NCHRP Synthesis 20-05/Topic 42-09 Cost Effective and Sustainable Road Slope Stabilization and Erosion Control

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Summary

In the United States and internationally, most roads are located in rural areas and have low traffic volumes. Globally it is estimated that 88 percent of roads are low volume roads. In the United States it is estimated 75 percent of roads are low volume roads maintained by some 35,000 local agencies. Low-volume roads often omit surface slope protection and this can lead to slope failure, erosion, and maintenance, safety and ecological issues. This report presents information on cost-effective and sustainable road slope stabilization techniques, with a focus on shallow or near-surface slope stabilization and related erosion control methods used on low-volume roads. To fully address this topic planning and site investigation are discussed as well as erosion control techniques, soil bioengineering and biotechnical techniques, mechanical stabilization and earthwork techniques.

Information presented in this report was obtained through an extensive literature review, and from survey and interview responses. Information gained from the literature review was used to develop a survey that gathered additional information from practitioners, scientists, contractors and vendors on current practices, effective practices, and emerging solutions that are used regionally, nationally, or internationally. The survey was distributed via email. Eighty one survey responses were received. From the survey responses 30 individuals were asked to be interviewed based on the information they made available in the survey. A total of 25 interviews were conducted over the phone, and in two cases written responses were received. Information gained from the literature review, and survey and interview responses was incorporated into this report as the body of the text, additional resources, references, erosion control and slope stabilization techniques and tools, best management practices, useful points, photographs, knowledge and research gaps.

There are many techniques that can be used to stabilize slopes including many cost-effective and sustainable options. Every worksite is unique and to ensure the appropriate slope stabilization technique is selected understanding the site-water, soil, and topography, and the user needs is critical. Consider using a multidisciplinary team with a diverse knowledge and experience base. Appropriate water management may be the key to preventing slope failures. This can be done by developing a water management plan. Vegetation and mechanical structures and be used alone or in conjunction to stabilize slopes effectively. When using vegetation to stabilize slopes, mulch and soil amendments can aid in onsite vegetation establishment. Saving and reusing topsoil and mulching with onsite materials are cost-effective and sustainable practice. Erosion control products should be considered for use at every site on any disturbed soil surface. It is much easier to prevent erosion than to fix a slope that has eroded. Methods used to control surface erosion or stabilize slopes can be used alone or as a component of a system. Earthwork techniques can be used to make slope surface less likely to erode and more stable.

Knowledge and research gaps identified include better understanding of products, techniques and tools used in erosion control and for slope stabilization, the need for cost-benefit analyses of products and techniques, establishment of standard practices and procedures, and the need for a user guide.

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1. Introduction

This report presents information on cost-effective and sustainable road slope stabilization techniques, with a focus on shallow or near-surface slope stabilization and related erosion control methods used on low-volume roads. It is recognized that many of the identified solutions apply to higher volume roads as well. Specific items that will be discussed in this report include the importance of soil and compost, the importance of having a surface and sub-surface water management plan, soil bioengineering/ biotechnical solutions, reinforced soil solutions, other vegetative and earthwork solutions, and appropriate erosion control measures to maximize the slope stabilization for a specific treatment.

In the United States and internationally, most roads are located in rural areas and have low traffic volumes. There are an estimated 21 million miles (33.8 million km) of roads on the planet. Of these, 18.6 million miles (30 million km) comprise rural low-volume roads (Faiz, 2011). In the United States there are approximately 4 million miles (6.4 million km) in the road system, of which 3 million miles (4.8 million km) are rural, low-volume roads maintained by some 35,000 local agencies. Low-volume roads often omit surface slope protection. This can lead to slope failure, erosion, and sedimentation, which contributes to water quality degradation and increased road maintenance demands, traffic delays, safety problems, damage to other resources and, in the long term, reduction in the service life of roads. Erosion of soil can cause flooding, increased water treatment costs, siltation of harbors and channels, loss of wildlife habitat, disruption of stream ecology, reduced recreational value, and adverse aesthetic impacts (Gray and Sotir, 1996).

Erosion is the process of separating and transporting sediment by water, wind or gravity. Removal of vegetation, disturbance of topsoil, compaction, and creation of steep slopes are among the many causes of erosion (Hayman and Vary, 1999). Water erosion is the most damaging type of erosion, especially in developing areas, and erosion control is thus a particular concern for new construction. Erosion and the sedimentation caused by erosion during and after highway construction can result in an unhealthy growing environment for vegetation, pose negative impacts on adjacent waterways, and in the long run require additional maintenance (Johnson et al., 2003).

In addition to reducing lifecycle repair and road maintenance costs, benefits of slope stabilization and erosion control are not always recognized. Those benefits include:

- Rural employment opportunities involving both skilled and unskilled labor;
- Low energy inputs;
- Protection of land and water resources;
- Preservation of local biodiversity (as native grass and plant species are used in bioremediation applications);
- Aesthetically pleasing road sights.

Many slope stabilization solutions being implemented around the world by low-volume road engineers and managers are successful and cost-effective, but relevant information on methods and techniques is not well disseminated or widely used.

In this context, a synthesis of effective practices is warranted and this work aims to compile available knowledge relevant to roadway slope stabilization and erosion control, with the primary audience being public road engineers and managers.

What is road slope stabilization?

Road slope stabilization is the practice of stabilizing slopes adjacent to roads. Hundreds of road slope stabilization methods have been developed and used around the world and are very effective. Road slope stabilization can be as simple as allowing native grass to re-establish on a disturbed slope or as extreme as building an engineered wall. The treatment measure is dependent on what is affected, cost, and feasibility. Royster (1982) found that treatment of one landslide may require extensive and immediate correction, while another slide may only require minimal control with periodic monitoring to achieve a similar level of service. Slope stabilization or erosion control requires a toolbox approach that considers the level of effectiveness and acceptability of the treatment. Site conditions and constraints can vary greatly and a "one-size-fits-all" approach is unlikely to work. Instead, the right tools have to be selected for the specific project in light of its unique erosion and slope stabilization problems. While seeding and constructing a rock wall are drastically different in terms of cost and sustainability, they are two tools in the toolbox and each has its place in road slope stabilization. The cost of slope stabilization and erosion control can range from minimal to astronomical. Field studies have shown that the combined use of structural and vegetative slope protection systems is more cost-effective than the use of either vegetation or structures alone (Gray and Leiser, 1982; Xu et al., 2006).

What causes instabilities?

Common causes and trigger events for erosion or soil instability include: excessive slope angle or height, poor drainage, low-strength foundation, removal of materials that anchor soil, increased loading, environmental factors, poor handling of fill materials, high groundwater table, unsuitable geologic features, liquefaction, and wildfires (Shah, 2008). Types of slope instabilities that can cause erosion include: creep, fall or topple, slides, flow and spread, and settlement (Collin et al., 2008). While triggers for landslides in transportation projects are often related to water (including intense rainfall, rapid snowmelt, water level changes, or stream erosion), slides can also be triggered by earthquakes, human activity or volcanic eruptions (Collin et al., 2008).

Improper road construction techniques including improper selection of equipment are a common cause of slope instabilities (Shah, 2008). One technique often used in mountainous regions is known as cut and cast, cut and fill, or side-cast construction. Side-cast fills are typically not compacted, not draining and are over steepened. Picture a road in a mountainous or hilly region where material has to be cut from the uphill side and cast onto the downhill side to create the road bench—the horizontal plane on which the road will be constructed. Figure 1 shows an idealized cross section of this technique in which the exact volume that was cut is perfectly cast adjacent to the cut. In reality, material is moved around to accommodate the actual shape of the hill or knob. For these roads, the cut-and-fill faces and fill portion, which are now steeper and disturbed, are areas of potential instability that should be treated. On flat ground, a raised road is often built with ditches to improve the drainage of water from the road (Figure

2). The created embankment may be prone to surface erosion if soil is left exposed.

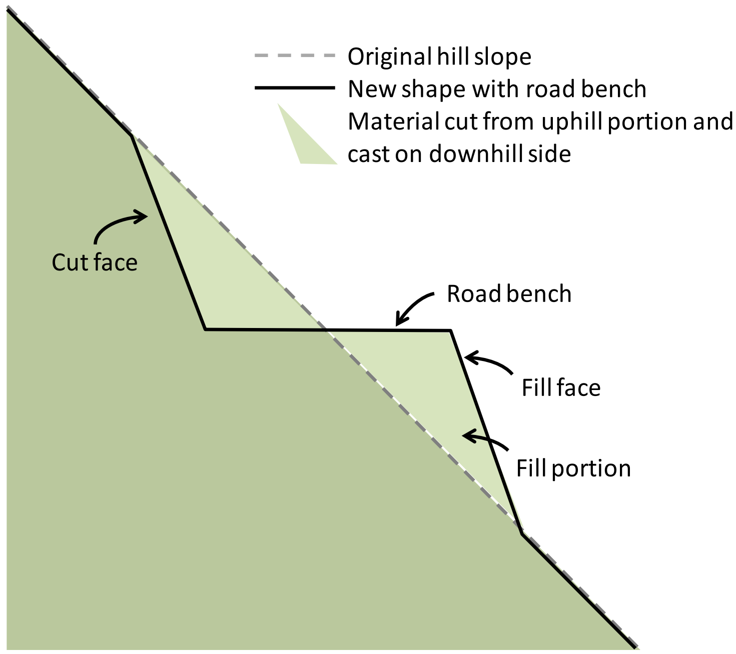

FIGURE 1 CROSS SECTION OF TYPICAL (IDEALIZED) SIDECAST CONSTRUCTION TECHNIQUE.

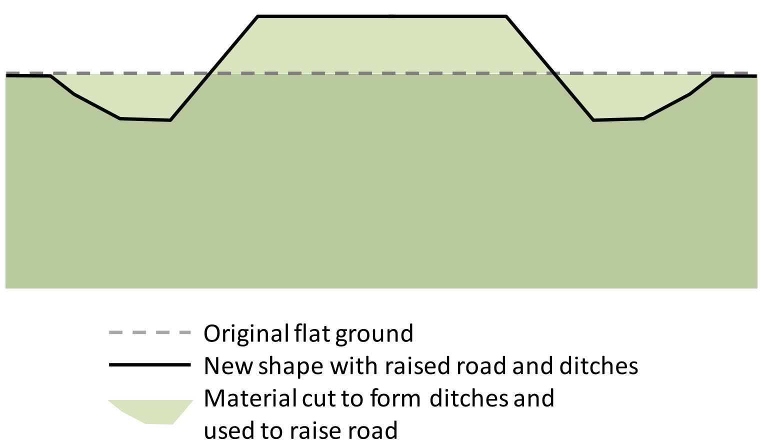

FIGURE 2 CROSS SECTION OF A TYPICAL RAISED ROAD WITH DITCHES CREATED ON BOTH SIDES FOR DRAINAGE.

Potential causes for instability in a slope could range from deep-seated failures (such as with landslides) to surface erosion (such as when steep slopes cause water to travel in concentrated flows, eroding a series of gullies). Slope failures are the movement of soil and they occur on both man-made and natural slopes. There are many types of slope failures, including rockfalls/rockslides, debris avalanches/debris flows, and slumps/earth flows (MSE, 1997). Human-induced modifications that may adversely affect external loads to slopes include grading of the existing slope or adjacent slopes, construction adjacent to the slope, construction damage caused by blasting, and vibrations of passing vehicles (Turner and Schuster, 1996). Slope re-grading can create an over-steep toe, or base of the slope, or an accumulation of material at the crest, which can lead to erosion (Turner and Schuster, 1996).

The shape of the slope can be a defining factor in the stability of the slope. Natural slopes are generally concave, which also happens to be the most stable type of slope and experiences the least amount of eroding (Schor and Gray, 2007). Many man-made slopes are linear (Schor and Gray, 2007) and research has found that in many cases a linear man-made slope will erode until it has become a concave slope (Gyasi-Agyei et al., 1996). Linear slopes created with benches are frequently used on larger slopes to reduce erosion potential, but modeling has found that linear slopes with contour benches tend to channel water in concentrated flow paths causing severe gullying over time (Schor and Gray, 2007).

How are road slopes stabilized?

Consideration of surface slope protection and addressing surface water and groundwater issues during road construction and maintenance activities can reduce erosion and enhance the long-term performance of slopes and embankments. A combination of adequate drainage, installation of protective devices and elements, and establishment of desirable vegetation offer the best means for soil conservation. For instance, seeding disturbed soil as areas of a project are completed can reduce erosion by 90 percent (Johnson et al., 2003).

There are dozens of techniques to stabilize road slopes and prevent surface erosion. *Erosion control* techniques generally protect the surface from being eroded by water and wind—examples include vegetative cover, crushed stone cover, mats, blankets, etc. The guiding principles are minimization of the exposed and disturbed areas and exposure time, management of on-site stormwater by reducing velocity and volume, installation of erosion and sediment control measures early in the construction phase and during structural maintenance, and keeping sediment on site (Johnson et al., 2003). Temporary erosion control measures should be used during construction, especially when the construction occurs in steep rolling topography, in cases where most of the drainage enters directly into adjacent water bodies or wetlands, or where the sub-soils are erosive (Alberta Transportation, 2003). After projects are completed and vegetation is established, permanent measures should be implemented. Common devices for permanent erosion control include: design elements, ditches and liners, detention pond, riprap, soil bioengineering and biotechnical stabilization, and vegetation establishment. It should be noted that many erosion problems could be simply avoided by good design practices (Alberta Transportation, 2003).

Soil bioengineering techniques utilize plant parts such as roots and stems to serve as structural and mechanical elements in slope protection systems (Gray and Sotir, 1996; Sotir and McCaffrey, 1997; Grace, 2002; Fox et al., 2010). The plants serve as soil reinforcement, aid in water drainage, or serve as barriers to earth movement (Gray and Sotir, 1996). The use of sod, or native grass sod, as a best management practices (BMP) is compatible with highway revegetation prescriptions and is a practice employed in several states (Dollhopf et al., 2008). *Biotechnical stabilization* utilizes structures in combination with plants to arrest and prevent slope failures and erosion with biological and mechanical elements functioning together in an integrated and complementary manner (Gray and Sotir, 1996). Biotechnical stabilization applies to retaining structures, revetments, and ground cover systems (e.g., sod grass that may be reinforced with netting) (Gray and Sotir, 1996). Retaining structures help hold back the slope and include walls of various shapes and materials. The combined use of structural and vegetative elements (e.g., contour wattling, willow cuttings, conventional slope planting in combination with a low gabion walls, bench structures constructed at the toe of a slope, or vegetation growth in the voids of structural walls) has been reported to be an attractive and cost-effective method to hold soil and prevent slope failures and erosion (Gray and Leiser, 1980). Other options include using stabilizing vegetation and structures, erosion control mats and mesh, earthwork (terracing, anchoring, effective site drainage, and slope modification), etc. Options may also include the use of lime piles (Rogers et al., 2000), fibers and chemicals (RITA, 2011), and electrochemical techniques (Wan and Mitchell, 1976; Johnson and Butterfield, 1977; Casagrande, 1983; Alshahabkeh et al., 2004; Paczkowska, 2005) for stabilizing weak soils. Slope reinforcement can utilize vegetation, concrete, polymers, and other materials. Natural materials, such as soil, rock, and timber are more environmentally compatible, and are better suited to vegetative treatments or slight modification than are manufactured materials (Sotir and Gray, 1992). Natural materials may also be available onsite at no cost (Sotir and Gray, 1992).

Mechanical Stabilization Techniques utilize non-vegetative or non-living components such as rock, concrete, geosynthetics, and steel pins to reinforce slopes. These techniques can provide stability to both cut and fill slopes. Structures are generally capable of resisting much higher lateral earth pressures and shear stresses than vegetation (Sotir and Gray, 1992). Mechanical stabilization techniques include retaining walls, mechanically stabilized earth, geosynthetically reinforced soil, and other in-situ reinforcement techniques. For anchoring shallow soils, in-situ earth reinforcements and recycled plastic pins have been reported for their use in slope stabilization (Pearlman et al., 1992; Loehr et al., 2000).

Earthwork techniques involve the physical movement of soil, rock, and/or vegetation for the purpose of erosion control and slope stabilization. This involves reshaping the surface slope by methods such as creating terraces or benches, flattening over-steepened slopes, soil roughening or land forming. Earthwork techniques can be used to control surface runoff and erosion and sedimentation during and after construction (EPA, 2008). Land grading can be used at sites with uneven or steep topography or on easily eroded soils to stabilize slopes, and terraces can be used to reduce sediment-laden runoff by slowing water flow down the slope, collecting and redistributing surface runoff into designed drainage channels (EPA, 2008).

To effectively control soil instabilities and erosion, a systematic approach is needed that takes into account government regulations and permitting requirements; design, construction, and maintenance considerations; various temporary and permanent control methods; and new technologies (Johnson et al., 2003). While every slope stabilization treatment method should be considered a tool in the toolbox, some treatments may be more appropriate for a site. There are many tried and true methods, and new methods are being continually developed. The current state of the practice has matured in such a way that practitioners no longer view specific slope stabilization treatments as good or bad, working or ineffective. Instead a multidisciplinary approach combining knowledge from multiple fields of study including geology, hydrology, engineering, landscape architecture, etc. and combining treatment measures to create site-specific slope stabilization treatments is used to solve slope stabilization issues.

How is a treatment determined to be cost-effective and or sustainable?

When considering road slope stabilization techniques for a site, there are generally many options. For example, on an exposed road cut the treatment options may be 1) to build a retaining wall, 2) to build a vegetated crib wall, or 3) to add top soil or compost to the eroding surface, hand seed the slope, and lay down erosion-control blankets. All three of these options could work well, but which one will be most cost-effective and sustainable? It may depend on what is available on site, how much space you have to work with, and how much it costs to bring materials into the site.

When selecting a treatment for road slope stabilization that is both cost-effective and sustainable, both the short- and long-term costs need to be considered. One way to ensure that a project is low cost and sustainable is to use local or on-site materials. Reusing on-site soil, rocks, tree stumps, downed trees, live vegetation, leaf litter, etc., can be very cost-effective. Use of on-site materials ensures that the project is sustainable through reduction of fuel and transportation costs that would accrue if these materials needed to be brought to the site. Native seed stock present in the local soil is another benefit. In a survey conducted to gain information for this project, survey respondents stated that short- and long-term costs are considered important in deciding on a road slope stabilization and/or erosion control measure, and are frequently considered together.

A sustainable road slope stabilization treatment is one that disturbs the least amount of soil, keeps topsoil on site, reuses onsite vegetation to strengthen the slope, and that incorporates native plants and poses minimal disturbance to the ecosystem. In a survey conducted to gain information for this project, 76 percent of survey respondents stated that they *always* or *frequently* consider how environmentally friendly or sustainable a road slope stabilization measure will be. While many survey respondents stated that a strong sense of environmental stewardship has led them to make sustainable decisions, an equal number of survey respondents stated that local and state mandates, federal laws, and permit requirements weigh heavily in making a sustainable road slope stabilization treatment choice.

Aesthetic considerations are also often appropriate when choosing the stabilization technique. It is a common belief that created slope stabilization structures should fit with the natural landscape, and once the project is completed the site should be restored as close to its previous condition as is possible (Schiechtl and Stern, 1996). Considerations include the balance and distribution of cut and fill material, the use of local building materials, the avoidance of deep and steep cuts into slopes wherever possible, and maintenance of the natural landscape.

2. Methods

The following synthesis is focused on providing information on cost-effective and sustainable shallow (less than 10 ft) or near-surface slope stabilization and related erosion-control treatments used on low-volume roads. Successful completion of this report required the following tasks be performed—a review of available literature, a survey, and interviews. Information on each of these tasks is presented below.

An extensive literature review was conducted to gather information on cost-effective and sustainable near-surface slope stabilization techniques used on low-volume roads. Technical documents, government reports, journal publications, conference presentations and proceedings, and textbooks were used initially to identify pertinent information. Information was also sought from local, state and federal and international governments and organizations, departments of transportation, manuals, field guides and reports, published specifications, and organizations and companies that work to promote erosion control and slope stabilization. Information gained in the literature review was used to create the body of the report, survey questions, and identify individuals and organizations for participation in the survey.

Based on information gained from the literature review, a survey was developed to gather additional information from practitioners, scientists, contractors and vendors on current practices, effective practices, and emerging solutions that are used regionally, nationally, or internationally. The survey asked participants to provide identifying information, followed by seven questions requesting information on the respondents' direct experience with erosion control and slope stabilization techniques (Appendix A). The survey was distributed electronically via email to individuals identified in the literature review and by project panel members. The survey was available online for two months and 81 responses were received. Survey responses were processed and summarized. Information identified in the survey that was incorporated into this report includes resources, references, erosion control and slope stabilization techniques and tools, best management practices, useful points, photographs, etc. Survey responses aided in focusing the synthesis on the most frequently used road slope stabilization techniques that are cost-effective and sustainable.

