing, low maintenance and drainage immediately after installation.

Hybrids and Dead Materials

Hybrid biotechnical forms combine vegetation and inert geotechnical materials, and blend the characteristics of each. Examples of hybrids include live crib walls, planted gabions, welded-wire walls, and slope gratings, and mechanically reinforced slopes. There are also numerous forms comprised of dead vegetation and these are aimed primarily at either erosion protection or growth enhancement. Biotechnical forms using dead materials include mulches, branch layers, brush mattresses, seed mats, woven fences, dead pole fences and drains, and others. Neither hybrids nor forms using dead materials are discussed further because this would depart from the focus of this paper. The interested reader is referred to publications by Schiechtl (1980) and Gray et al. (1982) for additional information.

APPLICATIONS

Vegetation and biotechnical forms can be applied to a broad range of problems including wind and water erosion, watercourse and shoreline protection, slope stabilization, and improvements to aesthetics, habitat and productivity. Vegetation solutions are usually semi-quantitative and use an observational approach. They are not designed to achieve a specific factor of safety, rather they are designed to reduce an existing risk of failure and satisfy other performance requirements.

Slope stability is probably the problem of greatest geotechnical interest to which vegetation and biotechnical methods can be applied. Slopes are ubiquitous and their stability is important. For natural slopes, stability is a concern when failure threatens significant values. For cut and fill slopes, stability is often a concern because earthmoving costs and land take are directly related to slope steepness.

Slope instabilities can be classified as surficial, shallow or deep, depending on the depth of an instability relative to typical root depths. This reference scheme is appropriate because stability is often strongly influenced by roots. Surficial failures are those which occur within 30 to 40cm of the ground surface. They include soil creep, solifluction, raveling and erosion. Potential failures can be addressed using grasses and herbs which commonly have dense root systems that penetrate to depths of about 0.4m. Shallow instabilities extend to depths between 0.4m and about 2m. They include shallow slumps, sloughs and earthflows, with planar or rotational forms. Potential shallow instabilities can be inhibited using shrubs and trees which commonly have root depths of 2m to 3m, and for deeper-rooting species, depths of 5m or more. Deep instabilities are, by definition, those which occur below the effective root depth. Although roots can influence moisture and stress conditions beyond their physical extent, through soil suction, anchoring, arching and buttressing, these effects are usually small compared with destabilizing forces. Deep instabilities, below the effective root depth, therefore cannot be practically remedied using vegetation or biotechnical methods.

The potential effects of vegetation on surficial and shallow instabilities are summarized in Table 3.

Table 3 - Potential Effects of Vegetation on Slope Instability

Effect	Slope Instability	
	Surface	Shallow
Interception	+1	
Infiltration	+/-1	+/-1
Evapotranspiration	+1	+1
Surface Matting	+1	+2
Root Reinforcing	+2	+1
Anchoring, Arching and Buttressing	+2	+1
Surcharging	-1	-1
Windthrowing	-2	-1
Insulation	+1	+2
Key: (+) Beneficial, (-) Adverse, (1) Primary, (2) Secondary		

The importance of instability versus root depth has been reported by Buchanan and Savigny (1990). Buchanan et al. investigated nine slope instabilities in forested terrain in the Pacific Northwest using detailed field examinations, laboratory tests and numeric modeling. They found that vegetation contributed significantly to slope stability prior to failure and that the magnitude of root cohesion could be related to vegetation type. Values of root cohesion ranged from 1.6 to 2.1kPa for forest understory, to greater than 3.0kPa for old growth forest. They also found that soil suction contributed significantly to the stability of unsaturated slopes and that subsurface materials which inhibited anchoring, such as smooth bedrock, significantly reduced the effectiveness of root cohesion.

The methods available for quantifying the effects of vegetation on slope stability can only be applied to existing vegetation. Failures can be back analyzed to determine the effects of root cohesion and soil suction, as per Buchanan et al. and others. Root reinforcing can be assessed by digging trial pits, counting root densities and performing either *in situ* shear tests or laboratory root tensile tests. Anchoring, arching and buttressing can be estimated by site surveys of trees and of subsurface materials. Vegetation effects on soil suction and groundwater levels can be measured using tensiometers and piezometers. Interception can be determined by comparing rainfall in covered and uncovered areas. Infiltration can be estimated by measuring and comparing rainfall and surface runoff quantities. None of the methods mentioned above can be used to quantitatively predict the effects of *proposed* vegetation.