A list was compiled of survey respondents who indicated they were willing to participate in follow-up interviews. Thirty individuals were selected and asked to be interviewed based on the information they made available in the survey. A total of 25 interviews were conducted, providing an 83 percent interview response rate. Interviews were conducted over the phone with the exception of two responses received via email, due to interviewees' location and language differences. Interviewees were asked 16 questions and instructed to only provide responses based on their direct experience (Appendix B). Interview responses were recorded with a digital recorder and then transcribed or recorded by hand during the interview process. Information gained from the interviews that was incorporated into this report includes additional resources, references, erosion control and slope stabilization techniques and tools, best management practices, useful points, photographs, knowledge gaps and research needs, etc.

Information presented in this report, gained through the literature review, survey and interviews is presented in the following format. The report begins with an introduction to the topic of cost-effective and sustainable road slope stabilization techniques. The Introduction defines road slope stabilization, identifies general techniques used to stabilize roads, and provides a discussion of the terms cost-effective and sustainable and how they relate to road slope stabilization treatments. This is followed by the Methodology section, which outlines how the literature review, survey and interviews were conducted and provides an outline of the report. The Methodology section is followed by a section titled The Basics. The Basics provides information on planning and site investigation, soil type and mechanics, and water management including surface and sub-surface drainage options. The next section, Erosion Control Techniques, defines erosion and outlines general causes, and provides examples of erosion control treatments and techniques including seeding, mulching, the use of blankets, mats and geotextiles, check dams, wattles, silt fences, and chemical soil stabilizers. The proceeding section Soil Bioengineering and Biotechnical Techniques defines these two techniques and provides a review of treatments on the topic including the use of live stakes, fascines, crib walls, gabions and rock walls in a combination of vegetation and structures to stabilize slopes. The next section, Mechanical Stabilization Techniques, defines this topic and provides information on retaining walls, mechanically stabilized earth and geosynthetically reinforced soil systems, geotextile walls, deep patch repairs and in-situ soil reinforcement techniques. The next section, Earthwork Techniques, defines this topic and provides information on benches, terraces, soil roughening, flattening over-steepened slopes, and landforming. The report closes with the Conclusions section, which provides a summary of findings from each section and a discussion of knowledge gaps and future research on this topic.

The report resembles a guide in structure, but it is more appropriate to use it as a reference document. Each section highlights current practices in road slope stabilization that are cost-effective and/or sustainable. Each topic has an ***Additional Resources*** section that provides references where additional information can be gathered.

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3. The Basics

There are three essential elements of good slope stabilization: proper planning and site investigation, understanding the soil, and knowing the surface and subsurface water conditions. This chapter summarizes literature and interview results on all three topics and additional resources for follow-up information are provided.

3.1 Planning and Site Investigation

When conducting slope stabilization work, it is more cost-effective to proactively apply appropriate techniques to control erosion and stabilize slopes than to repair them after they have failed. A full assessment of the site should be completed before a slope stabilization technique is selected. The project plan developed by Howell (1999) for the *Roadside Bio-engineering: Site Handbook* is a good example of how to develop a successful slope stabilization implementation plan (Table 1). Howell (1999) suggests that planning occur over at least one year, if possible, and that time be allowed in the second year, following construction, for site monitoring and maintenance.

TABLE 1 STEPS TO IMPLEMENT BIO-ENGINEERING TAKEN FROM (HOWELL, 1999)

Planning	Design	Implementation	Maintenance
• Initial work plan • Prioritize work • Divide site into segments and assess • Determine engineering and bio-engineering techniques to be used	• Design engineering and bio-engineering techniques • Select species • Calculate quantities, rates and finalize budget • Plan for plant needs • Arrange for implementation and required documents/permits	• Prepare for plant propagation • Make site arrangements • Implement engineering and bio-engineering techniques • Monitor work	• Maintain site

It is widely recognized that the more front-end work one can do to understand the site, the more likely it is that the best possible treatment will be selected. During the initial planning stages, think broadly at the watershed level and consider topography, geography, geology, etc. It may be helpful to consult historical rainfall and snowfall records for the site, geologic maps, nearby slope stability, records on previous work completed at the site, and previous work above and below the slope. Consider using a multidisciplinary team consisting of soil scientists, botanists, geologists, hydrologists, ecologists, landscape architects and geotechnical engineers to gain further information about the site characteristics. The aim of the site investigation should be to 1) recognize actual or potential slope movements, and 2) identify the type and cause of the movement (Turner and Schuster, 1996). This information will help in selecting the most appropriate prevention and correction strategy.

When starting a site investigation, the following five items need to be defined:

- the **purpose** of the site or road,
- the **scope** of the site, including topography, geology, groundwater, weather, and slope history,
- the extent of the project or **area** of the work site,
- the **depth** of the instability and/or stable support layer, and
- the **duration** of the project (Turner and Schuster, 1996).

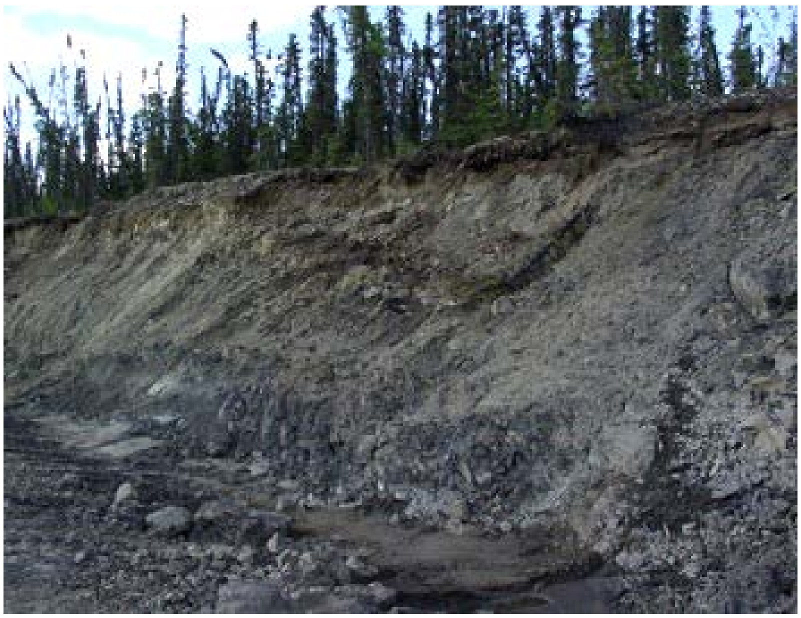

FIGURE 3 UNSTABLE SLOPE CAUSED BY FREEZE–THAW CYCLES IN ALASKA. PHOTO PROVIDED BY J. CURREY.

Signs of slope instability may include slumped soil (Figure 3); tension cracks; eroded material at the base of the slope (Figure 4); hummocky and broken or uneven terrain; leaning trees (Figure 5); water seeps, ponds, or channels; or other signs of surface erosion.

FIGURE 4 SHALLOW CUT FAILURE JUST BELOW GRASS ROOT DEPTH. PHOTO PROVIDED BY G. KELLER.

FIGURE 5 SLUMPED SLOPE WITH LEANING TREES. PHOTO PROVIDED BY G. KELLER.

Useful Points

- In the planning phase, consider the timing of each project component (S. Jennings, personal communication, April 12, 2011).
- At the planning level, consider all options and keep a broad focus. (S. Romero, personal communication, May 11, 2011)

- Consider using experienced engineers and contractors. (B. Johnson, personal communication, April 18, 2011)
- Know the areas of expertise of potential contractors. (S. Romero, personal communication, May 11, 2011)
- Consider using an experienced project manager on site who can coordinate efforts and operations for all aspects of the project. (K. Mohamed, personal communication, April 26, 2011)
- Consider conducting a lifecycle analysis for all treatments before they are used. (A. Faiz, personal communication, May 6, 2011)
- Every project is unique, and each treatment needs to be tailored to the site. (A. Faiz, personal communication, May 6, 2011)
- Talk with knowledgeable local personnel to understand the types and nature of problems in that area. (G. Keller, personal communication, April 26, 2011)

Additional Resources for Planning and Site Investigation

Adams, P. W. and C. W. Andrus. 1990. "Planning secondary roads to reduce erosion and sedimentation in humid tropic steeplands." In *Proceedings of Research Needs and Applications to Reduce Erosion and Sedimentation in Tropical Steeplands, Fiji Symposium*, June. IAHS-AISH Publ. No. 192.

Clayton, C. R. I., N. E. Simons and M. C. Matthews. 1982. *Site Investigation: A Handbook for Engineers*. New York: Halsted Press.

Ethiopia Roads Authority 2011. Design Manual for Low Volume Roads Part A, B and C. Final Draft, April. (http://www.dfid.gov.uk/r4d/PDF/Outputs/AfCap/Design-Manual-for-Low-Volume-Roads-Part-A.pdf)

Howell, J. 1999. *Roadside Bio-engineering: Site Handbook*. His Majesty's Government of Nepal. Ganabahal, Kathmandu.

Hunt, R. E. 2005. *Geotechnical Engineering Investigation Handbook*. Boca Raton, Florida: CRC Press, LLC.

Sara, M. N. 2003. *Site Assessment and Remediation Handbook*. Boca Raton, Florida: CRC Press, LLC.

Hearn, G. J. and R. W. Weeks. 1997. Principles of low cost road engineering in mountainous regions, with special reference to Nepal, Himalaya. Ed. C. J. Lawrence. Transport Research Laboratory, Overseas Road Note 16. Berkshire, United Kingdom.

Turner, K. A. and R. L. Schuster, eds. 1996. Landslides Investigation and Mitigation. TRB Special Report 241. Washington, D.C.: National Academy Press.

3.2 Soil Types and Soil Mechanics

Soil mechanics is the study of the engineering behavior of soil under different stress conditions. The basic components of soil are soil particles (grains), water, and air. The relationship between these components provides several important index properties such as density, moisture content, and degree of saturation. Other index properties that are important for classifying the soil and engineering soil structures (including slopes) include grain size distribution, Atterberg limits (particularly the plastic and liquid limits), and shear strength parameters.

Soil classification systems provide a means of grouping and identifying the expected behavior of soils. Laboratory tests for the grain size distribution, plastic limit and liquid limit of a soil are used for classification within the Unified Soil Classification System (USCS), which is the most widely used system. The AASHTO soil classification system was originally developed to classify soils for assessing their suitability as a subgrade or pavement layer. There are significant differences between the USCS and AASHTO systems, but the AASHTO system is still commonly used by DOTs and pavement engineers (Holtz et al., 2011). Grain size distribution is determined by a sieve analysis for the coarse-grained fraction of soils (above No. 200 sieve with 0.075 mm opening size). If the size distribution of the fine-grained portion of soil is desired a hydrometer is used. However, the more relevant property of the finer fraction of soils is plasticity index (PI). The plasticity index is the range in water content at which the soil behaves as a plastic solid. The PI is calculated from results of tests for the liquid limit and plastic limit of the finer portion (smaller than No. 40 sieve with 0.425 mm opening size) of the soil. Once the grain size distribution, plastic limit, and liquid limit are known the soil can be classified by USCS using ASTM 2487, Holtz and Kovacs (1981), Das (2007), Holtz et al. (2011), or any introductory geotechnical engineering or soil mechanics book. A few typical grain size distributions are shown in Figure 6 and typical compaction and drainage characteristics for USCS soil groups are provided in Table 2.

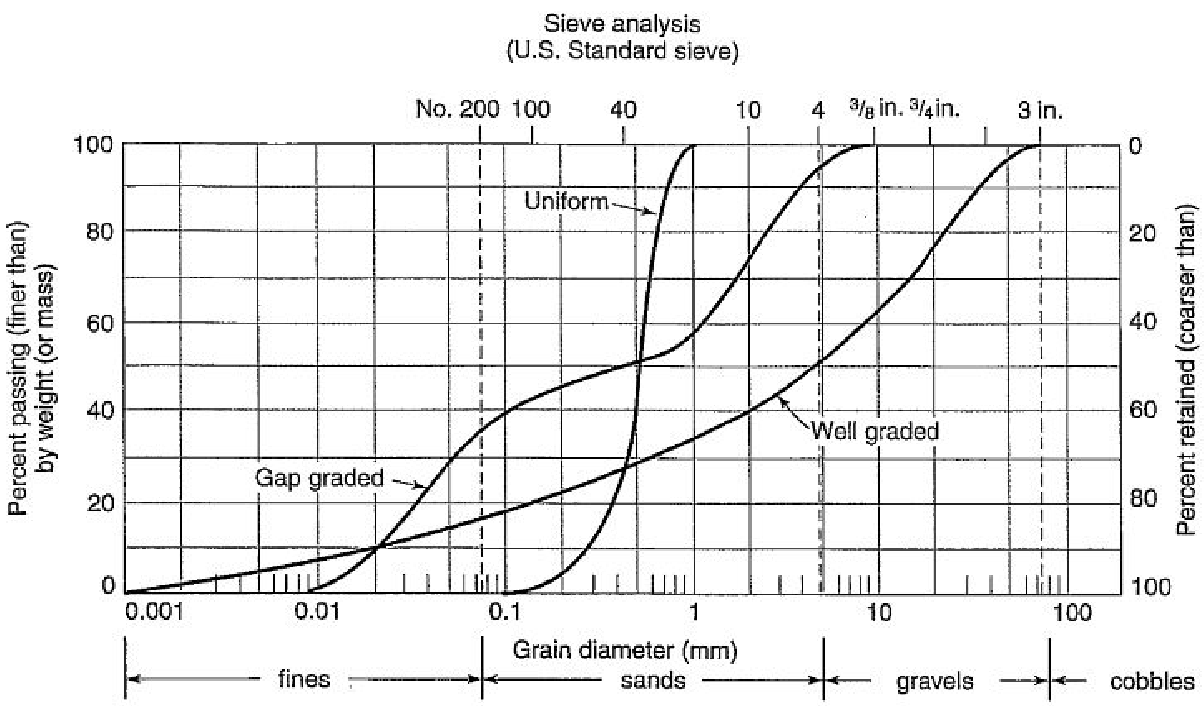

FIGURE 6 THREE TYPICAL GRAIN SIZE DISTRIBUTIONS TAKEN FROM (HOLTZ ET AL., 2011)

TABLE 2: USCS SOIL CLASSIFICATION AND TYPICAL PROPERTIES. TAKEN FROM (NAVFAC, 1986)

USCS Soil Classification		Compaction Characteristics & Recommended Equipment	Drainage & Permeability	Value as an Embankment Material
Group Symbol	Group Name			
GW	Well-graded gravel	Good: tractor, rubber-tired, steel wheel, or vibratory roller	Good drainage, pervious	Very stable
GP	Poorly graded gravel	Good: tractor, rubber-tired, steel wheel, or vibratory roller	Good drainage, previous	Reasonably stable
GM	Silty gravel	Good: rubber-tired or light sheepsfoot roller	Poor drainage, semipervious	Reasonably stable
GC	Clayey gravel	Good to fair: rubber-tired or sheepsfoot roller	Poor drainage, impervious	Reasonably stable
SW	Well-graded sand	Good: tractor, rubber-tired or vibratory roller	Good drainage, pervious	Very stable
SP	Poorly graded sand	Good: tractor, rubber-tired or vibratory roller	Good drainage, previous	Reasonably stable when dense
SM	Silty sand	Good: rubber-tired or sheepsfoot roller	Poor drainage, impervious	Reasonably stable when dense
SC	Clayey sand	Good to fair: rubber-tired or sheepsfoot roller	Poor drainage, impervious	Reasonably stable
ML	Silt	Good to poor: rubber-tired or sheepsfoot roller	Poor drainage, impervious	Fair stability, good compaction required
CL	Lean clay	Good to fair: sheepsfoot or rubber-tired roller	No drainage, impervious	Good stability
OL	Organic silt, Organic clay	Fair to poor: sheepsfoot or rubber-tired roller	Poor drainage, impervious	Unstable, should not be used
MH	Elastic silt	Fair to poor: sheepsfoot or rubber-tired roller	Poor drainage, impervious	Fair to poor stability, good compaction required
CH	Fat clay	Fair to poor: sheepsfoot roller	No drainage, impervious	Fair stability, expands, weakens, shrinks, cracks
OH	Organic silt, Organic clay	Fair to poor: sheepsfoot roller	No drainage, impervious	Unstable, should not be used
Pt	Peat	Not Suitable	Should not be used	Should not be used

Soils fail in shear. If the shear stress is greater than the shear strength of the soil, it will fail. Thus, it is important to know the shear strength of soil. The strength properties of soil are described in terms of friction (φ) and cohesion (c). These properties are determined from laboratory tests, such as the direct shear test and triaxial test. The triaxial laboratory test can be conducted under a variety of drainage conditions to provide parameters appropriate for drained and undrained analyses. Whether loading on soil should be thought of in terms of “drained” or “undrained” conditions depends on the permeability of the soil, the rate at which the load is applied, and the time period of interest (short or long term) after the load is applied (Holtz and Kovacs, 1981; Duncan and Wright, 2005).

- "Undrained signifies a condition where changes in loads occur more rapidly than water can flow in or out of the soil. The pore pressures increase or decrease in response to the changes in loads.
- Drained signifies a condition where changes in load are slow enough, or remain in place long enough, so that water is able to flow in or out of the soil, permitting the soil to reach a state of equilibrium with regard to water flow. The pore pressures in the drained condition are controlled by the hydraulic boundary conditions, and are unaffected by the changes in load" (Duncan and Wright, 2005).

The fundamental requirement for a stable slope is that "the shear strength of the soil must be greater than the shear stress required for equilibrium" (Duncan and Wright, 2005). Thus, factors that contribute to slope instabilities could be linked to decreases in shear strength and/or increases in shear stress. Duncan and Wright (2005) list the following processes responsible for these changes:

- Decreases in Shear Strength
    - Increased pore pressure (reduced effective stress)
    - Cracking
    - Swelling (increase in void ratio)
    - Development of slickensides
    - Decomposition of clayey rock fills
    - Creep under sustained loads
    - Leaching
    - Strain softening
    - Weathering
    - Cyclic loading
- Increases in Shear Stress
    - Loads at the top of the slope
    - Water pressure in cracks at the top of the slope
    - Increase in soil weight due to increased water content
    - Excavation at the bottom of the slope
    - Drop in water level at the base of a slope
    - Earthquake shaking

Water and the presence of clay minerals play a significant role in many of these processes, particularly those associated with decreases in shear strength.

> *"The percentage of clay in a soil and the activity of clay minerals are reflected qualitatively by the value of the plasticity index. For that reason PI affords a useful first indication of the potential for problems that a clayey soil poses: The higher the PI, the greater the potential for problems" (Duncan and Wright, 2005).*

In addition to water, soil erosion may also be caused by wind. He *et al.* (2007) found that there is a linear relationship between the logarithm of the wind velocity and the intensity of resulting erosion. They also reported on the effectiveness of three practices in preventing wind erosion of highway slopes. In descending order of effectiveness, they were hexagonal bricks, arched frame beams, and mechanical compaction, with the relative soil loss ratio of such treated slopes at 0.35, 0.55, and 0.91, respectively.

In practical terms, the following conditions lead to instability:

- Slopes that are excessively steep or that have been undercut,
- Slopes that are wet or saturated,
- Poorly compacted fill slopes,
- Steep slopes with shallow-rooted grasses that can be surcharged when saturated.

Additional Resources for Soil Types and Mechanics

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Holtz, R. D., W. D. Kovacs, and T. C. Sheahan. 2011. *An Introduction to Geotechnical Engineering, 2nd edition*. Upper Saddle River, N.J.: Pearson Education, Inc.

3.3 Water Management…Where is the water?

Call out box:

> *If you only look superficially, and don't address the water problem by considering the overall site hydrology, you can miss finding an appropriate solution (A. Faiz, personal communication, May 6, 2011).*

Water management, in both cut and fill slopes, is important to protect the slopes from erosion and shallow depth instabilities due to increases in pore water pressure (GSPW, 2003). Water may enter the roadway through cracks or surface defects on the road surface or water can infiltrate through cuts and fills (Orr, 1998). Capillary action may also draw moisture up from the water table, causing the road base to become saturated and weakened. Construction of roads may also modify the surface and subsurface flow pattern of water, causing no flow or reduced flow in some natural channels but concentrated flow in others (Shrestha and Manandhar, 2010).

In general, water management measures in slopes consist of surface and subsurface drainages that transport water to natural drainages safely and as quickly as possible (GSPW, 2003). Roadway drainage is the control of water within the road, including moving water off the road surface and removing excess subsurface water that would infiltrate the road base and subgrade (Orr, 1998). To effectively understand how to manage water at each site rainfall, topography, catchment area, ground surface conditions, soil parameters, groundwater conditions, and existing natural and artificial drainage systems should be studied and assessed to determine the required drainage solution (Turner and Schuster, 1996). If necessary, a combination of both surface and subsurface drains can be used to effectively manage surface and groundwater conditions (GSPW, 2003).

For each site, consider developing a water management plan that would answer the following questions:

- Where is the water source?
- Where does the water come to the surface?
- How is the water interacting with the different soil and rock types?
- Is an artificial drainage system needed for the slope?
- Can vegetation alter the hydrology and improve slope stability?

A good water management plan will include conservation of natural systems that interact with the road, which can be considered in the design and construction phases (Shrestha and Manandhar, 2010). Examples of this include widening of a road where possible, adding rolling dips and low-water fords that follow natural topography, and using bridges and surface stabilization as needed (Adams and Andrus, 1990).

3.4 Drainage Measures

Drainage of water from the road surface has significant implications for slope stability and can impact water quality, erosion, and road costs (Keller and Sherar, 2003). Poorly drained pavements and slopes adjacent to roads can cause premature deterioration and lead to costly repairs and replacements (Cedergren, 1989). Drainage issues that should be addressed in road design and construction include:

- roadway surface drainage,
- control of water in ditches and at pipe inlets and outlets,
- crossings of natural stream channels,
- wet area crossings,
- subsurface drainage, and
- selection and design of culverts, low-water crossings, and bridges.

Prior to installation of surface and subsurface drainage measures, drainage conditions and patterns should be studied. Specific observation should be made during rainy periods to monitor flow patterns, identify areas where ponding occurs, assess potential damage, and to determine preventive measures that can be used to minimize damage and to keep the drainage system functioning properly (McCuen et al., 2002).

Good water drainage begins in the design and construction phases of road building. Road surfaces should be shaped appropriately to effectively keep water from accumulating on the road surface. Standing water should be avoided, as it often creates or worsens potholes, ruts and sags (Keller and Sherar, 2003). Drainage ditches should be constructed only when necessary. For example, a road graded away from a cut slope (an outsloped road) without ditches disturbs less ground and is less expensive to construct than an insloped or crowned road with drainage ditches, although the fill slope may require explicit erosion control measures (Moll et al., 1997). Keep water drainage from roads and streams disconnected by using water retention basins. When installing drainage structures, make sure that there is some rational or statistical assessment of the expected flow.

Howell (1999) offers the following advice for drainage design:

- Always design drainage systems to run along natural drainage lines.
- Choose locations for the drain so that the maximum effect can be achieved using the least amount of construction.
- Always ensure the drain outlets are protected against erosion.
- Ensure the foundation is sound, as with all civil structures.
- A flexible design is usually an advantage (e.g., concrete masonry, a rigid design, can be easily cracked by the slightest movement in the slope, resulting in leakage problems).
- Compact the backfill material thoroughly during construction.
- Apply appropriate bio-engineering measures to enhance the effectiveness of the drain.

<u>Useful Points</u>

- On steep road grades, e.g., greater than 5:1 (20%), water becomes very difficult to control (Keller and Sherar, 2003).

3.4.1 Surface Drainage

Surface drainage is most commonly accomplished by proper grading of the road surface or the use of structures to channel water from the road surface in a manner that minimizes effects to adjacent areas (Copstead et al., 1989). Surface drainage systems include drains, berm drains, toe drains, drainage channels, and cascades. U-shaped gutters (Figure 7), reinforced concrete (Figure 8), and corrugated half-pipe drains can also be used to construct drainage ditches (GSPW, 2003). Surface water drains often use a combination of bio-engineering and civil engineering structures (Howell, 1999). Armor roadway ditches and leadoff ditches with rock riprap (Figure 9), masonry, concrete lining, geotextiles and/or grasses to protect highly erosive soils (Keller and Sherar, 2003). Ditch dike structures can also be used to dissipate energy and control ditch erosion. If ditch erosion is occurring, the best solution may be to place additional cross-drains to disperse and reduce the amount of water that is causing the erosion.

FIGURE 7 DOWN DRAIN. PHOTO PROVIDED BY G. KELLER.

FIGURE 8 CONCRETE SURFACE DRAINAGE. PHOTO PROVIDED BY G. KELLER.

There are three main ditch shapes: V, U, and trapezoid, and each can be filled or lined (Orr, 1998). V-shaped ditches are the easiest to construct; however the bottom of the V is prone to erosion and can be difficult to maintain. U-shaped, or rounded ditches are more efficient hydraulically than V-shaped ditches, are more desirable for erosion control, and are easy to maintain. Trapezoid, or flat-bottomed, ditches are the most efficient hydraulically and should be used for ditches that carry heavier flows. The flat bottom of the trapezoid ditch helps reduce erosion problems and spread water flow. Ditches may be filled or lined and will act similarly to trench drains. An example of a filled ditch that behaves like a trench drain would be lining a ditch with large stone and placing a perforated pipe at the bottom of the ditch. Ditches can be lined with native earth, geotextiles, grass, stone, and/or concrete, etc. (Orr, 1998). Lining the roadside ditch with geotextiles can reduce erosion rates. Ditches require cleaning, which entails the removal of sediment and vegetation from the bottom of the ditch.

Useful Points

- Place erosion protection or seeding before rainfalls on all newly exposed surfaces.
- Have erosion materials ready before starting a job, in case of rain (Orr, 1998).

FIGURE 9 GEOTEXTILE- AND ROCK-LINED DITCH EXAMPLE OF SURFACE DRAINAGE. PHOTO PROVIDED BY C. GILLIES.

Rolling dip cross-drains, or broad-base dips, are designed for dispersing surface water on roads with slower traffic (Keller and Sherar, 2003) (Figure 10). Relative to culvert pipes, rolling dips usually cost less, require less maintenance, and are less likely to plug and fail. Rolling dips are ideal for low-volume roads with low to moderate traffic speeds (less than 30 mph (or 50 kph)) and low average daily traffic. Consider constructing rolling dips rather than ditches with culvert cross-drains on roads with grades less than 5:1 (H:V) , or 20% (Copstead et al., 1989; Keller and Sherar, 2003). Rolling dips should be deep enough to provide adequate drainage, perpendicular to the road or angled 25 degrees or less, outsloped 3–5%, and long enough (50 to 200 ft (15 to 60 meters)) to allow vehicles and equipment to pass. In soft soils, it is important to armor the mound and dip with gravel or rock. Ideal spacing of rolling dip cross-drains is a function of the road grade and soil type (see Keller and Sherar, 2003, pg.55 Table 7.1, for recommended spacing).

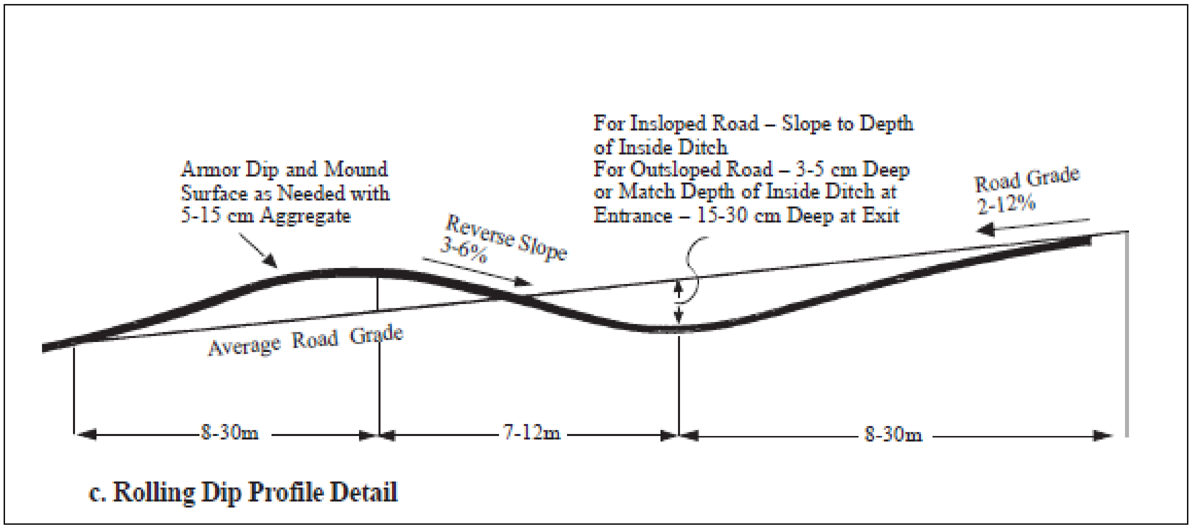

FIGURE 10 ROLLING DIP PROFILE. TAKEN FROM (KELLER AND SHERAR, 2003).

Use roadway cross-drain structures (e.g., rolling dips, culverts, and open-top culverts or flumes), to move water across the road from the inside ditch to the fill slope below the road (Keller and Sherar, 2003). Space the cross-drain structures close enough to remove all surface water (see Keller and Sherar, 2003, pg.55 Table 7.2, for recommended cross-drain spacing, or Copstead et al., 1989 pgs. 9-11, Tables 3 and 4). Surface cross-drains not only provide effective cross drainage, but also reduce the risk associated with plugged drain inlets, which can divert water over the road (Copstead et al., 1989). In areas of cut slope instability, frost-heave slough, or erodible ditches, properly located and constructed surface cross-drains can result in less erosion and disturbance to the surrounding watershed. Use a 3 to 5 percent road grade if creating an insloped road in areas with steep natural slopes, erodible soils, or on sharp turns. Provide cross drainage with culverts pipes or rolling dips and provide filter strip areas for infiltration and to trap sediment between drain outlets and waterways (Keller and Sherar, 2003).

In Table 3 Howell (1999) provides bio-engineering solutions to go with specific surface drainage treatments.

TABLE 3 SURFACE DRAIN OPTIONS. TAKEN FROM (HOWELL, 1999)

Structure	Bio-engineering	Main Sites	Advantages	Limitations
Unlined natural drainage system (rills, gullies).	Grasses in the rills, and grasses and other plants on the sides.	Existing landslide scars and debris masses.	A cheap form of surface drain. Allows for rapid drainage.	There is a risk of renewed erosion from heavy rain on weak materials.
Unlined earth ditches.	Grasses and other plants on sides and between feeder arms.	Slumping debris masses on slopes up to 1:1 (H:V) (45°), where the continued loss of material is not a problem.	A cheap form of surface drainage.	There is serious erosion hazard on steep main drains. Should be used only where further erosion is not a problem. Leakage into the ground may also occur.
Unbound rock-lined ditches.	Grasses between stones, and grasses and other plants on sides and between feeder arms.	Can be used at almost any site, however unstable, where the ground is firm enough to hold rock and water flow is not excessive.	A low-cost drain. Strong and flexible.	A membrane of polyethylene may be required to stop leakage back into the ground. Somewhat expensive to clean and maintain.
Bound cement masonry ditches.	Grasses and other plants on sides and between feeder arms.	For use on stable slopes with suitable material for good foundations.	A strong structure for heavy water discharge.	Relatively high cost. Very inflexible, high risk of cracking and failure due to subsidence and undermining.
Open gabion ditches	Grasses and other plants on sides and between feeder arms.	Can be used at almost any site, where the ground is firm enough to hold structure, and with heavy water discharge	A large and high cost type of drain. Very strong and flexible.	A member of polyethylene may be required to stop leakage back into the ground.

Culverts are commonly used as cross-drains for ditch relief and to pass water under a road along a natural drainage (Orr, 1998; Keller and Sherar, 2003). Culverts need to be properly sized, installed, and protected from erosion and scour. Culverts are most commonly made of concrete or corrugated metal, plastic pipe, and occasionally wood or masonry (Keller and Sherar, 2003). Culverts should have adequate flow capacity for the site, and the culvert size and shape should match the needs of the site (e.g., fish passage), and installation should be cost-effective.

There is a need to dissipate the energy of surface runoff as it is concentrated in natural and man-made channels. Armoring drain outlets to dissipate energy and prevent erosion can be done using rock, brush, logging slash, non-erosive soils, rock and/or vegetation (Keller and Sherar, 2003). If heavier water discharge is anticipated, check dams, interceptor drains, benches, and contour terracing can be effective countermeasures.

Useful Points

- Use closely spaced leadoff ditches to prevent accumulation of excessive water in roadway ditches (Keller and Sherar, 2003).
- Consider using a filter layer under or behind a selected treatment, such as rip rap or a gabion structure. A filter can be made of small gravel or a geotextile placed between a structure and the underlying soil (Keller and Sherar, 2003).

3.4.2 Sub-Surface Drainage

Sub-surface drains are used to drain shallow groundwater, less than 15 ft (5 meters) below the ground surface (GSPW, 2003). This includes water within the road surface, base and subgrade materials (Orr, 1998). Subsurface drains, including underdrains and french drains, do three things: 1) intercept water before it gets to the road, 2) lower the water table, and 3) remove excess free moisture (Orr, 1998). Sub-surface drains also collect seepage water from surface runoff and prevent it from raising the groundwater table (GSPW, 2003).

Underdrains are usually very narrow and have some form of pipe in them. They are installed by a special machine, and they may or may not be wrapped in geotextile (Orr, 1998). The geotextile filters out fine grained soils that would otherwise accumulate and plug the pipe. Two common ways to backfill the underdrain trench are placing a layer of geotextile in the trench and then placing pipe, followed by clean stone around the pipe. The other option is to fill the trench with washed concrete sand.

Trench drains, or French drains, are usually installed with a backhoe or excavator, are fairly wide compared to underdrains, and may or may not have a pipe at the bottom (Orr, 1998) (Figure 11). Using a pipe will greatly increase the life of the drain and help remove excess water. The trench can be lined with geotextile, then the pipe is placed, and then backfilled with clean stone ½ to ¼ inch in size.

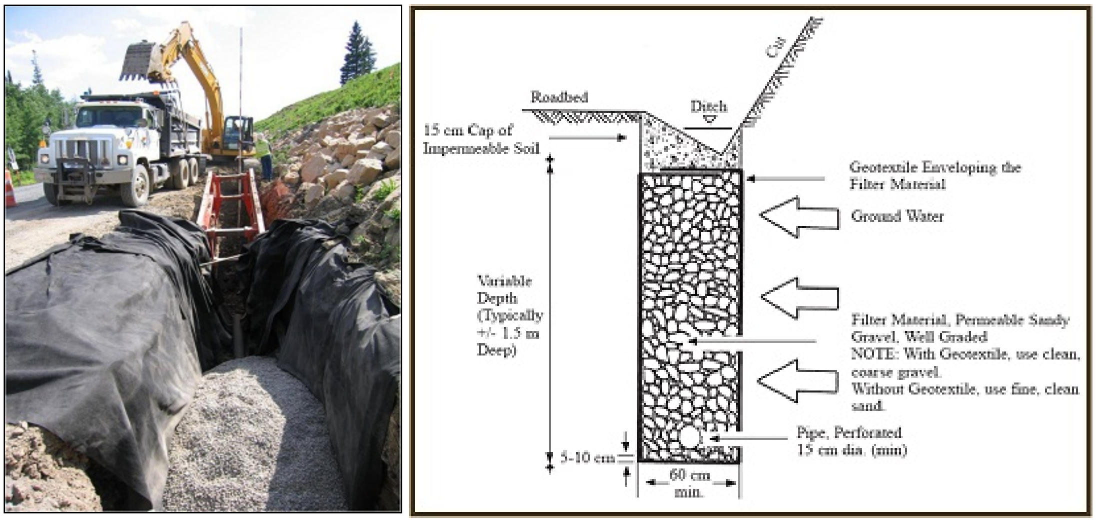

FIGURE 11 SUBSURFACE DRAINAGE. PHOTO AND DRAWING PROVIDED BY G. KELLER.

When installing subsurface drains always use filter protection such as a geotextile or properly sized sand or gravel. The purpose of the filter is to prevent migration of fine soil particles into underdrains, thereby allowing groundwater to drain from the soil without building up pressure. Even with a filter, subsurface drain pipes require periodic cleaning which can be done using a sewer cleaner (Orr, 1998). Deeper cleaning may be required if the pipe becomes completely plugged. Inlets and outlets should be cleared of debris and flow maintained, animal guards should be installed over them, and mowing crews should be careful to not crush or damage them.

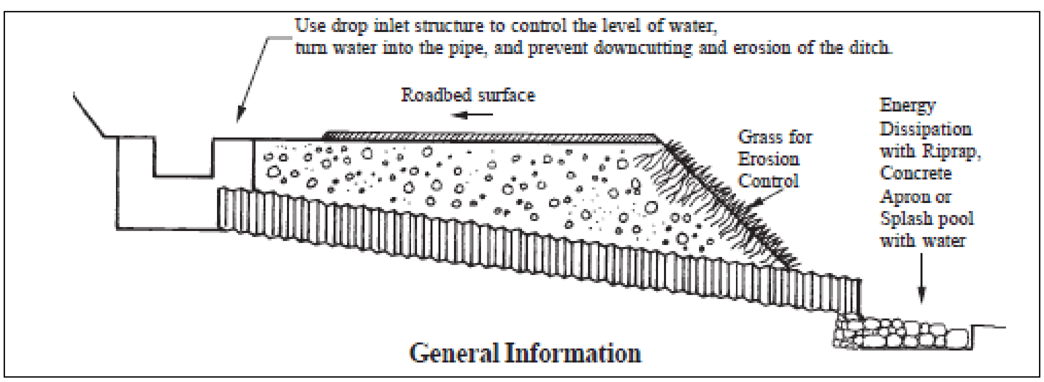

FIGURE 12 TYPICAL DROP INLET STRUCTURE WITH CULVERT CROSS-DRAIN. TAKEN FROM (KELLER AND SHERAR, 2003).

Cross-drain pipes are used to pass water under a roadway from a ditch on the cut-slope side of the road to the fill-slope side of the road. Cross-drain pipe should be placed at the bottom of the fill (Figure 12). The inlet should be protected with a drop inlet structure or catch basin, and the outlet should be armored against erosion (Keller and Sherar, 2003). Bedding and backfill materials should be high quality, granular, non-cohesive, less than 3 inches (7.5 cm) in diameter, well compacted and skewed 0 to 30 degrees perpendicular to the road (Keller and Sherar, 2003).

Horizontal drains have been used historically for landslide correction, but can also be used generally for slope stabilization. Horizontal drains are installed to reduce excess pore-water pressure, thereby increasing slope stability (Long, 1994) (Figure 13). Horizontal drains are drill-in drains that are inclined to match the subsurface geology. Horizontal drains have been shown to be a cost-effective alternative to major slope stabilization repairs, like buttressing, when subsurface water is involved in the mechanics of failure.

FIGURE 13 OUTLET OF HORIZONTAL SUBSURFACE SLOPE DRAINAGE. PHOTO PROVIDED BY M. LONG.

Consider having a geotechnical expert perform a subsurface investigation of the soil and rock characteristics in the design phase (Long, 1994). If economically feasible the following techniques are suggested—area reconnaissance, ground survey, subsurface exploration for rock and soil type and water concentration, permeability testing, and ground and surface water mapping. Test drains should be installed to confirm final drain locations. Following installation the site should be visited to ensure proper drainage is occurring (see Long, 1994, pgs. 788-796 for design calculations.)

Sub-surface drains are usually civil engineering structures and do not normally use bio-engineering measures (Howell, 1999); however, bio-engineering techniques can be used to strengthen the slope around the drain or outlet. In Table 3, Howell (1999) provides some examples of how this can be done.

TABLE 4 SUB-SURFACE DRAIN OPTIONS. ADAPTED FROM (HOWELL, 1999).