Analytical methods can be used to examine the sensitivity of slope stability to vegetation effects. For example, an infinite slope analysis of changes in the factor of safety of a forest slope arising from changes in groundwater water levels, root cohesion, surcharging and wind loading, was carried out. The pattern of changes approximates those which might be expected to occur over the lifecycle of a forested slope. The model used is shown in Figure 7. The following values were assumed to complete the calculations: C'_r=5kPa; Ø′=35°; ß=35°; h_z=2m; b=3m; $\gamma=18+(2h_w/h_z)$ kPa.

The computed results are presented in Table 4. The interpretation of the lifecycle of the slope is as follows. Initially, with the slope bare and with an intermediate groundwater level, the slope is marginally stable. At mid-life and just prior to harvesting, the slope is moderately to densely vegetated, the groundwater level is lower due to evapotranspiration, and there are root reinforcement, surcharging and wind loading effects. Overall, the factor of safety has increased because root reinforcing dominates other effects. The factor of safety is at a maximum immediately after harvesting because surcharge and wind loads have been eliminated while root reinforcement and low groundwater levels remain. Two years after harvesting, root strength has decayed by 40%, the ground water has risen to an intermediate level in the absence of evapotranspiration and the factor of safety has decreased significantly. After 7 years, root reinforcement is at a minimum because old roots have decayed significantly while the number and strength of new roots is still small; the stability of the slope is once again marginal. In the final case, a storm raises the ground water to the ground surface and failure results. The key results from the analysis are that stability is most sensitive to groundwater level and root strength. Other site, soil and vegetation conditions could be evaluated using the model.

Figure 7 - Infinite Slope Model for Vegetated Slope *(after Coppin et al., 1990)*

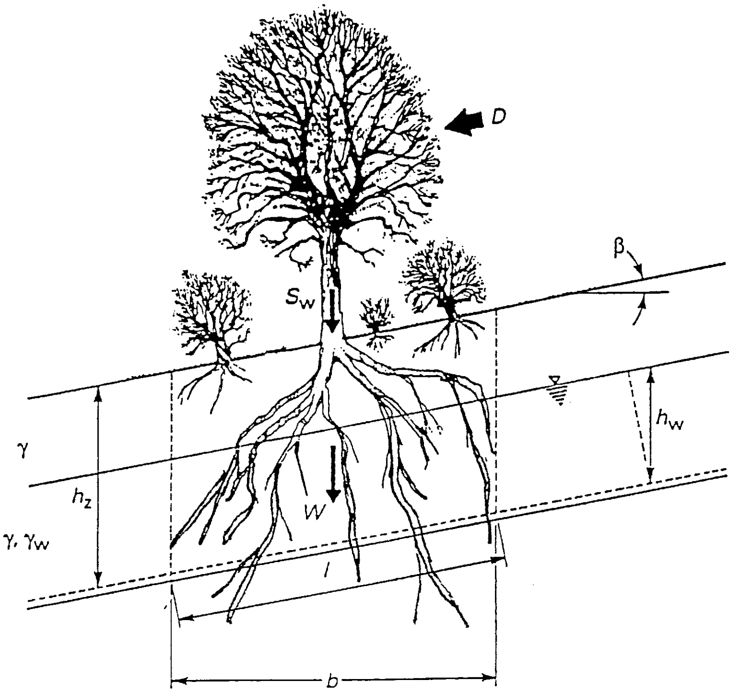


Table 4 - Results of Stability Analysis of Forest Slope at Various Lifecycle Stages