Structure	Bio-engineering	Main Sites	Advantages	Limitations
French drain* or underdrain with pipe.	Grasses and other plants along the sides and between feeder arms.	Almost any site where the ground is firm enough to hold the structure and the flow of water is not too heavy for this construction technique.	A relatively low-cost and common sub-surface type of drain. Very flexible. A good option for unstable slopes.	A membrane of permeable geotextile should be used. If the water flow is heavy, piping may occur under ground. The outlet should be monitored periodically.
Site-specific design of drain to pick up seepage water. An open ditch or a drain with a flexible gabion lining is preferred.	Planted grasses and other species along the sides.	Any slope with obvious seepage lines.	Specific drains can be designed for any site, for optimum water collection.	Great care is needed to ensure all seepage water is trapped by the drain. Movement in the slope may affect this.
Horizontal drains.	Plant grasses at the pipe outlet.	Moderate to deep-seated slides.	Can lower the groundwater level in the slope.	May or may not intercept and drain all of the groundwater.

*Perforated pipe of durable, high-grade black polyethylene, 6 in (150 mm) diameter with approximately 40 holes of 0.2 in (5 mm) per 3.28 ft (or meter) in drainage composed of medium aggregate. Drain can be made more resistant to disruption by building it in a wire gabion casing.

Additional Resources for Water Management and Drainage

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Keller, G. and J. Sherar. 2003. Low-Volume Roads Engineering—Best Management Practices Field Guide. USDA Forest Service, Office of International Programs and U.S. Agency for International Development, Washington, DC. (http://www.fs.fed.us/global/topic/welcome.htm#12).

Long, M. T. 1991. Horizontal Drains: An update on methods and procedures for exploration, design, and construction of drain systems, in Transportation Research Record No. 1291, Fifth International Conference on Low Volume Roads, May 19-23, 1991, Raleigh, North Carolina, Volume 2, pp. 166-172. Transportation Research Board, Washington, D.C.

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3. Erosion Control Techniques

This section summarizes literature and interview results on erosion control techniques. Erosion is the process of separating and transporting sediment by water, wind, gravity, or other geologic processes (Atkins et al., 2001). It is a natural process that can be accelerated by vegetation removal, topsoil disturbance or compaction, creation of steep slopes, etc. (Hyman and Vary, 1999). It has been reported that the logarithm of sediment yield (in kg/km^2) features a positive linear relationship with the logarithm of runoff depth (in mm), based on a field study of embankment slopes along the Qinghai–Tibet highway in China (Xu et al., 2005). The same study also confirmed that there is a positive linear relationship between the runoff depth and the product of rain intensity (in mm/h) and rain precipitation (in mm).

Three types of erosion are common: surface, rill and gulley (Orr, 1998) (Figure 14). Surface, or sheet, erosion occurs when rainfall dislodges soil on the surface of material, and the water and soil flow down a slope in sheets. Rill erosion occurs when the velocity of the water flow is great enough to dislodge soil in addition to that dislodged by rainfall. Typical rill erosion has small, narrow channels that form in banks and on slopes not protected from erosion. Gully erosion occurs when rill erosion combines and concentrates the flow of runoff into gullies. While soils erode differently, for most road materials it can be assumed that exposed soils will erode and cause sedimentation. Generally speaking, the flatter the slope the fewer erosion problems occur.

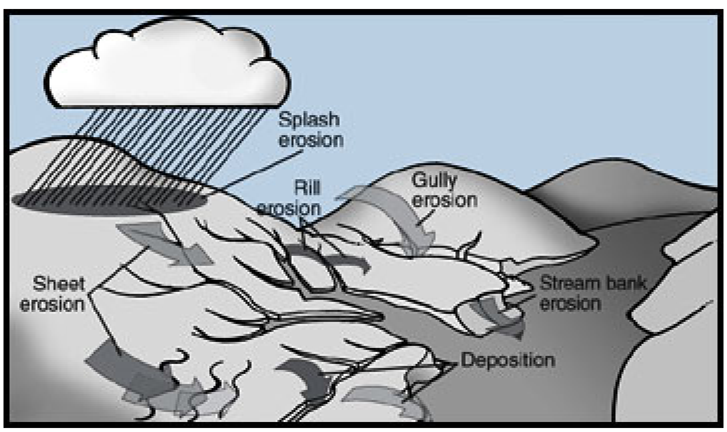

FIGURE 14 TYPES OF SOIL EROSION BY WATER. FROM WWW.EXTENSION.MISSOURI.EDU.

Erosion control is the proactive prevention of the loss of surface soil. Erosion control has been shown to have a higher level of effectiveness than sediment control—trying to catch the soil once it has eroded away (Atkins et al., 2001). The main goals of erosion control are to minimize potential erosion from disturbed sites and to then limit the transport of sediment from these sites.

For effective erosion control consider a systematic approach that includes design, construction, and maintenance considerations, various temporary and permanent erosion control methods, and new technologies (Johnson et al., 2003). It also takes into account government regulations and permitting requirements. It is important to consider erosion control in the design stage of a project, and a detailed erosion control plan should be developed before construction begins in order to identify the erosion problem areas and to devise effective and economical measures that can be implemented to prevent or, at the least, control erosion (SDDOT, 2004).

General practices that can aid in erosion control include confining operations to periods of dry weather, minimizing traffic through areas, and selecting equipment that will create less soil disturbance (Atkins et al., 2001).

Temporary erosion control measures should be used during construction, especially when the construction occurs in steep, rolling topography, where most of the drainage enters directly into adjacent water bodies or wetlands, or where the sub-soils are erosive. In selecting such measures, consider the following factors: purpose, grade or slope, amount of onsite water flow, length of time the treatment will be effective, ease of construction, maintenance requirements, and cost. Common devices for temporary erosion control include earth diversions and swales, erosion control blankets and stabilization mats, mulching and turf establishment, ditch checks, sandbag barriers, silt fences, soil berms, temporary slope stabilization and pipe downdrains, and triangle silt dikes. Note that temporary sediment control measures (biorolls, drainage swales, inlet protection, perimeter control, sediment basins, sediment traps, silt curtains, silt fences, standpipes, and treatment basins) are also needed during construction to prevent off-site damage from sediment flowing into lakes, rivers, streams, and adjacent lands.

After projects are completed and vegetation is established, permanent measures should be implemented for erosion control purposes. Common devices for permanent erosion control include ditches and liners, detention ponds, riprap, runoff spreaders, soil bioengineering, and turf establishment. It has been reported that engineering measures (concrete prefabricated panes, LAttice, or runoff interception and drainage) can be quickly effective in reducing runoff and soil loss from road sideslopes, while re-vegetation has great potential once the vegetation cover is well established. The findings were based on a field evaluation of various erosion control measures along the Qinghai–Tibet highway in China—an area that features “high altitude, low summer rainfall and permanently poor vegetation cover.” A combined measure (LAttice plus Common Seedling) was found to be most effective in both short- term and long- term erosion control (Xu et al., 2005).

Many erosion control methods are frequently used alone or in conjunction with soil stabilization. In this section some examples of cost-effective and sustainable erosion control treatments most frequently used in conjunction with soil stabilization techniques will be presented.

<u>Useful Points</u>

- Consider erosion control/stabilization work as quickly and early in the project as you can.(J. Haag, personal communication, April 19, 2011)
- When working on slopes steeper than 3:1 (H:V), consider using soil stabilization blankets that can be pinned down or used in conjunction with mulch. It seems to save time and money in the long run. (B. Johnson, personal communication, April 18, 2011)

- Consider putting in place interim erosion control measures during seasonal shutdowns (Keller and Sherar, 2003).

Additional Resources for Erosion Control

American Association of State Highway and Transportation Officials (ASSHTO) (http://transportation.org/)

Atkins, R.J., M.R. Leslie, D.F. Polster, M.P. Wise, and R.H. Wong. 2001. Best Management Practices Handbook: Hillslope Restoration in British Columbia. B.C. Ministry of Forests. Resource Tenures and Engineering Branch. Victoria, B.C. Watershed Restoration Program. (http://www.ieca.org/resources/federalstatewebsites.asp)

CDM, Inc. 2004. Erosion and Sediment Control Best Management Practices: Report. Revised May 2004 (http://www.mdt.state.mt.us/research/projects/env/erosion.shtml).

California Department of Transportation (Caltrans). 2011. Stormwater and Water Pollution Control. Caltrans Division of Construction (http://www.dot.ca.gov/hq/construc/stormwater/stormwater1.htm).

Environmental Protection Agency (EPA). 2008. National Pollutant Discharge Elimination System: National Menu of Stormwater Best Management Practices. Stormwater Best Management Practices (http://cfpub1.epa.gov/npdes/stormwater/menuofbmps/index.cfm).

Federal Highway Administration (FHWA). 1995. *Best Management Practices for Erosion and Sediment Control*. FHWA-SLP-94-005. Federal Highway Administration, Sterling, VA.

International Erosion Control Association (IECA) (www.ieca.org).

Johnson, A. Moffatt and E. Slattery. 2003. *Erosion Control Handbook for Local Roads*. Minnesota Local Road Research Board (LRRB) Manual Number 2003-08.

Local Soil and Water Conservation Districts.

Natural Resources Conservation Service (NRCS) (www.nrcs.usda.gov).

Orr, D. 1998 (Updated 2003). Roadway and roadside drainage. CLRP Publication No. 98-5. Ithaca, NY: Cornell Local Roads Program and New York LTAP Center, Ithaca. NY. 104p. (http://www.clrp.cornell.edu/workshops/pdf/drainage_08_reprint-web.pdf).

South Dakota Department of Transportation (SDDOT). 2004. “Roadside Development.” *Road Design Manual* (http://www.sddot.com/pe/roaddesign/docs/rdmanual/rdmch14.pdf).

3.1. Grass Seeding

Seeding with grasses is one of the most common methods used to protect soils, and in many states and countries it is a standard specification. Grass is very effective at covering soil and protecting soil from wind and water erosion (Shah, 2008). When seeding with grasses it is ideal to use a mixture of creeping and clumping types. Creeping grasses form a continuous root system, or mat. Clumping grasses leave gaps between the plants that can be vulnerable to erosion, but they can grow large with deep roots (Hearn and Weeks, 1997). Seed mixtures normally include grasses that germinate rapidly—such as rye or annual grass—to provide immediate short-term protection, and slower-growing perennial grasses that take more time to establish but that provide long-term protection. The optimum seed mix depends on the soil, site, and climatic conditions (Schor and Gray, 2007). It is also very important to consider use native seed varieties at each site. With the help of a botanist, horticulturalist, ecologist or your local conservation agency the appropriate seed varieties can be chosen for each site.

To ensure the highest success rate always scarify, or loosen, the surface soil (Howell, 1999). Once the seed has been sown, apply mulch, netting, or sheeting to protect the seeds and to keep the moisture in. If grass seeds are sown on steep angled slopes (greater than 30 degrees) consider netting the mulch (Howell, 1999). Maintenance may include protection from grazing animals, weeding and possible thinning of shrubs if included in the seed mix. The timing of planting is critical. For example, seeds should be sown in the late fall, winter or spring (Sotir and Gray, 1992). In temperate zones watering may be necessary initially to ensure establishment of the seeds if they are sown at other times. At each site, seeds should be matched to the site conditions.

Grasses can be established by manual or hand seeding, hydro-seeding, or with turf or sod (Hearn and Weeks, 1997). Use of turf and/or sod is not discussed in this section because of the high relative cost compared to hand- or hydro-seeding. It is sometimes possible to get local sod farms to grow native grass sod (Dollhopf et al., 2008). If this is the best treatment option for your site, contact local sod farms directly to check on availability of native grass sod or the option to grow a test plot.

Call out box:

> *"A low-cost technique that is highly effective and underutilized is native-grass-sod-lined ditches. Several companies are developing native grass sod in rolls up to 4 feet wide. It can easily be installed in ditches or in areas of concentrated flow around culverts, bridge abutments, etc. Sod is 'expensive' compared to seed, but it is inexpensive compared to fabric-lined channels and much more effective."(S. Jennings, personal communication, April 12, 2011)*

3.1.1. Hand Seeding

Hand seeding is accomplished by throwing seed by hand directly onto a site. The use of grass seed allows for easy vegetative coverage of large areas (Howell, 1999). Grass seeding is often used in conjunction with mulching and netting to aid in grass establishment. Initially the grass armors against erosion and later, as roots develop, it also acts to reinforce shallow soil (Howell, 1999). Grass seed should be sown on soils that drain well.

3.1.2. Hydro-seeding

Hydro-seeding utilizes high pressure pumps to apply a slurry of water, wood fiber mulch, seed and fertilizer onto a slope (NRCS, 2011) (Figure 15). Hydro-mulching is the application of a slurry of water, wood fiber mulch and often a tackifier. The terms hydro-seeding and hydro-mulching are often used interchangeably. The benefits are the same as hand seeding; initially the grass armors the soil against erosion and then once the roots are established it reinforces shallow soil. The benefit of hydro-seeding is that it can be used on just about any site (Howell, 1999) and has a high success rate (Hearn and Weeks, 1997). Often the limiting factor is the length of the hose used for spraying the hydro-seed, or how far the pumps can spray the materials (approximately 300 feet (100 meters) or less) (Howell, 1999). Grass seed should be sown on soils that drain well.

FIGURE 15 HYDRO SEEDING OF A SLOPE. PHOTO PROVIDED BY M. LONG.

3.1.3. Grass Slips

Grass slips, or small clumps of grass pulled from a larger mass, can be planted horizontally, vertically, diagonally, in a random pattern or for full coverage (Hearn and Weeks, 1997). The varying planting patterns can help create contours to the slope and channel or slow the surface flow of water depending on your needs (Hearn and Weeks, 1997).

3.1.4. Deeply Rooted Grasses

Another category of grasses that have been used to stabilize structures, including earth embankments and road cuts, water and drainage ways, and at building sites are deeply rooted grasses like Vetiver (Grimshaw and Faiz, 1995). Vetiver grass (*Vetiveria zizanioides*) is a densely tufted perennial grass that grows in large clumps with very branched and spongy root mass (World Bank, 1990). Vetiver grass has been proven to aid in soil and moisture conservation and has a wide geographic and ecological area of adoption. Vetiver has been shown to decrease water runoff by up to 57 percent and reduce soil loss by more than 80 percent as compared to stone barriers, other vegetation and bare ground (Rao et al., 1992). Over time, as the hedge grows larger and the vegetation becomes denser, these numbers further improve (Rao et al., 1993).

Vetiver grass has not been observed to be an invasive species; generally it produces no seeds but if seeds are produced they tend to be sterile (Grimshaw and Faiz, 1995). Vetiver hedges can take two months to four years to establish. Vetiver can grow in a wide range of soil types and pH levels. Vetiver will not survive prolonged exposure to subzero temperatures typically seen in the continental Northern Hemisphere.

Vetiver grass can be planted horizontally across slopes to create a bench, slow the migration of water and trap sediment, in gullies to slow water flow, or to stabilize soil around engineered structures (Grimshaw and Faiz, 1995). Vetiver has been used for slope stabilization in Bangladesh, Brazil, China, and Thailand for decades. Vetiver is an inexpensive slope stabilization tool that improves performance with time.

Useful Points

- When there isn't a mixture of shallow and deep-rooted vegetation you can end up with the sod looking like a bunch of carpet at the bottom of the slope. Grass and legume seed roots only stabilizes the surface; you need woody species (or plants with deeper) roots to stabilize at depth. (D. Polster, personal communication, April 29, 2011)
- You can never put too much grass seed down.(D. Orr, personal communication, May 3, 2011)

Additional Resources for Grass Seeding

Andreu, V., H. Khuder, S. B. Mickovski, I. A. Spanos, J. E. Norris, L. K. A. Dorren, B. C. Nicoll, A. Achim, J. L. Rubio, L. Jouneau, and F. Berger. 2008. "Ecotechnological Solutions for Unstable Slopes: Ground Bio- and Eco-Engineering Techniques and Strategies." In *Slope Stability and Erosion Control: Ecotechnological Solutions*. Norris, J. E., A. Stokes, S. B. Mickovski, E. Cammeraat, R. Van Beek, B. C. Nicoll, A. Achim (eds). Dordrecht, The Netherlands: Springer.

Caltrans. 2003. Statewide Stormwater Quality Practice Guidelines. CTSW-RT-02-009.

FHWA. 1995. *Best Management Practices for Erosion and Sediment Control*. FHWA-SLP-94-005. Federal Highway Administration, Sterling, VA.

Grimshaw, R.G. and A. Faiz. 1995. "Vetiver Grass: Application for Stabilization of Structures*." In Proceedings of the Sixth International Conference on Low-Volume Roads.* Minneapolis, MN, June 25-29.

Goldman, S., K. Jackson and T.A. Bursztynsky. 1986. *Erosion and Sediment Control Handbook*. New York: McGraw Hill.

Hearn, G. J. and R. W. Weeks. 1997. Principles of low cost road engineering in mountainous regions, with special reference to Nepal, Himalaya. Ed. C. J. Lawrence. Transportation Research Library Overseas Road Note 16. Berkshire, United Kingdom.

Howell, J. 1999. *Roadside Bio-engineering: Site Handbook*. His Majesty's Government of Nepal. Ganabahal, Kathmandu.

Natural Resources Conservation Service (NRCS). 2011.

(http://www.wy.nrcs.usda.gov/technical/ewpfactsheets/hydroseed.html)

Shah, B. H. 2008. *Field Manual on Slope Stabilization*. United Nations Development Program, Pakistan. September.

World Bank. 1990. Vetiver grass — The Hedge Against Erosion, 3rd ed. The World Bank, Washington, DC.

3.2. Mulch and Compost

Mulch is used as a temporary measure to help with the establishment and growth of vegetation, but mulch alone will not protect a slope from eroding or establish vegetative cover (Howell, 1999). Mulch can be organic—such as compost, grass clippings, straw, bark, or leaf litter, or inorganic—such as stone (Sotir and Gray, 2011). Mulch can be applied in various ways, including spreading it over the entire slope, over sown seeds, or placed around individual plants (Howell, 1999). Mulch helps to keep soil cool and moist and enhances growth and early establishment of shrub and tree seedlings (Howell, 1999). A good option for armoring sown grass seed is to mulch the entire site with chopped plant material or brushwood cleared from the site (Howell, 1999).

Mulching is suitable for any site with slopes up to 45 degrees and with well-draining materials (Howell, 1999). If you are using mulch on slopes greater than 45 degrees, erosion-control netting or blankets may be necessary to keep the material in place. Mulching is a temporary measure and therefore no maintenance is required (Howell, 1999).

Compost is decomposed or aged organic matter. Compost can be used as mulch or added to the soil as an amendment. Compost can be used to create a berm or dike to control erosion (EPA, 2008). Compost berms can be placed perpendicular to sheet flow and are generally trapezoidal in cross section. Compost filter berms are generally placed along the perimeter of a site or at intervals on a slope, reducing the speed of sheet flow and retaining sediment and pollutants. Compost berms can be used in place of silt fences, and do not need to be removed from the site once work is completed. Compost can also be used to fill wattles or fiber rolls, check dams, and/or be vegetated. The quality of the compost is important to consider (see the National Menu of Stormwater Best Management Practices (EPA, 2008) for additional information).

Research has shown that compost can improve vegetation establishment and density. Test sections in arid, southwest Montana monitored by Ament et al. (2011) demonstrated that 0.5–1 inch of compost was sufficient to establish 16–25 percent vegetation density at a cost of $16,000–$33,000 (using a blower truck—i.e., hydro-mulch). The same study demonstrated coconut fiber and thin plastic netting were more effective at retaining compost than soil tackifiers. Field studies in Washington (in both the wetter western and drier eastern parts of the state) also showed compost improved vegetation establishment and density while reducing weeds and erosion (Lewis et al., 2001). The researcher found better results when the compost was incorporated (raked) into the soil, including enhanced grass growth, increased soil workability, and a more diverse grass community.

Call out box:

> *"Compost blanket application of 1-3 cm is very environmentally friendly in terms of reusing waste, aids in erosion control and vegetation establishment. The costs associated with these treatments range from low to high depending on the site-specific characteristics such as procurement cost, transportation cost, method of application, etc. Compost can be considered high cost compared to leaving bare soil in an eroded condition, but I take the position that bare and erosive transportation corridors are unacceptable." (S. Jennings, personal communication, April 12, 2011)*

Additional Resources for Mulch and Compost

Caltrans. 2003. Statewide Stormwater Quality Practice Guidelines. CTSW-RT-02-009.

EPA. 2008. National Pollutant Discharge Elimination System: National Menu of Stormwater Best Management Practices. Stormwater Best Management Practices (http://cfpub1.epa.gov/npdes/stormwater/menuofbmps/index.cfm).

FHWA. 1995. *Best Management Practices for Erosion and Sediment Control*. FHWA-SLP-94-005. Federal Highway Administration, Sterling, VA.

Howell, J. 1999. *Roadside Bio-engineering: Site Handbook*. His Majesty's Government of Nepal. Ganabahal, Kathmandu.

3.3. Erosion-Control Geotextiles

Erosion-control geotextiles, including blankets and mats, are generic terms given to woven or bonded fabrics that are placed directly on soil for temporary erosion control (TIRRS, 2001; EPA, 2008). Erosion control blankets and mats protect the surface from raindrop impact (TIRRS, 2001), wind and stormwater erosion, and they allow vegetation to grow (EPA, 2008). Geotextiles can be biodegradable, such as jute, wood fiber, paper or cotton, or synthetic and made of plastic.

Geotextiles can be used to stabilize the flow of water in channels or swales, to protect seedlings or vegetation, to protect exposed soil, or to separate soil from other slope stabilization treatments such as riprap (EPA, 2008). Lay the geotextiles so it has continuous contact with the soil surface or erosion can occur. Geotextiles should also be pinned in place. This can be done with stakes made of wood, metal, corn plastic, or live cuttings (NRCS, 2007).

Plastic geotextiles can trap and harm small animals (Figure 16), even if photodegradable, therefore consider more easily biodegradable fiber materials (TIRRS, 2001).

FIGURE 16 EASTERN RACER (*COLUBER CONSTRICTOR*) CAUGHT IN EROSION NETTING IN HIGHWAY RIGHT OF WAY, MONTANA. PHOTO PROVIDED BY T. ALLEN.

Additional Resources forErosion-Control Geotextiles

Caltrans. 2003. Statewide Stormwater Quality Practice Guidelines. CTSW-RT-02-009.

EPA. 2008. National Pollutant Discharge Elimination System: National Menu of Stormwater Best Management Practices. Stormwater Best Management Practices (http://cfpub1.epa.gov/npdes/stormwater/menuofbmps/index.cfm).

FHWA. 1995. *Best Management Practices for Erosion and Sediment Control*. FHWA-SLP-94-005. Federal Highway Administration, Sterling, VA.

NRCS. 2007. Temporary Erosion Control Around the Home Following a Fire: Jute Netting. NRCS Fact Sheet. California FS-54 (ftp://ftp-fc.sc.egov.usda.gov/CA/programs/EWP/2007/FS54.pdf).

Orr, D. 1998 (Updated 2003). Roadway and roadside drainage. CLRP Publication No. 98-5. Ithaca, NY: Cornell Local Roads Program and New York LTAP Center, Ithaca. NY. 104p. (http://www.clrp.cornell.edu/workshops/pdf/drainage_08_reprint-web.pdf)

Tahoe Interagency Roadway Runoff Subcommittee (TIRRS). 2001. Planning Guidance for Implementing Permanent Storm Water Best Management Practices in the Lake Tahoe Basin, Chapter 6. Slope Stabilization Techniques.

3.3.1. Jute and other Biodegradable Netting

Jute is a rough fiber that is woven to create an organic and biodegradable net. Jute netting protects the soil surface, armoring against erosion and catching small debris, and allows seeds to hold and germinate, improves the microclimate on the slope surface by holding moisture and increasing infiltration. As it decays it acts as a mulch for the growing vegetation (Howell, 1999) (Figure 17). Any use of jute netting is a temporary measure designed to enhance vegetation establishment.

It is sometimes possible to have netting made locally from jute grown in the region (Hearn and Weeks, 1997). In Brazil, low-cost bio-textiles made from native palms for use as biodegradable erosion control mats were proven to be successful at reducing soil loss while maintaining soil moisture and anchoring seeds. Other common materials used are coir fiber, excelsior mats and straw. Coir is made from the husks of coconuts. Coir can be woven into mesh or net, or made into blankets (Coir Institute, 2011). Excelsior mats are composed of dried, shredded wood and covered with a fine paper net (Goldman et al., 1986).

FIGURE 17 BIODEGRADABLE NETTING WITH PLANTED VEGETATION, FLORAS CREEK, OREGON. PHOTO PROVIDED BY M. LONG.

Standard netting is used on steep, hard slopes where conditions are too harsh for vegetation to establish itself without assistance (Howell, 1999). Normal use is on slope angles of 45 to 60 degrees (Howell, 1999). Netting is best used on well-drained materials that are too hard to allow vegetation to become established unaided, or on slopes exposed to hot sun and where extreme drought would otherwise be a problem (Howell, 1999). It should not be used on soft or poorly drained materials, and never used on materials with a high rate of shallow slumping (Howell, 1999). Jute netting should be anchored in place with pins or staples (NRCS, 2007).

Jute netting can be easily integrated with soil bioengineering by planting grass slips through the holes in the netting in a random pattern fairly close together, or, if deeper reinforcement is required, the surface can be seeded with shrubs or small trees before the netting is laid down (Howell, 1999).

No maintenance is necessary for the jute netting; it will rot away over time (Howell, 1999). Jute netting does not protect a surface, if used alone, and has been found to last for two or three seasons of rains before it degrades (Howell, 1999), but may last longer in less extreme climates.

Additional Resources for Jute and other Biodegradable Netting

Goldman, S., K. Jackson and T. A. Bursztynsky. 1986. *Erosion and Sediment Control Handbook*. New York: McGraw Hill.

Howell, J. 1999. Roadside Bio-engineering: Site Handbook. His Majesty's Government of Nepal. Ganabahal, Kathmandu.

NRCS. 2007. Temporary Erosion Control Around the Home Following a Fire: Jute Netting. NRCS Fact Sheet. California FS-54 (ftp://ftp-fc.sc.egov.usda.gov/CA/programs/EWP/2007/FS54.pdf).

3.3.2. Other Netting

There are many other erosion-control netting options. Many of these are made of non-biodegradable materials and therefore persist in the environment. Use of these products is not as sustainable a practice as using biodegradable products, and additional time for clean-up of the product once it has served its purpose may be necessary. Note that non-biodegradable netting is also used to reinforce sod, encase wattles, and for many other purposes.

3.3.3. Rock Blankets or Riprap

Rock blankets are created by placing a layer of loose rock or aggregate over an erodible soil surface (TIRRS, 2001) (Figure 18). Rock blankets can be used with a variety of other techniques, such as seeding or planting of cuttings, or between other erosion-control measures to break up a slope. Ideally rock would be available locally or on site and would match the surrounding landscape. Rock blankets are best used in areas where revegetation is difficult, and is often used on steep slopes above retaining walls. This technique should not be used on slopes greater than 2:1 (EPA, 2008).

FIGURE 18 RIPRAP, OR ROCK BLANKET. PHOTO PROVIDED BY G. KELLER.

To install a rock blanket excavate out the loose material or clear the slope if necessary, if seeding, then broadcast the seed (TIRRS, 2001). Then place rock or aggregate. Geotextiles can be placed over the soil before the rock is placed to reduce soil erosion. Rock joint planting can also be used to further stabilize the slope.

Rock blankets should not be used where they would pose a public safety hazard. Rock blankets should require little to no maintenance. Follow-up maintenance may include periodic inspection is to see if rocks have dislodged (TIRRS, 2001).

Additional Resources Rock Blankets and Riprap

EPA. 2008. National Pollutant Discharge Elimination System: National Menu of Stormwater Best Management Practices. Stormwater Best Management Practices (http://cfpub1.epa.gov/npdes/stormwater/menuofbmps/index.cfm).

Goldman, S., K. Jackson and T. A. Bursztynsky. 1986. *Erosion and Sediment Control Handbook*. New York: McGraw Hill.

Orr, D. 1998 (Updated 2003). Roadway and roadside drainage. CLRP Publication No. 98-5. Ithaca, NY: Cornell Local Roads Program and New York LTAP Center, Ithaca. NY. 104p. (http://www.clrp.cornell.edu/workshops/pdf/drainage_08_reprint-web.pdf).

TIRRS. 2001. Planning Guidance for Implementing Permanent Storm Water Best Management Practices in the Lake Tahoe Basin, Chapter 6. Slope Stabilization Techniques.

3.4. Check Dams

Check dams are a physical construction that prevents down-cutting of water in gullies (Howell, 1999). Check dams work by reducing the gradient of a gully by providing periodic steps that trap the water, and safely discharge the water at a lower velocity to the next step. By trapping sediment on their upstream side, check dams create a stepped channel bed profile, thus reducing velocities and channel down-cutting, and ultimately halting the progression of erosion (Hearn and Weeks, 1997). Check dams can be used in any type of gully or rill that is in danger of enlarging or on any slope where there is a danger of water scour (Howell, 1999). There are many ways to construct check dams including loose stone, gabion baskets, concrete, stone masonry, live brush wood, palisades, and vegetated poles (Shah, 2008) (Figure 19, 20 and 21). The selection of materials to be used may be based on what is available on site, and whether vegetation is desired as a permanent measure.

FIGURE 19 WOODEN CHECK DAMS WITH ROCK REINFORCEMENT. PHOTO PROVIDED BY D. ORR.

It is important to consider the location, spacing, and size of the check dams. When selecting a location for a check dam you want to achieve the maximum effect with the minimum amount of construction (Howell, 1999). Check dams are normally placed where they can protect weak parts of a gully from scour, utilizing natural topography such as natural nick points, debris piles or foundations, or bedrock anchor points. In situations where the gully is too steep or irregular, the check dams should be placed where a stable cross-section is available with strong-points for keying-in the structure (Hearn and Weeks, 1997).

FIGURE 20 STONE CHECK DAMS. PHOTO PROVIDED BY D. ORR.

FIGURE 21 ROCK PILE CHECK DAM. PHOTO PROVIDED BY D. ORR.

3.4.1. Live Check Dams or Vegetated Pole Check Dams

To create live or vegetated pole check dams, large woody cuttings are planted across a gully, usually following the contour, forming a strong barrier and trapping material moving down-slope (Howell, 1999). Over time a small step will form in the gully floor.

This technique can be used in gullies with slopes up to 2:1 (45 degrees) (Howell, 1999). This technique should not be used in areas with high rates of slumping. Spacing of live check dams varies with slope steepness and profile, normally 9-16 feet (3-5 meters) apart is sufficient. Within the live check dam, spacing of the cuttings can be very close (less than an inch apart), but on gentle slopes spacing can be wider. Planting a double, offset line of cuttings will make a much stronger live check dam. Generally little to no maintenance is needed with the exception of replacing failed sections or thinning of established vegetation (Howell, 1999).

Useful Points

- The size of the check dams may need to be increased down-slope to accommodate additional water drainage from the watershed.(S. Jennings, personal communication, April, 12, 2011)

Additional Resources Check Dams

Caltrans. 2003. Statewide Stormwater Quality Practice Guidelines. CTSW-RT-02-009.

FHWA. 1995. *Best Management Practices for Erosion and Sediment Control*. FHWA-SLP-94-005. Federal Highway Administration, Sterling, VA.

Goldman, S., K. Jackson and T. A. Bursztynsky. 1986. *Erosion and Sediment Control Handbook*. New York: McGraw Hill.

Grimshaw, R. G. and A. Faiz. 1995. "Vetiver Grass: Application for Stabilization of Structures*." In Proceedings of the Sixth International Conference on Low-Volume Roads.* Minneapolis, MN, June 25-29.

Hearn, G. J. and R. W. Weeks. 1997. Principles of low cost road engineering in mountainous regions, with special reference to Nepal, Himalaya. Ed. C. J. Lawrence. Transportation Research Library Overseas Road Note 16. Berkshire, United Kingdom.

Howell, J. 1999. *Roadside Bio-engineering: Site Handbook*. His Majesty's Government of Nepal. Ganabahal, Kathmandu.

Shah, B. H. 2008. *Field Manual of Slope Stabilization*. United Nations Development Program, Pakistan. September.

3.5. Wattles or Fiber Rolls

Wattles, or fiber rolls, are tube-shaped erosion control devices that are filled with straw, rice husks, flax, coconut fiber, or composting material that is wrapped in netting (Caltrans, 2003; SWS, 2008). The netting can be made of biodegradable materials such as jute, coir or burlap, or non-biodegradable polypropylene (SWS, 2008). Live fascines—bundles of live plant material planted partially in the ground—can also be used and serve the same purpose. Wattles can be made to varying diameters and lengths (Etra, 2011). Wattles are used to break up slopes and reduce water velocity on the slope, protecting against sheet flow and concentrated water flow (Caltrans, 2003; SWS, 2008). Wattles also help to reduce sediment loss by trapping water long enough for the sediment to settle out (SQH, 2000).

Wattles should be used immediately after grading and prior to seeding or mulching (SWS, 2008). To install, dig a trench approximately half the diameter of the roll, place the roll in the trench, and use wooden stakes (SQH, 2000) or live cuttings to anchor the roll. Anchors should be placed 2–3 feet apart

(SQH, 2000). Maintenance may include removing sediment built up on the upslope side, re-anchoring, or repairing or replacing split, torn, or unraveling rolls (Caltrans, 2003; SWS, 2008).

Additional Resources *for Wattles and Fiber Rolls*

California Stormwater BMP Handbook. 2003. (www.cabmphandbooks.com/Documents/Construction/SE-5.pdf)

Caltrans. 2003. Statewide Stormwater Quality Practice Guidelines. CTSW-RT-02-009.

Storm Water Services, City of Springfield, Missouri (SWS). 2008. Runoff Management, Fiber rolls/wattles (RM-10) (www.sprfieldmo.gov/stormwater/pdfs/BMP%20PDFs/RM%20BMPs/FIBER%20ROLLS-WATTLES.pdf).

Etra, J. 2011. "Fiber roles or Sediment Logs: the rest of the story." *Environmental Connection* 5(2):20–21.

Stormwater Quality Handbooks (SQH). 2000. *Construction Site Best Management Practices (BMPs) Manual*, State of California Department of Transportation (Caltrans), November.

3.6. Straw Bales Barriers

A straw bale barrier is a linear sediment barrier consisting of straw bales designed to intercept and slow the flow of water and filter sediment-laden sheet flow runoff (Caltrans, 2003). Straw bale barriers allow sediment to settle from runoff before water leaves a disturbed area (Caltrans, 2003). Straw bales are readily available in most locations. One disadvantage of straw bale barriers is they are bulky and heavy when wet (Caltrans, 2003).

Straw bale barriers are a short-term erosion control measure that are best used at the base of a slope or down slope of disturbed soil (Caltrans, 2003). Straw bale barriers can be placed around stockpiles, such as a stockpile of topsoil that will be used again later in the project, and can be used to protect drain inlets and ditch lines (Caltrans, 2003).

Maintenance of straw bale barriers may include replacing damaged straw bales, repair of washouts, or removal of accumulated sediment behind the straw bale. The straw bales should be removed and accumulated sediment should be redistributed once work is complete (Caltrans, 2003).

Additional Resources *for Straw Bale Barriers*

Caltrans. 2003. Statewide Stormwater Quality Practice Guidelines. CTSW-RT-02-009.

FHWA. 1995. *Best Management Practices for Erosion and Sediment Control*. FHWA-SLP-94-005. Federal Highway Administration, Sterling, VA.

Goldman, S., K. Jackson and T. A. Bursztynsky. 1986. *Erosion and Sediment Control Handbook*. New York: McGraw Hill.

3.7. Silt Fences

Silt fences are a linear barrier of permeable fabric designed to intercept and slow the flow of sediment-laden runoff (Caltrans, 2003). Silt fences allow sediment to settle from the runoff before water leaves the site (Caltrans, 2003). Silt fences are difficult to construct and maintain and their use is for short-term maintenance only (Caltrans, 2003). While silt fences are widely used, they are often not installed correctly, not maintained, or not removed once the work is complete. Additionally, silt fences are made of non-biodegradable materials.

Erosion control professionals have recently called for more stringent specifications to be placed on silt fence installation techniques (Sprague and Carpenter, 2011). Currently two techniques—static slicing and trench-based installations—can both be used to achieve maximum silt fence performance. Static slicing requires the insertion of a narrow custom-shaped blade into the ground, while silt fence fabric is simultaneously pulled into the opening that is created. Four passes of a tractor tire are used to achieve appropriate compaction. Static slicing was pioneered by Iowa DOT in the 1990's and has been adopted by other mid-western states. Trench-based installation of silt fences requires a trench be dug and cleaned out, fabric placed in the trench, and then the fabric is buried and the trench compacted.

Additional Resources *for Silt Fences*

Caltrans. 2003. Statewide Stormwater Quality Practice Guidelines. CTSW-RT-02-009.

FHWA. 1995. *Best Management Practices for Erosion and Sediment Control*. FHWA-SLP-94-005. Federal Highway Administration, Sterling, VA.

Goldman, S., K. Jackson and T. A. Bursztynsky. 1986. *Erosion and Sediment Control Handbook*. New York: McGraw Hill.

Sprague, J. and T. Carpenter. 2011. "Silt Fence Installation Efficacy: Definitive Research Call for Toughening Specifications and Introducing New Technology." International Erosion Control Association (www.ieca.org/resources/documents/Article/ArticleSFInstallationEfficacy.asp).

3.8. Chemical Soil Stabilizers

Chemical stabilization is an effective tool for temporary stabilization of surface soil. Vinyl, asphalt, rubber, anionic and nonionic polyacrylamide (PAM), biopolymers, etc. are examples of chemical stabilizers that can be sprayed onto an exposed soil surface to hold the soil in place and minimize erosion from runoff and wind (EPA, 2008). Chemical soil stabilizers can be used in areas where vegetation cannot be established, or on rough grading, cut and fill areas, temporary stockpiles, temporary or permanent seeding, or for site winterization, dormant seeding in the fall, staging areas, or other disturbed soils (IUM, 2011).

When asked to provide an example of an underutilized tool, technique or method of erosion control, Skip Ragsdale (personal communication, April 18, 2011) said:

> *Anionic polyacrylamide. There was a new Interstate project in which the sculpted road was going to sit unpaved from November through May. Usually they put three inches of gravel down for erosion control (estimated cost $400,000) but instead they sprayed anionic PAM (cost $3500) and they had no erosion issues at the site. [PAM is] very underutilized for short-term bare soil*

treatment.

PAM creates an electrochemical reaction that draws fine particles close together, making larger particles that are more resistant to erosion and large enough to settle from suspension (Cohn, 2001). PAM has been used historically in agriculture to reduce soil loss in irrigation channels. When used for slope stabilization PAM should only be used where sheet flow is present. PAM should not be used on slopes greater than 4:1 unless additional erosion-control measures such as mulch, geotextiles or mats are used (IUM, 2011). PAM should not be applied to frozen soil or where ice is present. PAM works best in soils with significant amounts of fine silts, clays, and colloidal particles. Over-application can reduce soil infiltration rates. PAM breaks down over time and areas of application should be inspected regularly for signs of erosion. When applied to a soil surface for erosion control, PAM has been shown to reduce run-off volumes by 10–15 percent, further enhancing seed germination from additional water and aeration of soil.

Biopolymers that chemically stabilize soil include chitosan, cellulose and starch xanthates, and cellulose microfibrils (Orts et al., 2000). Chitosan, a naturally occurring poly saccharide is derived from chitin in shellfish. Chitosan's ability to work is dependent on the pH of the water. Tests have shown optimal flocculation of suspended river silt and kaolinite at pH 7–7.5 (Divakaran and Sivasankara Pillai, 2002). Cellulose and xanthates have been used historically as soil stabilizers. Cotton microfibrils are a new product that shows potential for soil stabilization.

The EPA currently allows the use of PAM in water treatment. Some countries including Japan, Germany and The Netherlands have banned or highly restricted its use in drinking water treatment. The EPA permits chitosan use in drinking water, waste water and industrial water.

Additional Resources Chemical Soil Stabilizers

Cohn, W. 2001. "Polyacyrlamide (PAM) for Erosion Control Applications." Presented at the Southeastern Pennsylvania Stormwater Management Symposium.

Divakaran, R. and V. N. Sivasankara Pillai. 2002. "Flocculation of river silt using chitosan." *Water Research* 36:2414–2418.

Illinois Urban Manual (IUM). 2011. Practice Standard, Polyacrylamide (PAM) for Temporary Soil Stabilization (no.) Code 893 (http://aiswcd.org/IUM/standards/urbst893.html).

Nichols, E. Synthetic and Natural Cationic Polymers for Clarification of Environmental Water and the Significance of Cationicity. White paper. Scientific Director of Water Treatment Technologies.

Orts, W. J., R. E. Sojka and G. M. Glenn. 2000. "Biopolymer additives to reduce erosion-induced soil losses during irrigation." *Industrial Crops and Products* 11(1):19–29.

Sojka, R. E., D. L. Bjorneberg, J. A. Entry, R. D. Lentz and W. J. Orts. 2007. "Polyacrylamide in Agriculture and Environmental Land Management.” *Advances in Agronomy* 92:75–162.