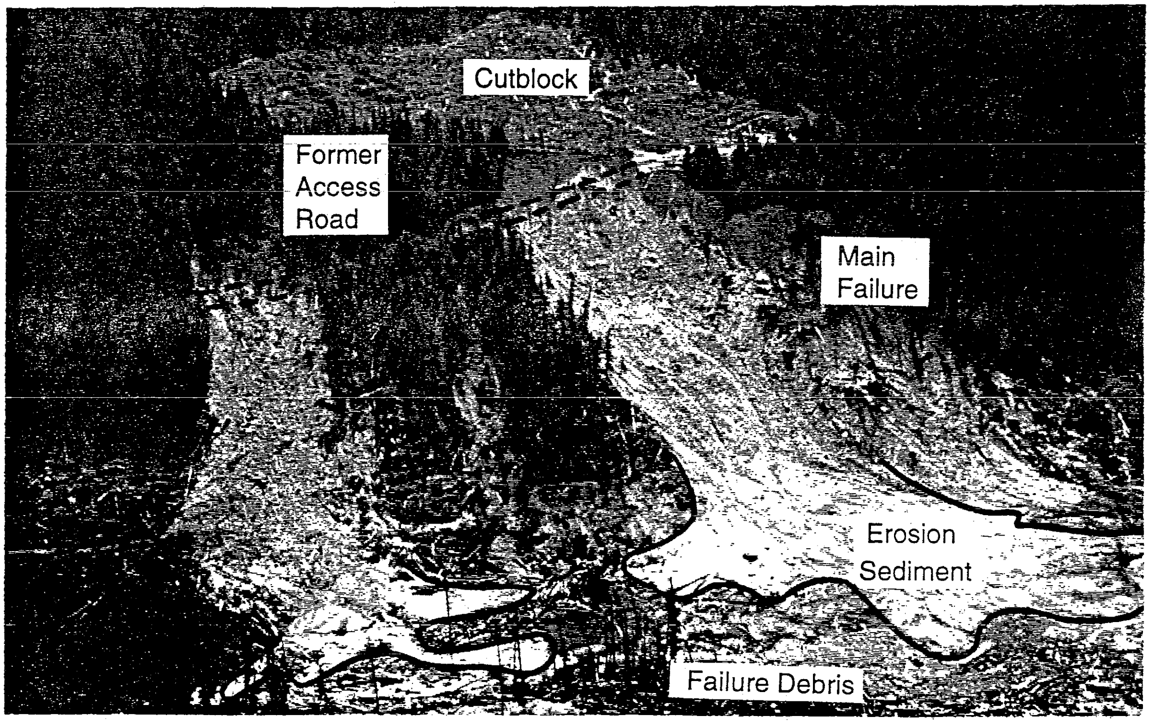
Lifecycle Stage - Slope Condition	Water Level h_w (m)	Root Cohesion C_r', (kPa)	Surcharge S_w (kPa)	Wind Load d, (kPa)	Factor of Safety
Bare	1	0	0	0	1.02
Moderately Vegetated	0.5	2	0.5	0.5	1.24
Densely Vegetated	0	3	1	1	1.40
Just Harvested	0	3 *(fresh root)*	0 *(no trees)*	0 *(no trees)*	1.47
2 Years After Harvesting	1 *(as per bare slope)*	1.8 *(60% fresh root strength)*	0	0	1.12
7 Years After Harvesting	1 *(as per bare slope)*	0.9 *(30% fresh root strength)*	0	0	1.07
7 Years After Harvesting Plus Storm Event	2	0.9	0	0	0.82

CASE HISTORY

Site Description and History

In June of 1990, two large debris avalanches occurred at a site adjacent to Sixth creek, near Salmon Arm, British Columbia, Canada. The total area disturbed by the failures, including the impacts on Sixth creek, was approximately 10 hectares. The site, as it appeared in 1995, is shown in Photograph 1. The photograph shows a cut block, failure areas, vestiges of a partially destroyed forest road ascending the slope, failure debris, and erosion materials. Photograph 2 shows the roughly one kilometer of Sixth creek disturbed by the failures. It includes a sediment fan at the toe of the larger failure (left of the photo) and remnants of failure debris which flowed into and then down the valley.