4. Soil Bioengineering and Biotechnical Techniques

This section summarizes literature and interview results on soil bioengineering and biotechnical stabilization techniques. Soil bioengineering is a technique that uses plants and plant material alone, while biotechnical techniques use plants in conjunction with more traditional engineering measures and structures to stabilize slopes (Gray and Sotir, 1996; Schiechtl and Stern, 1996) and alleviate shallow, rapid landslides and eroding stream banks (Lewis et al., 2001). Both soil bioengineering and biotechnical techniques contribute to sustainable development practices, as they enhance the aesthetics of the highway environment and reduce the ecological impacts of highway construction, maintenance and operations. In soil bioengineering systems, plants (grasses and shrubs, especially deep-rooted species) are an important structural component in reducing the risk of slope erosion (Jiang et al., 2004). Soil bioengineering measures are designed to aid or enhance the reestablishment of vegetation (Sotir and Gray, 1992). Properly designed and installed vegetative portions of systems should become self-repairing, with only minor maintenance to maintain healthy and vigorous vegetation. Soil bioengineering frequently mimics nature by using locally available materials and a minimum of heavy equipment, and is an inexpensive way to treat slope stabilization (Lewis et al., 2001).

Call out box:

> *[Soil] bioengineering is a technique that has been used for decades in countries such as Nepal, or in other cases (e.g., in Pakistan) has been recently adopted as a viable soil stabilization method (A. Faiz, personal communication, May 6, 2011).*

Soil bioengineering has six main functions:

1. to *catch* eroded materials with physical barriers (e.g. walls, vegetation),
2. to *armor* the slope from erosion caused by runoff or rain splash using vegetative cover, or partial armoring using lines of vegetation,
3. to *reinforce* soil physically with plant roots,
4. to *anchor* surface material to deeper layers using large vegetation with deep roots or rock bolts,
5. to *support* soil by buttressing with retaining walls or large vegetation,
6. and to *drain* excess water from the slope through the use of drains and vegetation (Howell, 1999; Schor and Gray, 2007).

When using soil bioengineering and biotechnical stabilization practices on slopes consider a partnership among many disciplines, including soil scientists, hydrologists, botanists, engineering geologists, maintenance personnel, civil engineers, and landscape architects (Lewis et al., 2001).

Some basic concepts that will aid in selection of soil bioengineering and biotechnical treatments include the following:

- Fit the system to the site. Consider topography, geology, soils, vegetation, and hydrology. Avoid extensive grading and earthwork in critical areas.

- Test soils to determine if amendments are necessary.
- Use onsite vegetation whenever possible.
- Limit the amount of disturbed areas at each site. Any materials removed from the site should be kept on site and reused if possible.
- Clear sites during times of low precipitation.
- Stockpile or protect the topsoil and reuse during planting.
- Utilize temporary erosion and sediment control measures.
- Divert, drain, and/or store excess water (Sotir and Gray, 1992).

When *planning* to use soil bioengineering or biotechnical treatments for soil stabilization, the following design measures should be considered: necessary earthwork required to prepare the site, scheduling and timing of the work to ensure optimal timing for site construction and planting, appropriate use of vegetation to avoid damaging structures, appropriate content and property of fill material to ensure mechanical and hydraulic properties are met while supporting plant life (Sotir and Gray, 1992). Soil bioengineering systems generally require minimal access for equipment and cause relatively minor site disturbance during installation (Sotir and Gray, 1992).

The *timing* of implementation of a soil bioengineered and biotechnical treatments is an important part of planning. Consider planting during the dormant season, usually late fall, winter in temperate zones, or early spring (Sotir and Gray, 1992). Installation of live cuttings should begin concurrently with earthmoving operations if they are carried out during the dormant season. All construction operations should be phased together when possible.

The selection of *plant species* is also important. First of all, the architectural features of plant root systems play a significant role in the effectiveness of plants in shallow slope stabilization and/or erosion control (Reubens et al., 2007). Secondly, wherever possible, native plant species (e.g., in the form of native multi-species grass sod) are preferred since they tend to tolerate drought; little irrigation is necessary, fertilizer, pesticides or herbicides; and demand less mowing (Dollhopf et al., 2008). Over time, highway agencies could see significant savings in labor, fuel, maintenance equipment costs and reduced chemical use. Chen et al. (2007) reported that the use of native shrubs and grass species along with micro-environment improvements ensured the long-term viability of hydro-seeded vegetation along slopes in the arid Loess Plateau of China. Finally, mixture seeding is a desirable method in establishing a viable plant community for roadside slope protection. Chen et al. (2011) systematically evaluated 19 woody plants and 8 herbaceous plants in terms of their early growth ability, stress resistance and growth potential once introduced to mild slopes along a freeway segment in Hubei, China. For this specific region, the field results indicated that the *Indigofera pseudotinctoria* and *Pinus massoniana* ranked the best and the worst, respectively. The authors suggested that the mixture seeding should utilize woody plants featuring high stress resistance and outstanding growth potential as target species in conjunction with herbaceous plants featuring high early growth ability as protective species.

Soil bioengineering and biotechnical projects ideally use onsite stockpiled topsoil as the planting medium (Sotir and Gray, 1992). Soil bioengineering and biotechnical systems need to be installed in a planting medium that includes fines and organic material and is capable of supporting plant growth. It has been reported that “amendment of soils through the addition of topsoil is an important technique in roadfill revegetation in (semiarid) Mediterranean environments” (Tormo et al., 2007). Similarly, for slopes along the Qinghai-Tibet highway in the permafrost region of China, the vegetation established by local-topsoil-amended spray seeding was much better than that of ordinary spray seeding (Chen et al., 2009). The same study also found that the addition of more water retainer and soil stabilizer (instead of mulch) improved the performance of ordinary spray seeding. The selected soil backfill does not need to be organic topsoil, but it enough organic material needs to be present able to support plant growth. Onsite soil should be tested for nutrient content, metals and pH prior to installation of vegetation. Soil around the vegetation should be compacted to densities approximating the surrounding natural soil densities, and soil around plants should be free of voids (Sotir and Gray, 1992).

Call out box:

> *“Initial failures of a small portion of a system normally can be repaired easily and inexpensively. Neglect of small failures, however, can result in the failure of large portions of a system” (Sotir and Gray, 1992).*

Vegetation alone plays an important role in stabilizing slopes by intercepting and absorbing water, retaining soil below ground with roots and above ground with stems, retarding runoff velocity by providing a break in the path of the water and increasing surface roughness, and increasing water infiltration rates, soil porosity and permeability (Schor and Gray, 2007). Each type of vegetation serves a critical function. Grasses, or herbaceous cover, protect sloped surfaces from rain and wind erosion. Shrubs, trees, and other vegetation with deeper roots are more effective at preventing shallow soil failures, as they provide mechanical reinforcement and restraint with the roots and stems and modify the slope hydrology by root uptake and by foliage interception (Schor and Gray, 2007).

Where the main function of structural elements is to allow vegetation to become established and take over the role of slope stabilization, the eventual deterioration of the structures is not a cause for concern (Sotir and Gray, 1992).

Field studies have shown instances where combined slope protection systems have proven to be more cost-effective than the use of vegetative treatments or structural solutions alone (Sotir and Gray, 1992). Lewis et al. (2001) found that where 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 can be a favorable economic alternative in roadside management. The cost of soil bioengineering at three sites in Washington State ranged from $1.50 to $3.50 per square foot (Lewis et al., 2001). Many interviewees stated that on slope stabilization projects in which they have participated, the overall cost of the soil bioengineering or biotechnical component represented about 1 percent of the total project budget.

Soil bioengineering and biotechnical treatments should not be considered the solution to every slope failure and surface erosion problem (Sotir and Gray, 1992). In some cases hand seeding with grass seed will be the most cost-effective solution for the site, while at another site a better solution may be an engineered retaining wall, with or without a vegetative component.

Additional Resources for Soil Bioengineering and Biotechnical Techniques

Andreu, V., H. Khuder, S. B. Mickovski, I. A. Spanos, J. E. Norris, L. K. A. Dorren, B. C. Nicoll, A. Achim, J. L. Rubio, L. Jouneau, and F. Berger. 2008. "Ecotechnological Solutions for Unstable Slopes: Ground Bio- and Eco-Engineering Techniques and Strategies." In *Slope Stability and Erosion Control: Ecotechnological Solutions*. Norris, J. E., A. Stokes, S. B. Mickovski, E. Cammeraat, R. Van Beek, B. C. Nicoll, A. Achim (eds). Dordrecht, The Netherlands: Springer.

Atkins, R. J., M. R. Leslie, D. F. Polster, M. P. Wise, and R. H. Wong. 2001. Best Management Practices Handbook: Hillslope Restoration in British Columbia. B.C. Ministry of Forests. Resource Tenures and Engineering Branch. Victoria, B.C. Watershed Restoration Program. (http://www.ieca.org/resources/federalstatewebsites.asp)

Lewis, L., S. L. Salisbury and S. Hagen. 2001. Soil Bioengineering for Upland Slope Stabilization. Washington State Department of Transportation, WA-RD 491.1.

Fox, P. J., T. H. Wu, and B. Trenner. 2010. Bio-Engineering for Land Stabilization. Final report prepared for the Ohio Department of Transportation, Columbus, OH.

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

Howell, J. 1999. *Roadside Bio-engineering: Site Handbook*. His Majesty's Government of Nepal. Ganabahal, Kathmandu.

Lewis, L. 2000. Soil Bioengineering: An Alternative for Roadside Management A Practical Guide. USDA-FS, T&DP, 0077 1801-SDTDC.

Ramakrishna, A.S. and D. Sapzova. 2011. Using Bioengineering to Stabilize Landslide-Prone Hill Slides. Innovations in Development, Mizoram Roads Project. The World Bank, India.

Schiechtl, H. M. and R. Stern, translated by L. Jaklitsch. 1996. *Ground Bioengineering Techniques for Slope Protection and Erosion Control.* UK editor, David H. Baker. Oxford: Wiley-Blackwell.

Schiechtl, H., translated by N. K. Horstmann. 1980. *Bioengineering for land reclamation and conservation.* Edmonton, Alberta: The University of Alberta Press.

Schor, B. and D. H. Gray. 2007. *Landforming: An environmental approach to hillside development, mine* *reclamation and watershed restoration.* Hoboken, N.J.: John Wiley & Sons.

Sotir, R. B. and D. H. Gray. 1992. "Chapter 18: Soil Bioengineering for Upland Slope Protection and Erosion Reduction." In *Engineering Field Handbook.* USDA Natural Resources Conservation Service.

4.1. Live Stakes

Live staking involves the insertion and tamping of live, rootable, vegetative cuttings into the ground (Figure 22) (Sotir and Gray, 1992). When correctly prepared and planted, or placed, the live stakes will root and grow. A system of stakes creates a living root mat that stabilizes the soil by reinforcing and binding soil particles together and by extracting excess soil moisture. In the United States, willow is a good woody plant that roots rapidly and begins to dry out a slope soon after installation (Sotir and Gray, 1992). Live stakes are an appropriate technique for repair of small earth slips and slumps that are frequently wet.

Live staking is a technique for relatively uncomplicated site conditions when construction time is limited and an inexpensive method is necessary (Sotir and Gray, 1992). Live staking can also be used to pin down, or anchor, erosion control materials on the surface. Live stakes are also well suited for stabilization of intervening areas between other soil bioengineering techniques, such as live fascines.

FIGURE 22 LIVE STAKE USED TO PIN DOWN MATTING. PHOTO PROVIDED BY G. KELLER.

Live cuttings should be.5–1.5 inch in diameter (1.3–4 cm) and 2–3 feet long (0.6–1 meter) (Sotir and Gray, 1992). Side branches should be cleanly removed with bark intact. Basal ends should be cut at a 45-degree angle for easy insertion into soil and the top should be cut square. Cuttings should be installed on the same day they are prepared or as soon as possible. Spacing of cuttings should be 2–3 feet (0.6–1 meter) apart in a triangular pattern with 2–4 per square yard (or meter), buds facing up (Sotir and Gray, 1992). Four-fifths of the length of the live stake should be installed in the ground and soil compacted around it after installation, with care taken to not split the stakes.

Additional Resources for Live Stakes

Sotir, R. B. and D. H. Gray. 1992. “Chapter 18: Soil Bioengineering for Upland Slope Protection and Erosion Reduction.” In *Engineering Field Handbook.* USDA Natural Resources Conservation Service.

Shah, B. H. 2008. *Field Manual on Slope Stabilization*. United Nations Development Program, Pakistan. September.

4.2. Live Fascines

The word fascine means a bundle of sticks (Howell, 1999). In this technique, bundles of live branches are laid in shallow trenches and partially buried. After burial in the trenches, they put out roots and shoots, forming a strong line of vegetation, also called *live contour wattling*. Live fascines mechanically reinforce the soil with roots, deplete soil water through transpiration and interception, and buttress the soil with the embedded stems (Howell, 1999; Sotir and Gray, 1992). Live fascines also serve to dissipate the energy of downward moving water by trapping debris and providing a series of benches on which grasses, seedlings, and transplants establish more easily (Sotir and Gray, 1992). In certain locations fascines can be angled to provide drainage (Howell, 1999). Fascines immediately reduce surface erosion or rilling and are well suited for steep, rocky slopes where digging is difficult (Sotir and Gray, 1992).

Woody species, such as shrub willow or dogwood, are made into sausage-like bundles, which are generally oriented parallel to the slope contour (Sotir and Gray, 1992) (Figure 23). Portions of fascines will root and become part of the stabilizing cover. Live fascines provide an immediate increase in surface stability and can further improve soil stability to a depth of 1–3 feet (0.3–1 meter) as the roots develop.

FIGURE 23 LIVE FASCINES. PHOTO PROVIDED BY G. KELLER.

Fascines are best used on consolidated debris and fill slopes or soft cut slopes (Howell, 1999). If the soil material is too hard, growth will be unacceptably slow. When time is an issue, brush layering may be a more appropriate option as they establish more quickly than fascines. Fascines can be used on slopes up to 45 degrees while wattle fences can be used on slopes up to 30 degrees (Howell, 1999). Contour fascines work well in well-draining materials, and for poor draining materials a herringbone pattern is suggested, as this pattern aids in drainage.

The spacing of the fascines depends on slope steepness, but as a general rule:

Slopes less than 30 degrees	10–15 feet (3–4.5 meters) intervals
Slopes 30 to 45 degrees	5–8 feet (1.5–2.5 meters) intervals (Howell, 1999).

Little or no maintenance is expected to be necessary for fascines with the exception of thinning established vegetation as needed over time (Howell, 1999). Wattle fences are often too weak to support the volume of debris that is caught in them; fascines have been shown to be more effective (Howell, 1999).

Additional Resources for Live Fascines

Howell, J. 1999. *Roadside Bio-engineering: Site Handbook*. His Majesty's Government of Nepal. Ganabahal, Kathmandu.

Sotir, R. B. and D. H. Gray. 1992. "Chapter 18: Soil Bioengineering for Upland Slope Protection and Erosion Reduction." In *Engineering Field Handbook.* USDA Natural Resources Conservation Service.

Shah, B. H. 2008 *Field Manual on Slope Stabilization*. United Nations Development Program, Pakistan.

September.

4.3. Brush Layering and Palisades

To build brush layering systems, woody cuttings are laid in lines across the slope, generally following natural or created contours (Howell, 1999) (Figure 24). Brush layers form a barrier and prevent the development of rills, and trap sediment and debris moving down slope. Brush layering is somewhat similar to live fascine systems because both involve the cutting and placement of live branch cuttings on slopes, but the two techniques differ in the orientation of the branches and the depth to which they are placed in the slope (Sotir and Gray, 1992). In brush layering, the cuttings are oriented more or less perpendicular to the slope contour, similar to live stakes. The brush branches reinforce the slope and the portions of the brush that protrude from the slope face assist in retarding runoff and reducing surface erosion (Sotir and Gray, 1992). The main function of brush layering is to catch debris and to armor and reinforce the slope (Howell, 1999). After installation, over time a terrace or bench will develop. In certain locations, brush layers can be angled to create a drainage channel.

FIGURE 24 BRUSH LAYERING WITH LIVE STAKES. PHOTO PROVIDED BY G. KELLER.

Brush layering consists of placing live branch cuttings in small 2–3 feet (0.6–1 meter) benches that have been excavated from the slope (Sotir and Gray, 1992). Bench excavation should start at the toe of the slope. The surface of the bench should be sloped so that the outside edge is higher than the inside. Live branch cuttings should be placed on the bench in a crisscross or overlapping configuration with the brush growing tips aligned toward the outside of the bench. Backfill is then placed on top of the branches and compacted to eliminate air spaces, with brush tips extending beyond the compacted fill. Each lower bench is backfilled with soil from excavating the bench above. Consider brush layering on slopes up to 2:1 in steepness and no greater than 15 feet (4.5 meters) in vertical height (Sotir and Gray, 1992). Mulching between benches is suggested.

This technique can be used on a wide range of sites up to 45 degrees (Howell, 1999). This technique is particularly effective on debris piles, fill slopes and high embankments. Avoid using this technique on materials that drain poorly or materials that frequently slump.

Spacing between brush layering depends on the steepness of the slope (Howell, 1999). The following guidelines can be used generally:

Slope less than 30 degrees	5–7 feet (1.5–2 meters) intervals
Slope 30 to 45 degrees	3 feet (1 meter) intervals
Slopes 30 to 60 degrees	3 feet (1 meter) intervals (palisades only) (Howell, 1999).

There is generally no need for maintenance except for replacement of failures if they occur, or thinning of vegetation once it is established (Howell, 1999). Brush layering can be complex and careful tailoring to specific site and soil conditions may need to be considered (Sotir and Gray, 1992).

Additional Resources for Brush Layering or Palisades

Howell, J. 1999. *Roadside Bio-engineering: Site Handbook*. His Majesty's Government of Nepal. Ganabahal, Kathmandu.

Sotir, R. B. and D. H. Gray. 1992. "Chapter 18: Soil Bioengineering for Upland Slope Protection and Erosion Reduction." In *Engineering Field Handbook.* USDA Natural Resources Conservation Service.

Shah, B. H. 2008. *Field Manual of Slope Stabilization*. United Nations Development Program, Pakistan. September.

4.4. Branch packing

Branch packing consists of alternating layers of live branch cuttings and compacted backfill to repair small localized slumps and holes in slopes (Sotir and Gray, 1992) (Figure 25). This method is very similar to brush layering. The main differences been brush layering and branch packing is branch packing uses live material placed horizontally and inert material placed vertically into the slope and is better at repairing holes in embankments or small slumps.

Live brush cuttings should be0.5–2 inches (1.3–5 cm) in diameter and long enough to reach the back of the trench and extend slightly from the slope surface (Sotir and Gray, 1992). Wooden stakes, the inert material, should be 5–8 feet (1.5–2.5 meter) long poles that are 3–4 inches (7.5–10 cm) in diameter, or 2-by-4 lumber.

To install, start at the lowest point in the trench and drive the wooden stakes vertically 3–4 feet (1–1.5

meters) into the ground, and set 1–1.5 feet (0.3–0.5 meters) apart (Sotir and Gray, 1992). A layer of living branches 4–6 inches (10–15 cm) thick is placed in the bottom of the trench between the vertical stakes in a crisscross pattern with the growing tips pointing out. Each layer of branches is followed by a layer of compacted soil (Sotir and Gray, 1992). Soil should be moist or moistened to insure the live branches do not dry out.

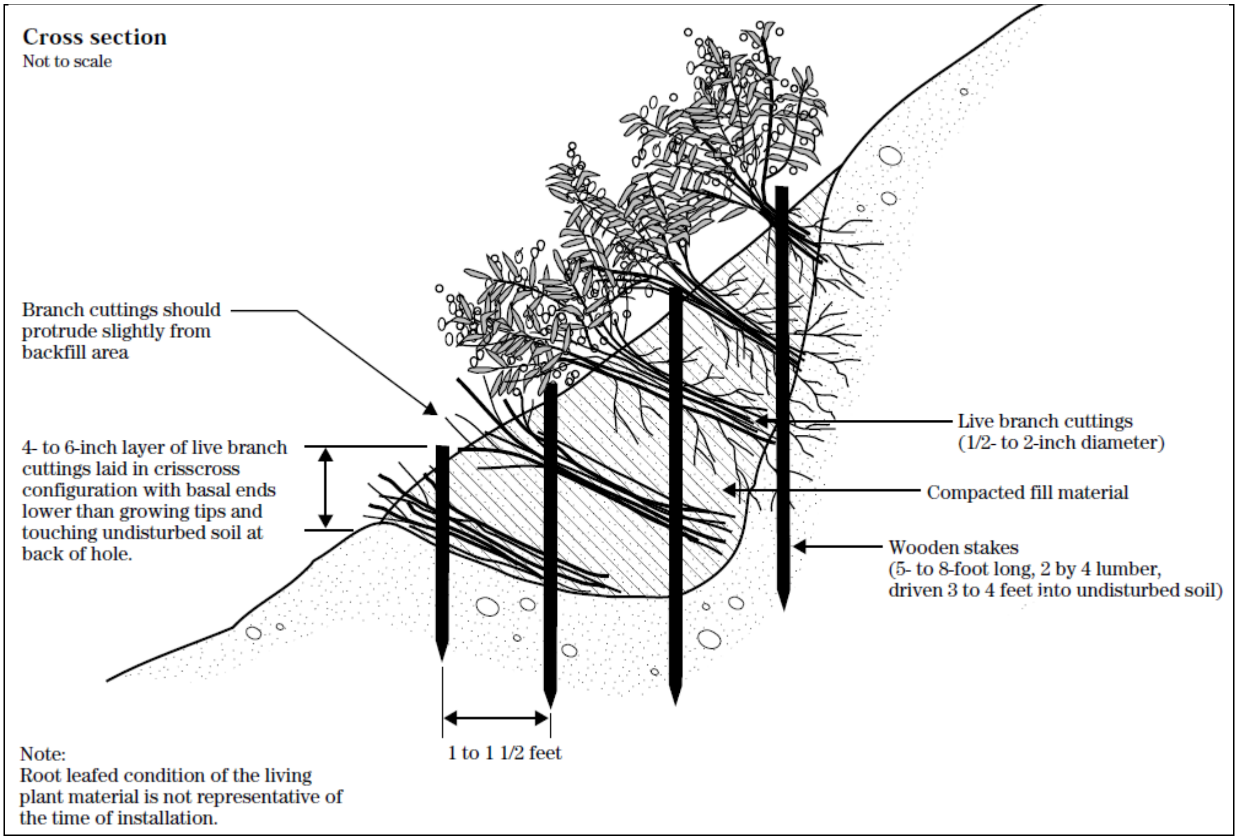

FIGURE 25 CROSS SECTION OF BRANCH PACKING. TAKEN FROM (SOTIR AND GRAY, 1992)

Branch packing is not effective in areas where slumping is greater than 4 feet (1.2 meters) deep or 5 feet (1.5 meters) wide (Sotir and Gray, 1992).

Another method, called live gulley repair (Sotir and Gray, 1992, pg. 28), is a combination of brush layering and branch packing. Live gully repair utilizes alternating layers of live branch cuttings and compacted soil to repair small rills and gullies (Sotir and Gray, 1992). For additional information on this technique please see Natural Resources Conservation Service, Engineering Field Handbook, page 28 (Sotir and Gray, 1992).

Additional Resources for Branch Packing

Sotir, R. B. and D. H. Gray. 1992. "Chapter 18: Soil Bioengineering for Upland Slope Protection and Erosion Reduction." In *Engineering Field Handbook.* USDA Natural Resources Conservation Service.

Shah, B. H. 2008 *Field Manual on Slope Stabilization*. United Nations Development Program, Pakistan.

September.

4.5. Rock Joint Planting

Joint planting or vegetative riprap involves planting live cuttings into soil between the joints or open spaces between rocks that have been placed on a slope (Figure 26) (Sotir and Gray, 1992). Joint planting works well with rock blankets and rock walls. This technique is very similar to live stakes.

Roots from the plants will improve drainage by removing soil moisture, and over time create a living root mat in the soil base and around rocks (Sotir and Gray, 1992). The root system of the mat will help to bind or reinforce the soil and to prevent loss of fines between and below the rocks (Sotir and Gray, 1992).

The live cuttings should be 0.5–1.5 inches (1.2–4 cm) in diameter, long enough to extend into the soil behind the rock surface, and have the branches removed (Sotir and Gray, 1992). To install, plant live branch cuttings into the openings of the rock during or after construction by tamping them with a soft mallet or by hand. Orient the live cuttings perpendicular to the slope with growing tips protruding slightly from the finished face of the rock.

FIGURE 26 ROCK JOINT PLANTING. PHOTO PROVIDED BY G. KELLER.

Additional Resources for Rock Joint Planting

Kling, P., M. Pyles, D. Hibbs and B. Kauffman. 2001. The role of vegetated riprap in highway applications, Final report. Federal Highway Administration. Washington, D.C. SPR 324.

Sotir, R. B. and D. H. Gray. 1992. “Chapter 18: Soil Bioengineering for Upland Slope Protection and Erosion Reduction.” In *Engineering Field Handbook.* USDA Natural Resources Conservation Service.

4.6. Live and Timber Crib Walls

A live crib wall consists of a hollow, box-like interlocking arrangement of untreated log or timber members (Figure 27) (Sotir and Gray, 1992). The structure is filled with suitable backfill material and layers of live branch cuttings, which root inside the crib structure and extend into the slope (NRCS, 1992). Once the live cuttings root and become established, the resulting vegetation gradually takes over the structural function of the wood members (Sotir and Gray, 1992). Crib walls provide immediate erosion protection while the established vegetation provides long-term stability.

The technique is appropriate at the base of a slope where a low wall may be needed to stabilize the toe of the slope, to prevent small failures, and to reduce its steepness (Figure 6) (Sotir and Gray, 1992). Crib walls are useful where space is limited and a more vertical structure is needed (Sotir and Gray, 1992). Timber crib walls cost less to construct than concrete crib walls, especially when timber can be harvested or gathered from the site (Shah, 2008). Crib walls are not designed for or intended to resist large, lateral earth stresses (Sotir and Gray, 1992).

FIGURE 27 LIVE CRIB WALL, FROM A DISTANCE (LEFT) AND CLOSE UP (RIGHT). PHOTOS PROVIDED BY G. KELLER

To install a crib wall start at the lowest point and excavate loose material down 2–3 feet (0.6–1 meter) until the foundation is stable (Sotir and Gray, 1992). Excavate the back of the stable foundation, at the slope, slightly deeper than the front—this will add stability to the structure. Crib walls should be built with round or square timbers, 4-10 inches (10–25 cm) in diameter (Sotir and Gray, 1992; Shah, 2008). Place the first course of logs or timber at the front and back about 4–5 feet (1.2–1.5 meters) apart and parallel to the slope contour (Sotir and Gray, 1992). Place the next course of logs or timbers at right angles, or perpendicular, to the slope on top of the previous course of logs, or timber, allowing 3–6 inches (7.5–15 cm) of overhang. Repeat these steps for each additional course of crib wall, securing each course with nails or rebar.

As the crib wall structure gets built up, beginning at ground level, place live branch cuttings on the backfill perpendicular to the slope, and then cover the cuttings with backfill and compact it (Sotir and Gray, 1992). Live branch cuttings should be 0.5–2 inches (1.2–5 cm) in diameter and long enough to reach the back of the wooden crib structure, with less than 10 inches (25 cm) protruding from the wall (Sotir and Gray, 1992; Shah, 2008). Live branch cuttings should be placed on each course to the top of the crib wall with growing tips coming out of the face of the crib wall (Sotir and Gray, 1992). When the fill material is tamped into openings between the poles, large hollow spaces should be avoided to ensure that the branches will root properly (Shah, 2008). Vegetation should be planted at a density of 10 live stakes per 3 feet (0.9 meter) or as necessary. This may vary with the type of vegetation used for cuttings and the slope steepness.

The constructed crib wall should be tilted back, or battered, if the system is built on a smooth, evenly sloped surface (Sotir and Gray, 1992). Crib walls can also be constructed in a stair-step fashion so that each successive level of timber is set back 6–10 inches (15–25 cm) toward the slope face at a 1:10 angle toward the slope, but never placed vertically (Sotir and Gray, 1992; Shah, 2008). Crib walls should be constructed to a maximum height of 6–10 feet (2–3 meters).

Live crib walls can be complex and careful tailoring to specific site and soil conditions may need to be considered (Sotir and Gray, 1992).

4.6.1. Vegetated Concrete Crib Walls

Another option is a vegetated concrete crib wall (Figure 28). Prefabricated concrete slabs or hollow bricks are used to create the wall (Shah, 2008; Zhang and Chen, 2008). There are different types of concrete crib walls, but generally 4-foot-long (1.2-meter-long) concrete slabs are prepared that are 6 inches (15 cm) thick and 1 foot (30 cm) thick at both ends (Shah, 2008). The footer slabs have sockets on both sides and the header slabs have convex ends on both sides (Shah, 2008).

To build a vegetated concrete crib wall:

- Clear and excavate material from the site to create a solid base.
- Place concrete slabs to create a solid foundation.
- Place the concrete slabs at a 1:5 slope gradient, sloping back toward the slope face.
- Build up the wall by placing the footers parallel to the slope with 2-foot (0.6-meter) gaps between each concrete slab.
- Place headers over footers.
- Fill soil in the gaps between the concrete slabs.
- Plant cuttings in the gaps between the concrete slabs.
- Drainage should be considered at the base of the wall (Shah, 2008).

FIGURE 28 POST-EARTHQUAKE (2005) SLOPE STABILIZATION USING A MASONRY CRIB WALL AND LAYERED PLANTING OF NATIVE TREES AND BUSHES, BALAKOT-KAGHAN ROAD (N-15), PAKISTAN. PHOTO PROVIDED BY A. FAIZ.

Additional Resources for Crib Walls

Sotir, R. B. and D. H. Gray. 1992. "Chapter 18: Soil Bioengineering for Upland Slope Protection and Erosion Reduction." In *Engineering Field Handbook.* USDA Natural Resources Conservation Service.

Shah, B. H. 2008. *Field Manual of Slope Stabilization*. United Nations Development Program, Pakistan. September.

4.7. Vegetated Rock Gabions

Vegetated gabions begin as rectangular containers fabricated from a triple-twisted, hexagonal mesh of heavily galvanized steel wire (Sotir and Gray, 1992). Empty gabions are placed in position, wired to adjoining gabions, filled with stones and then folded shut and wired at the ends and sides. Live branches are placed on each consecutive layer between the rock-filled baskets (Figure 29). These will take root inside the gabion baskets and in the soil behind the structures (Sotir and Gray, 1992). In time, roots consolidate the structure and bind it to the slope.

The technique is appropriate for the base of a slope where a low wall may be necessary to stabilize the toes of the slope and reduce its steepness (Sotir and Gray, 1992). This technique is not designed for or intended to resist large, lateral earth stresses. The gabion wall should be constructed to a maximum height of 5 feet (1.5 meters), including the excavated foundation. This technique is used where space is limited and a more vertical structure is required.

Cuttings used should be 0.5–1 inches (1.3–2.5 cm) in diameter and long enough to reach beyond the back of the rock basket structure in to the backfill (Sotir and Gray, 1992).

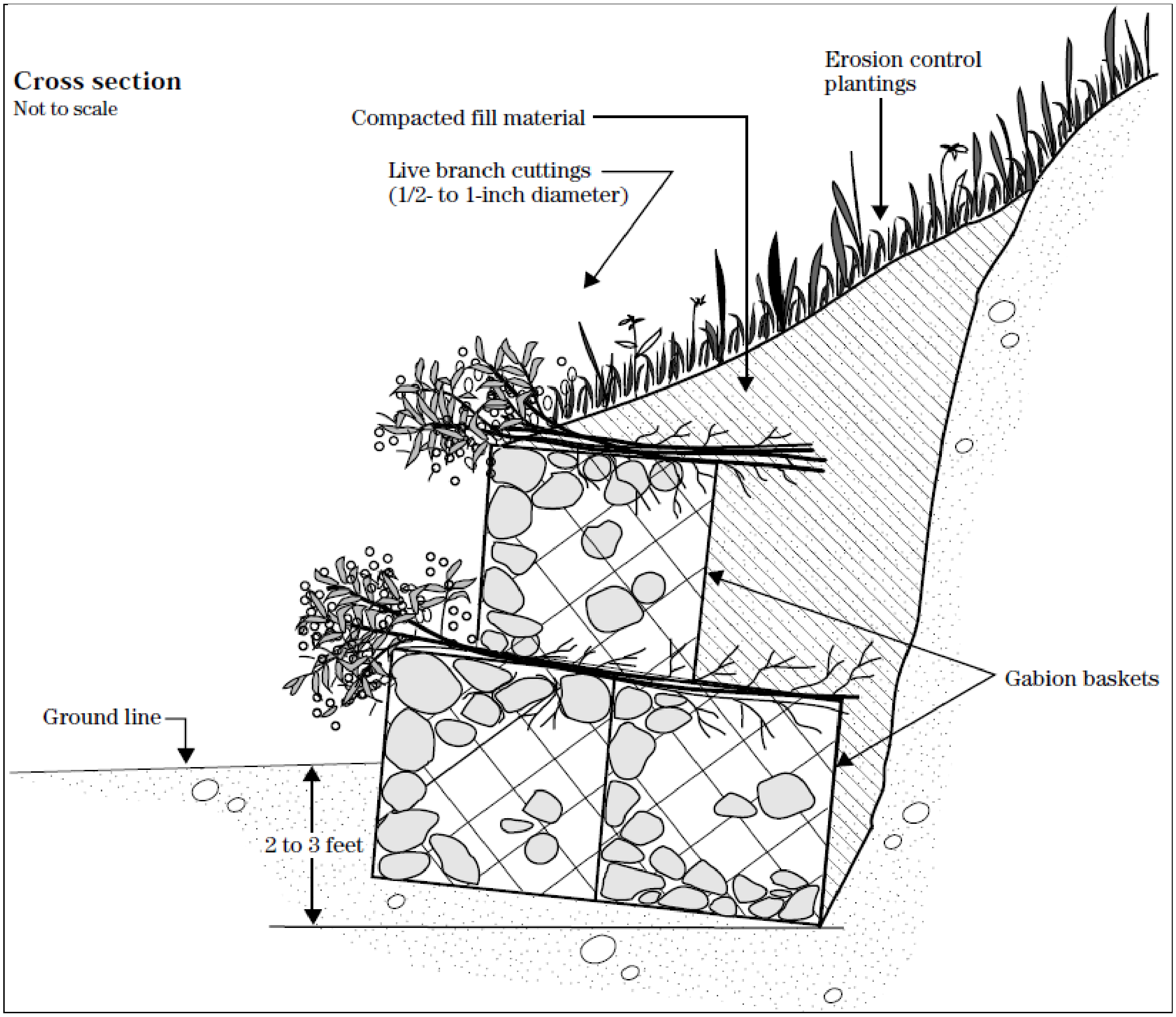

FIGURE 29 CROSS SECTION OF A VEGETATED GABION WALL. TAKEN FROM (SOTIR AND GRAY, 1992).

To install, start at the lowest point of the slope and excavate loose material 2–3 feet (0.6–0.9 meters) below the ground surface to create a stable foundation (Sotir and Gray, 1992). Excavate the back of the stable foundation, closest to the slope, slightly deeper than the front to add stability to the structure. Place gabion wire baskets in the bottom of the excavation pit and fill with rock. Place backfill between and behind the wire baskets. Place live branch cuttings on the wire baskets perpendicular to the slope with the growing tips oriented away from the slope extending slightly beyond the gabion baskets (Sotir and Gray, 1992). Extend the live cuttings beyond the backs of the wire baskets in to the fill material. Place soil over the cuttings and compact it. Repeat this sequence until the structure reaches the appropriate height (Sotir and Gray, 1992) (Figure 8).

Gabion walls are strengthened by trees growing on them (Howell, 1999). There are two types: stone-filled gabions and earth-filled gabions. Vegetated stone gabions tend to come about naturally where trees have seeded existing gabion walls, although they could be seeded artificially. There is little concern for distortion of the wire gabion boxes (Howell, 1999). The benefit is that the trees will provide flexible binding to the structure once the wire has corroded. For stone-filled gabions, trees are unlikely to contribute much to the strength of the structure until the wire has become seriously corroded.

Vegetated earth-filled gabions are a lower cost alternative to stone-filled gabions (Howell, 1999). They are created by placing a fill of in-situ earth behind a single layer of dry stone within the gabion basket (Howell, 1999). Tree seedlings are then planted on the gabion (Howell, 1999). Plants should be spaced 1.5 feet (0.5 meters) in a random pattern (Howell, 1999). Maintenance may include thinning of vegetation to maintain the site. This technique is not well studied or implemented.

4.7.1. Vegetated Soft Gabion Wall

There is another technique called *vegetated soft gabion walls* that has been used successfully in Pakistan (Figure 30) (Shah, 2008). Soft gabions are made of jute or synthetic fiber bags, originally used for fertilizer or sugar, which are filled with soil or aggregate and placed to create a soft retaining wall. This technique can be used where stones are not available for gabion construction.

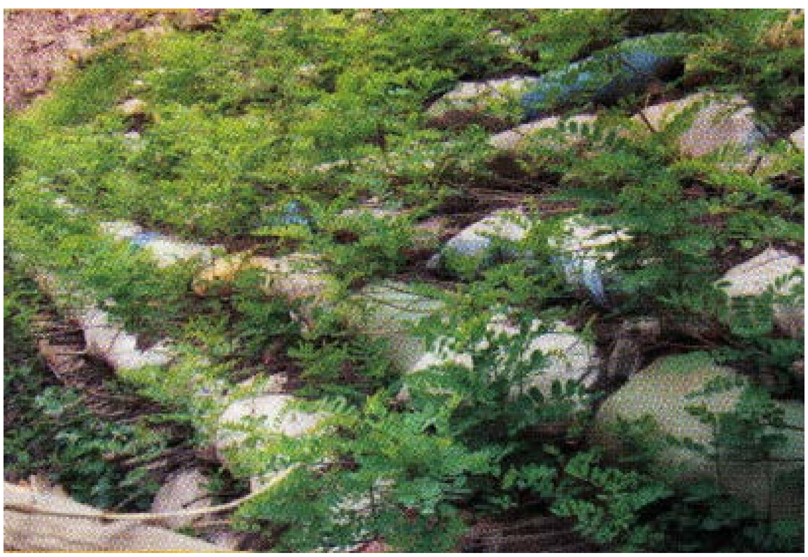

FIGURE 30 PHOTOGRAPH OF A VEGETATED SOFT GABION WALL. TAKEN FROM (SHAH, 2008).

The steps to create a vegetated soft gabion wall are as follows (Shah, 2008):

- Clear the area where the wall will be built and excavate out the base to a solid soil layer.
- Fill the empty bags with soil or aggregate, and place the filled bags side by side with their open end directed toward the cut slope.
- Push soil from slope onto the bags and cover them fully.
- Place a layer of fresh cuttings on the soil surface with ends directed toward the slope.

- Cover the cuttings with another layer of soil from the slope.
- Place another layer of soil-filled bags lengthwise over the buried cuttings set back 6 inches (15 cm) from the front of the first layer of bags.
- Place another layer of soil over the bags and put down another layer of cuttings, bury with soil and repeat this process until the wall height is achieved.
- Establish proper drainage at the base of the wall.

Maintenance may include cutting back or pruning of the established plants.

Additional Resources for Vegetated Gabion Walls

Howell, J. 1999. *Roadside Bio-engineering: Site Handbook.* His Majesty's Government of Nepal. Ganabahal, Kathmandu.

Sotir, R. B. and D. H. Gray. 1992. "Chapter 18: Soil Bioengineering for Upland Slope Protection and Erosion Reduction." In *Engineering Field Handbook.* USDA Natural Resources Conservation Service.

4.8. Vegetated Rock Walls

A vegetated rock wall is a combination of rock and live branch cuttings used to stabilize and protect the toe of steep slopes (Sotir and Gray, 1992) (Figure 31). Vegetated rock walls differ from conventional retaining structures in that they are placed against relatively undisturbed earth and are not intended to resist large lateral pressures.