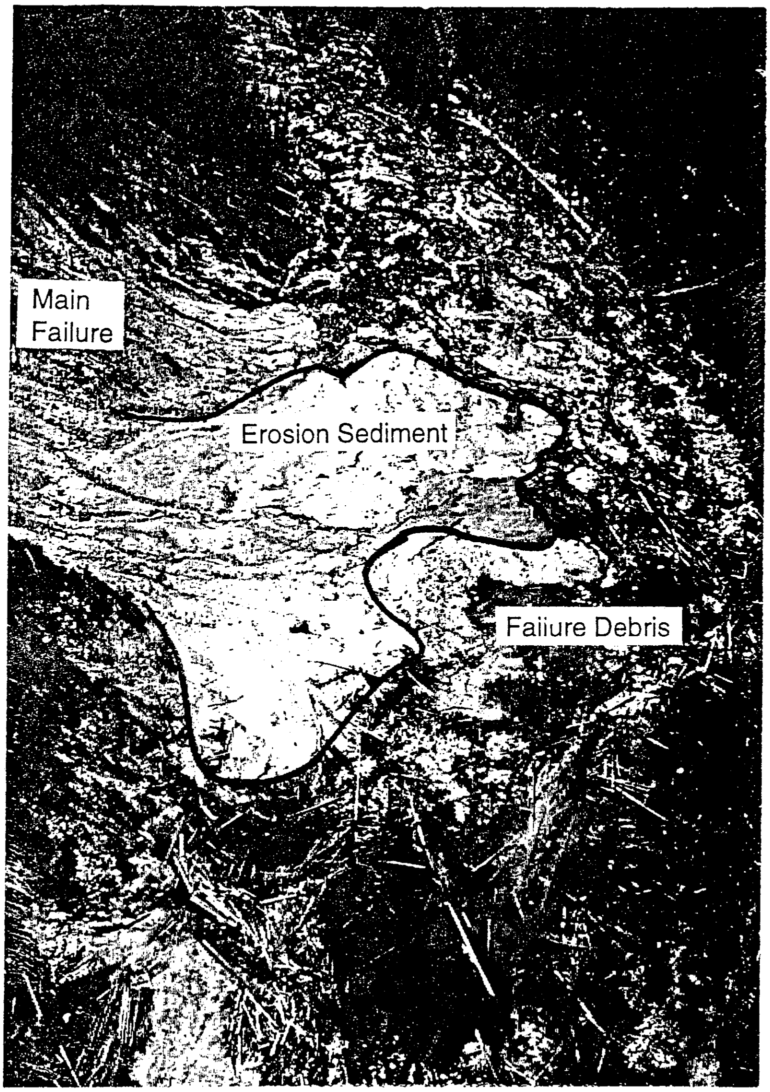
Photograph 1 - Sixth Creek Debris Avalanche Site, June 1995



The site is remote and difficult to access. It is separated from the nearest paved road by over 50km of forest road. Roads near the site have been deactivated and key roads at the site were destroyed by the failures.

Several factors, most of which are vegetation-related, could have contributed to the failures. Lower portions of the future failures were harvested in 1986 which, after root decay, would have resulted in reduced root reinforcing. An access road was constructed across the future failures in 1986. During construction, steep cuts and loose sidecast fills were probably created, vegetation was removed and soils were exposed. These changes could have decreased both slope stability and root reinforcing, and increased infiltration. The cutblock was harvested during the winter of 1989 and spring of 1990.

Photograph 2 - Sixth Creek Failure Debris and Erosion Sediment, June 1995



Harvesting would have decreased rainfall interception, reduced evapotranspiration, and increased infiltration. In May and June 1990, the area received abnormally large rainfalls. Catastrophic failure occurred in June 1990. Failure debris moved rapidly down slope, crossed the valley bottom and then moved downstream. An estimated 200,000 cubic metres of material were deposited in the valley bottom, temporarily blocking the creek. Since 1990 the site has degenerated as a result of ongoing erosion, mass wasting and sedimentation.

Rehabilitation Objectives and Approach

The objectives of rehabilitation were to improve fish habitat, forest productivity, wildlife habitat and aesthetic values at the site. These values were significantly reduced by the original failures, and have been diminished continually by ongoing processes. Vegetation and biotechnical methods were selected to rehabilitate the site because the site is large, remote and difficult to access, and vegetation is compatible with the values to be enhanced. These methods were also chosen because of their adaptability to variable site conditions and their ability to self-heal should they be damaged by future instabilities.

Site Conditions

In August 1995 the geometry of the main failure was as follows. It was bounded by oversteep head and side scarps ranging from 2m to 15m high and sloped at 45° to 90° from the horizontal. Below the scarps were loose slumped materials 5m to 35m high at 35° to 45° slopes. Below these materials were deeply rilled and gullied slopes 5m to 60m high, at 22° to 25° slopes. The toe of the man slope consisted of a deposition fan at 6° to 8°, which extended for 20m to 100m, and terminated at the creek. In the forests adjacent to the failures, slopes were typically 38° to 48° and there were extensive signs of historic instabilities; tension cracks, slumped and exposed soils, terraces, scarps and distorted vegetation.

Native soils consisted of colluvial sand and gravel with trace to little amounts of silt, cobbles and boulders. In their intact state the soils were loose to compact, weakly cemented and highly friable. However, the vast majority of soils on site consisted of materials recently disturbed by mass wasting, erosion or sedimentation. Mass wasted materials on the slopes were generally loose, positioned at the angle of repose and lacking cementation, making them prone to erosion and sloughing. Mass wasted materials in the creek were similar to parent slope material, with the addition of more organic materials incorporated during the original failures. Materials subject to erosion consisted of coarse residuals left in place and finer sediments deposited at the toe of the main slope near the creek. Gullies were heavily armored with cobbles and larger particles due to erosion of finer particles.

The hydrology of the site is strongly influenced by precipitation. Most of the precipitation incident to the cutblock, approximately 1000mm per annum, infiltrates the ground. It exits onto the main failure area through seepage zones approximately 1/4 to 1/3 of the slope height above the slope base during the summer: the elevation varies seasonally. The main failure had a central channel up to 3m deep, with a bouldery bed indicative of periodic large flows. Both failures were heavily dissected by rills, gullies and small channels up to 2m deep. Water was very close to the ground surface on deposition fans during July 1995 and water probably flows above ground during wet weather.

A negligible proportion of disturbed soils have naturally recolonized since 1990. Almost all organic material was either removed during failure or eroded afterwards, and the remaining mineral soils are infertile and have poor moisture retention. Recolonization has been retarded by exposure to erosive agents (wind, water and gravity) and by other processes which have kept soils mobile. More stable, finer, fertile soils at the toe of slopes have developed some vegetation. The growing season is relatively short and extends from mid-April until late-October. Soil moisture maximums and minimums occur in the late spring and late summer, respectively.

Recommended Vegetation and Biotechnical Solutions

Several vegetation and biotechnical forms have been recommended to arrest and/or control erosion, mass wasting and sedimentation processes, restore forest productivity, habitat and aesthetics, and rehabilitate the aquatic environment. The recommendations address low soil fertility, long slopes, active soils and several other factors. The rehabilitation measures are to be implemented in 1996.

Heli-Hydroseeding

All exposed soils, both disturbed and intact, are to be heli-hydroseeded. This technique provides access to the entire site and applies a stabilizing mixture of grass and legume seeds, fertilizer, water and erosion control agents to the soils. The agents, consisting of mulch and tackifier, reduce seed and soil erodibility, reduce rainfall and surface runoff erosivity, and improve aesthetics. The mulch also improves the near-surface micro-climate which promotes growth.

Table 5 shows the recommended mix of grass and legume seeds. The constituent seeds have a range of germination periods, growth strategies, growth rates, water requirements and persistences. Their diversity maximizes the probability of establishment and will create a cover with a broad range of leaf and root characteristics. The legumes improve soil fertility through nitrogen 'fixing'. The grasses and legumes, once developed, will trap mobile sediments and detritus, and will assist to develop a humus layer favourable for growth of local vegetation.

Table 5 - Recommended Grass and Legume Seed Mix

Species	Composition		Germination	Growth	Persistence
	(% by weight)	*(% by number)*	Period *(Days)*	Rate	
Boreal C.R.F.	25	22	7 - 21	Moderate	High
Perennial Ryegrass	20	6	7 - 14	Rapid	Low
Carlton Bromegrass	20	3	7 - 14	Moderate	High
Climax Timothy	10	18	7 - 10	Moderate	Med-High
Redtop	5	34	7 - 10	Moderate	High
Alsike Clover	14	13	1 - 5	Fair	Medium
Birdsfoot Trefoil	6	4	5 - 12	Poor	High

Dry seeding, in which seed and fertilizer are broadcast by hand or helicopter, would be an acceptable alternative to hydroseeding for soils in the valley bottom, however, high creek flows would have to be avoided until seeds became established.

Livestakes

Livestakes are to be installed into seepage zones on the lower portions of slopes and on loose colluvium on steep upper portions, where additional stability is required. Areas adjacent to the creek are also to be livestaked, in clumps, to provide erosion resistance during periods of high water. Dry areas are to be avoided because livestake mortality would be high.

Wattles

Wattles are not recommended because they require good soil contact and abundant water during establishment. Neither condition is likely to exist where wattles would be useful.

Brushlayers

Brushlayers are to be installed in three bands across the failures, breaking the long slopes into shorter segments. Their purpose is to improve slope stability and erosion resistance. The brushlayers will reinforce near-surface soils and impede surface water. They will also catch mobile sediments, detritus, windblown seeds and microflora. Each band is to consist of three brushlayers spaced approximately 2m apart. Because brushlayers are set deeper into the slope they have a greater likelihood of success than wattles.

Brushlayers are also recommended along all creek banks which rise above average water levels by more than about 1m. They will reduce soil erodibility through rooting and physical protection, and reduce flow velocities adjacent to bank soils during high flows. The brushlayers will provide shade, cover, a source of nutrients and other enhancements to the riparian habitat. They will also improve the habitat for small fauna and aid the establishment of other vegetation.

Live Fascine Drains

No live fascine drains are recommended because all major flows down the surface of the failures occur in well-armored channels. Fascine drains would have been appropriate if the site had been rehabilitated soon after failure.

Implementation, Maintenance and Re-stocking

The biotechnical forms comprised of live cuttings have similar inputs. Willows cuttings, or other species which root adventitiously, such as cottonwood, poplar and dogwood, are to be used. Sources are available close to the site. Live materials are to be kept moist and installed while dormant. Wet soil conditions are preferred because they aid establishment, however, periods of heavy rains should be avoided because of increased erosion.

Because site conditions are severe, periodic monitoring and maintenance are recommended. These activities will help prevent unnecessary site degradation and expedite site rehabilitation. Vegetation disturbed by additional mass wasting could be repaired and exposed soils stabilized. Cuttings for repairs could be sourced locally or taken from successful biotechnical forms on site. Fertilization and re-seeding could be required every year for several years until a humus layer has developed.

The site is to be re-stocked with commercial species once suitable growing conditions have been established. Re-stocking will complete the rehabilitation activities.

CONCLUSIONS

Vegetation and biotechnical methods can be applied to a wide range of problems, including erosion, slope instability and slope failure rehabilitation. They are well-suited to remote and/or inaccessible sites with variable soil conditions, where simple, flexible, cost-effective solutions with modest performance requirements are required. Vegetation methods are often appropriate for improving the habitat, productivity and aesthetics of disturbed natural areas. Vegetation solutions can have favourable cost/benefit profiles when all lifecycle costs are evaluated.

Vegetation is fundamentally different from the inert materials commonly used by geotechnical engineers. Its constituents, plants, are alive and they grow, propagate, and evolve towards a self-sustaining community. They respond to their environment and they influence it. Biomass and metabolic activity changes with seasonal and longer-term cycles. Leaves, stems and roots interact with the soil, rain, wind and gravity. They can affect the organic content and porosity of soils. They can intercept or impede rain, reduce surface runoff volumes and velocities, alter infiltration rates and amounts, and affect both subsurface flows and the groundwater level. Vegetation can also alter the stability of soils and slopes through reinforcing, arching, buttressing, surcharging and windloading. Roots are especially important on marginally stable slopes where their presence can be critical to stability.

Live vegetation can be formed into biotechnical structures to concentrate its effects. These structures are stronger and more robust than vegetation alone. The most common biotechnical forms used for earth retention are livestakes, wattles, brushlayers and live drain fascines. They can be constructed from cuttings, often available locally, and usually do not require special equipment, labour or other materials. Monitoring and maintenance can, however, be required until vegetation has become established.

The effects of existing vegetation can be quantified through field measurements, back analysis of failures and/or laboratory tests. The relative magnitude of root reinforcing, groundwater lowering, windloading and other effects can be evaluated using modeling. To estimate the effects of proposed vegetation, collective knowledge about and experience with plant behaviour is used. Vegetation designs are usually semi-empirical and involve an observational approach.

A case history has been presented to illustrate the potential utility of vegetation and biotechnical methods to slope failure rehabilitation. Recommendations such as heli-hydroseeding, livestaking, wattling and brushlayering, have been made which are aimed at controlling and arresting ongoing erosion, mass wasting and sedimentation problems. These techniques, once implemented, will begin to improve the fish and wildlife habitat, forest productivity, and site aesthetics. These techniques were the most appropriate solution for this site.

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