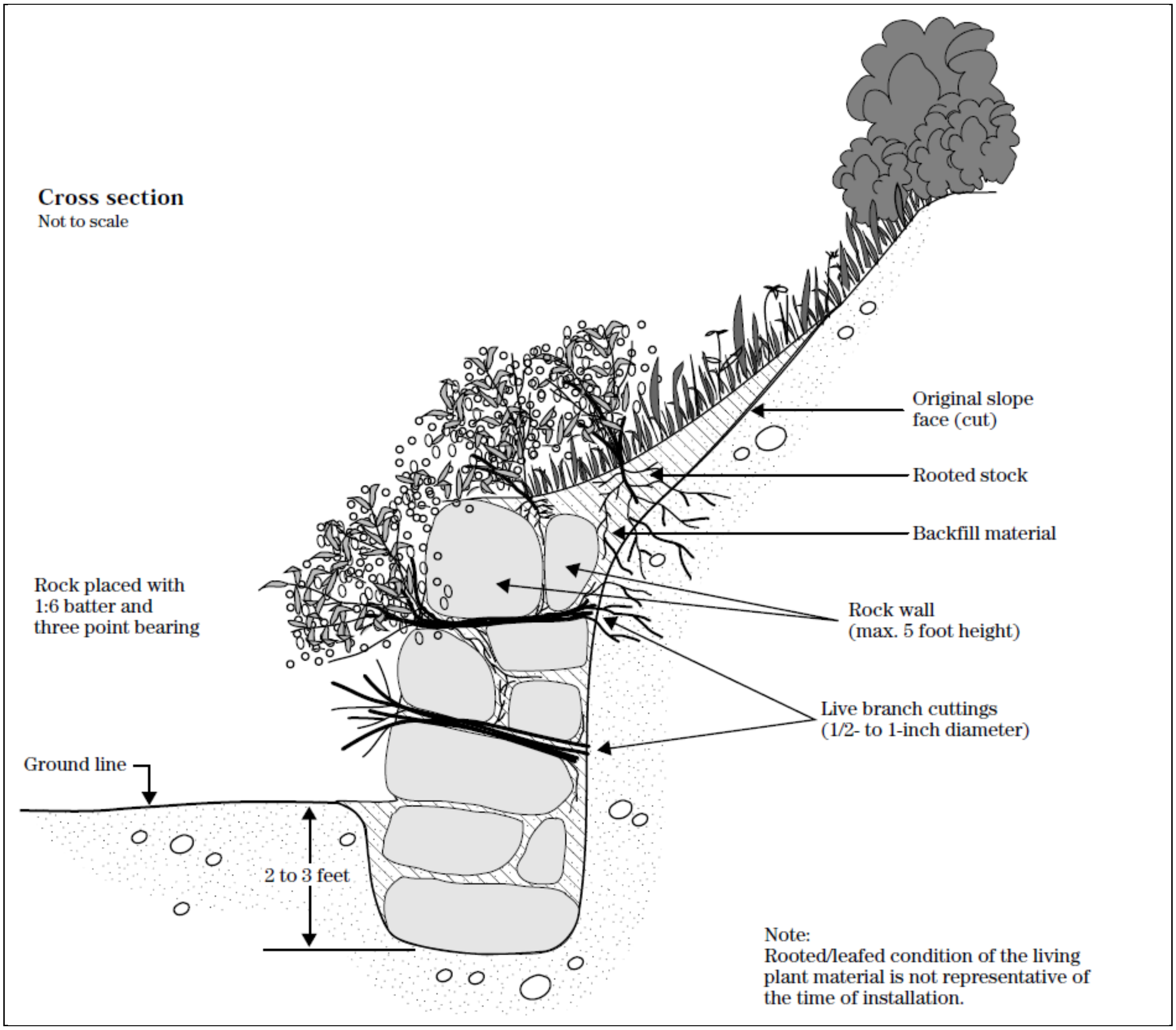

FIGURE 31 CROSS SECTION OF A VEGETATED ROCK WALL .TAKEN FROM (SOTIR AND GRAY, 1992).

Vegetated rock walls are appropriate where a low wall may be needed to stabilize the toe of the slope and reduce its steepness. Vegetated rock walls are useful where space is limited and natural rock is available (Sotir and Gray, 1992).

To build a vegetated rock wall, live cuttings should be 0.5–1 inch (1.2–2.5 cm) in diameter and long enough to reach beyond the rock structure into the fill or undisturbed soil behind the structure (Sotir and Gray, 1992). Rocks used should be 8–24 inches (20–60 cm) in diameter, with larger boulders used at the base.

To install, start at the lowest point of the slope, and remove loose soil until a stable base is reached, generally 2–3 feet (0.6–1 meter) below the ground elevation (Sotir and Gray, 1992). Excavate the back of the stable foundation, closest to the slope, slightly deeper than the front to add stability to the structure. Excavate the minimum amount from the existing slope to provide a suitable recess for the wall. Well-draining base material should be used if deep frost penetration may be an issue. Place rocks with at least three load-bearing points contacting the foundation material or underlying rock course (Sotir and Gray, 1992). They should also be placed so that their center of gravity is as low as possible, with the long axis slanting inward toward the slope if possible. When a rock wall is constructed adjacent to an impervious structure, place a drainage system at the back of the foundation and outside the toe of the wall to provide an appropriate drainage outlet (Sotir and Gray, 1992). The overall height of the rock wall including the excavated base should not exceed 5 feet (1.5 meters).

A wall can be constructed with a sloping bench behind it to provide a base on which live branch cuttings can be placed during construction (Sotir and Gray, 1992). Live cuttings should be tamped or placed into the openings of the rock wall during or after construction. The base ends of the branches should extend into the backfill or undisturbed soil behind the wall. Live cuttings should be oriented perpendicular to the slope contour with growing tips protruding slightly from the finished wall face (Sotir and Gray, 1992).

Additional Resources for Vegetated Rock Walls

Sotir, R. B. and D. H. Gray. 1992. “Chapter 18: Soil Bioengineering for Upland Slope Protection and Erosion Reduction.” In *Engineering Field Handbook.* USDA Natural Resources Conservation Service.

5. Mechanical Stabilization Techniques

This section summarizes literature and interview results on mechanical stabilization techniques. This chapter provides information about techniques that utilize non-vegetative or non-living components such as rock, concrete, geosynthetics, and steel pins to reinforce slopes. These techniques can provide stability to both cut and fill slopes. Structures are generally capable of resisting much higher lateral earth pressures and shear stresses than vegetation (Sotir and Gray, 1992). Similarly, as demonstrated by nonlinear finite element analysis, polymeric reinforcement within a soil slope can alter the probable failure mechanism within the slope, significantly reduce the shearing, horizontal, and vertical strains, and thus greatly reduce the slope movements (Chalaturnyk et al., 1990). Depending on the soil type, tensile strength and aspect ratio of fibers, volumetric fiber content, etc., the inclusion of fiber reinforcement in soil can induce distributed tension within the soil, and the soil failure can be governed by pullout or breakage of individual fibers (Zornberg, 2002). The inclusion of anchors in slopes can enhance the safety factor by providing an additional shearing resistance on the slip surface, which is a function of the orientation, position, and spacing of anchors (Cai, 2003). Depending on the slope to be stabilized, reinforced soil slope techniques should be tailored to address the specific site challenges. To implement reinforced soil slope techniques, one can first assess the additional shear force needed for slope stability (indicated by the design safety factor) and then analyze the available forces provided by the reinforcement layers or anchors, followed by the selection of the type, number, location or spacing of the reinforcement within the slope. The lifecycle performance of the reinforcement materials has to be considered at the design stage, as such materials may deteriorate over time in the soil due to exposure to environmental and mechanical loadings (Jewell and Greenwood, 1988).

The following sections present a description of various reinforced soil slope techniques, which may be used individually or in combination for slope stabilization.

5.1. Retaining Walls

Retaining structures are used to hold back (retain) material at a steep angle and are very useful when space (or right-of-way) is limited. Low retaining structures at the toe of a slope make it possible to grade the slope back to a more stable angle that can be successfully re-vegetated without loss of land at the crest (Sotir and Gray, 1992). Such structures can also protect the toe against scour and prevent undermining of the cut slope (Gray and Sotir, 1996). Short structures at the top of a fill slope can provide a more stable road bench or extra width to accommodate a road shoulder.

Retaining structures can be built external to the slope (such as a concrete or masonry retaining wall), or utilize reinforced soil (such as a burrito wall or deep patch). While some of these techniques can apply to large failures, the focus of this synthesis is on shallow instabilities and appropriate low-cost, sustainable solutions and so the focus of this section will be on smaller applications.

5.1.1. Low Masonry or Concrete Walls (with slope planting)

Masonry or poured concrete retaining walls are rigid structures that do not tolerate differential settlement or movement and are only appropriate at sites where little additional movement is expected. Because of this limitation, their use is more restricted than gabion walls or reinforced soil systems. Masonry or concrete walls can have various cross-sections (Figure 32). Gravity walls can be constructed with plain concrete, stone masonry, or concrete with reinforcing bar. Masonry walls that incorporate mortar and stone are easier to construct and stronger than dry stone masonry walls, but they do not drain as well (Hearn and Weeks, 1997). Cantilever walls use reinforced concrete and have a stem connected to a base slab (Das, 2007).

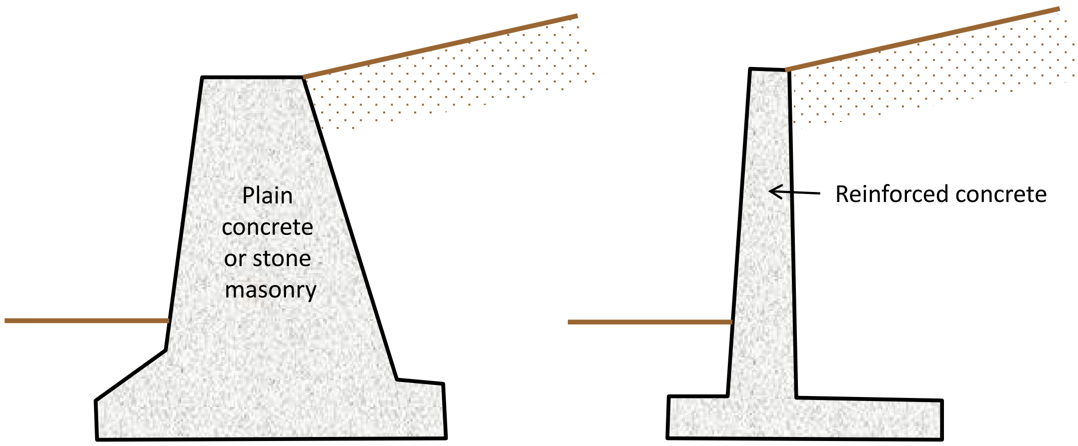

FIGURE 32 CROSS SECTION OF GRAVITY (LEFT) AND CANTILEVER (RIGHT) RETAINING WALLS. ADAPTED FROM (DAS, 2007).

A schematic of a low cantilever retaining wall used to flatten a slope and establish vegetation is shown in Figure 33. Retaining walls with free-draining compacted backfill can be designed and constructed more efficiently than those using poor-quality, cohesive backfill soils. In either case a drainage system should be installed behind the wall (Anderson et al., 1997; Das, 2007; Shah, 2008).

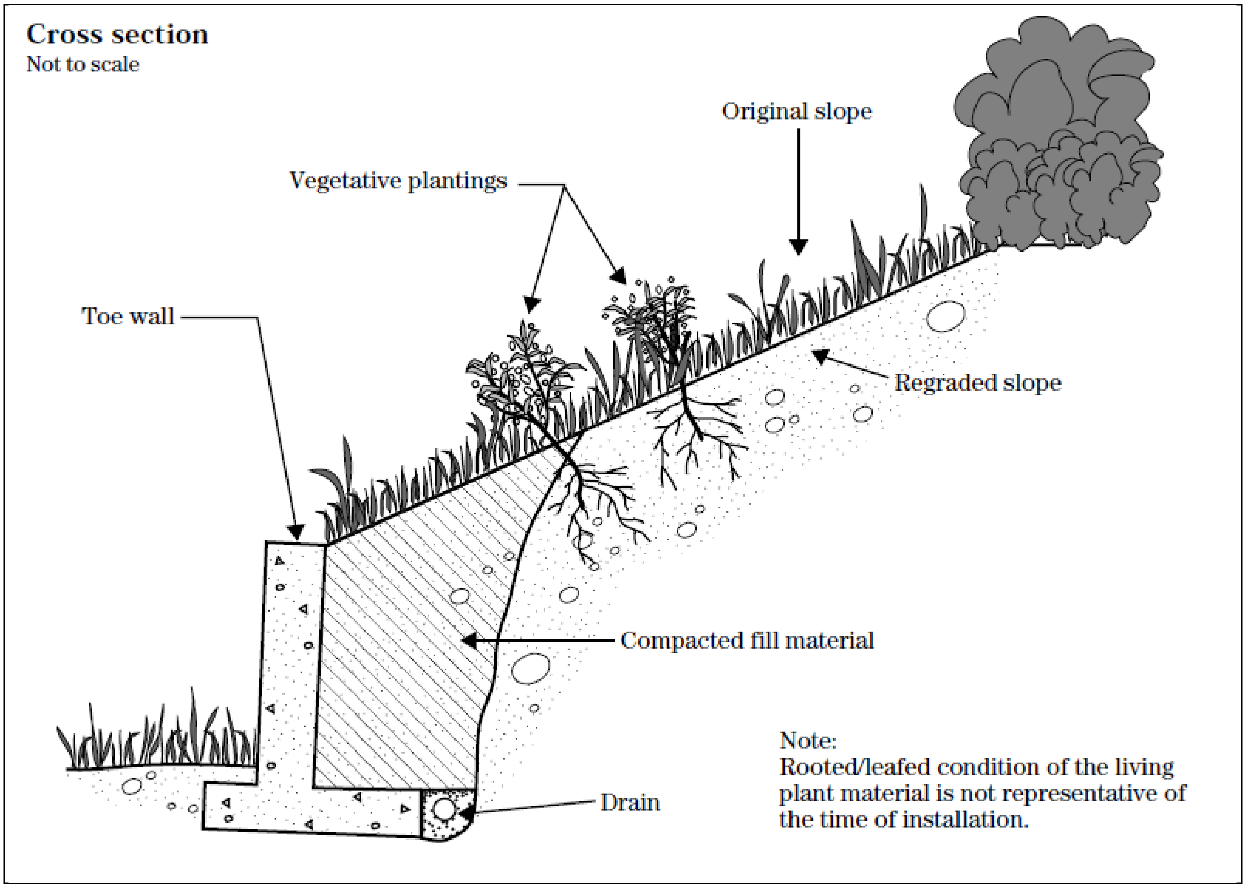

FIGURE 33 CROSS SECTION OF A LOW WALL WITH VEGETATION PLANTED ON THE SLOPE FOR STABILIZATION. TAKEND FROM (SOTIR AND GRAY, 1992).

The decision to use a dry masonry, mortared masonry, or concrete retaining wall will be greatly influenced by the familiarity and experience of local practitioners. Reinforced concrete is very common in the United States and there is no shortage of engineers or contractors with adequate experience to design and construct concrete retaining walls. In developing countries with larger labor pools and experienced masons, dry masonry or mortared masonry structures are more common (Anderson et al., 1997; Shah, 2008).

Additional Resources for Retaining Walls

Das, B. M. 2007. Principles of Foundation Engineering, 6th ed. Cengage Learning, Stamford, CT, 750pp.

Hearn, G. J. and R. W. Weeks. 1997. Principles of low cost road engineering in mountainous regions, with special reference to Nepal, Himalaya. Ed. C. J. Lawrence. Transportation Research Library Overseas Road Note 16. Berkshire, United Kingdom.

Keller, G. and J. Sherar. 2003. Low-Volume Roads Engineering—Best Management Practices Field Guide. USDA Forest Service, Office of International Programs and U.S. Agency for International Development, Washington, DC. (http://www.fs.fed.us/global/topic/welcome.htm#12).

Shah, B. H. 2008. *Field Manual of Slope Stabilization*. United Nations Development Program, Pakistan. September.

Sotir, R. B. and M. A. McCaffrey. 1997. "Stabilization of High Soil and Rock Cut Slope by Soil Bioengineering and Conventional Engineering." *Transportation Research Record* 1589, Paper No. 971260.

5.1.2. Gabion Walls

Gabion baskets are made of heavy wire mesh and assembled on site, set in place, then filled with rock. Once the rock has been placed inside the gabion basket use horizontal and vertical wire support ties to achieve the reported strength. Gabion walls are composed of stacked gabion baskets and are considered unbound structures. Their strength comes from the mechanical interlock between the stones/rocks (Hearn and Weeks, 1997). To achieve the maximum level of strength in the gabion wall, the baskets should be filled to the greatest possible density, which is generally achieved by hand packing rather than mechanically packing. Packing of the gabion baskets is an art and skill that is learned through practice. For specific information about how to pack rock, rock types to be used, and wire mess gauges and tying, see Hearn and Weeks (1997), pages 121–122.

Gabion basket manufacturers have a wealth of standard designs for various wall heights and soil types that ensure stability against overturning, sliding, bearing-capacity failure, and deep-seated slope failure (Kandaris, 1999). Gabion walls can be used at the toe of a cut slope or top of a fill slope (Figure 34). The walls can be vertical or stepped and are adaptable to a wide range of slope geometries (Kandaris, 1999). Gabion walls can accommodate settlement without rupture and provide free drainage through the wall. They are usually preferred at sites with poor foundations, wet soils, high groundwater, or slope movement caused by creep, sliding and seismicity (Hearn and Weeks, 1997).


FIGURE 34 LOW GABION WALL AND GABION WALL STABILIZATION AT TOP OF FILL SLOPE IN TIMOR. PHOTOS PROVIDED BY G. KELLER AND C. BENNETT.

Useful Points

- We have had issues with contractors not knowing how to load gabion baskets or not installing gabion basket cross ties. Cross ties should be installed every foot in both directions otherwise the gabion basket will not achieve the design strength.(B. Johnson, personal communication, April, 18, 2011)

Additional Resources for Gabion Walls

Hearn, G. J. and R. W. Weeks. 1997. Principles of low cost road engineering in mountainous regions, with special reference to Nepal, Himalaya. Ed. C.J. Lawrence. Transportation Research Library Overseas Road Note 16. Berkshire, United Kingdom.

Keller, G. and J. Sherar. 2003. Low-Volume Roads Engineering—Best Management Practices Field Guide. USDA Forest Service, Office of International Programs and U.S. Agency for International Development, Washington, DC. (http://www.fs.fed.us/global/topic/welcome.htm#12).

Shah, B. H. 2008. *Field Manual of Slope Stabilization*. United Nations Development Program, Pakistan. September.

5.2. Mechanically Stabilized Earth/Geosynthetic Reinforced Soil Systems

Retaining walls can also be built with reinforced soil. These are commonly referred to as mechanically stabilized earth walls (MSE walls). MSE walls can use different reinforcing elements (e.g., strips of metal or sheets of geosynthetics) and different facing systems (e.g., concrete panels, modular blocks, or shotcrete). Geosynthetic reinforced slopes can also retain soil to, for example, support a road bench. The technology has been around long enough to be thoroughly studied with *computer models* (e.g., Hatami and Bathurst, 2005; Vulova and Leshchinsky, 2003; Karpurapu and Bathurst, 1995), *laboratory experiments* (e.g., Wu and Helwany, 2001; Zornberg et al., 1998; Helwany, 1994), and *field studies* (Abele, 2006; Liang and Almoh'd, 2004; Tatsuoka et al., 1992).

There is still some debate in the geotechnical engineering community about the fundamental theory of the behavior of geosynthetics in MSE walls versus reinforced soil slopes (VanBuskirk, 2010; Adams et al., 2011). In any case, several techniques have been shown over the years to be cost-effective and sustainable solutions to slope instabilities. The following specific techniques are presented in more detail: shallow MSE walls, geotextile walls, reinforced soil slopes, and deep patch embankment repair.

5.2.1. Shallow MSE Walls

MSE walls are constructed with reinforced soil (Figure 35). The reinforcement can be metal strips (galvanized or epoxy-coated steel), welded wire steel grids, or geogrids. The walls have a vertical or near-vertical face and include a facing system to prevent raveling and erosion. The facing elements could be precast concrete panels, modular concrete blocks, metal sheets, gabions, welded wire mesh, shotcrete, or wood lagging and panels. Hybrid systems are popular; for example a geogrid-reinforced MSE wall with gabion-basket facing was used at several locations along a new highway in Nantahala National Forest in North Carolina (Simac et al., 1997). A variety of proprietary facing–reinforcement systems exist, but since most process patents for MSE walls have expired many options exist for contractors to purchase and erect them. MSE walls can be designed and built to accommodate complex geometries and to heights greater than 80 feet. They offer several advantages over gravity and cantilever concrete retaining walls: simpler and faster construction, less site preparation, lower cost, more tolerance for differential settlement, and reduced right-of-way acquisition (Elias et al., 2001).

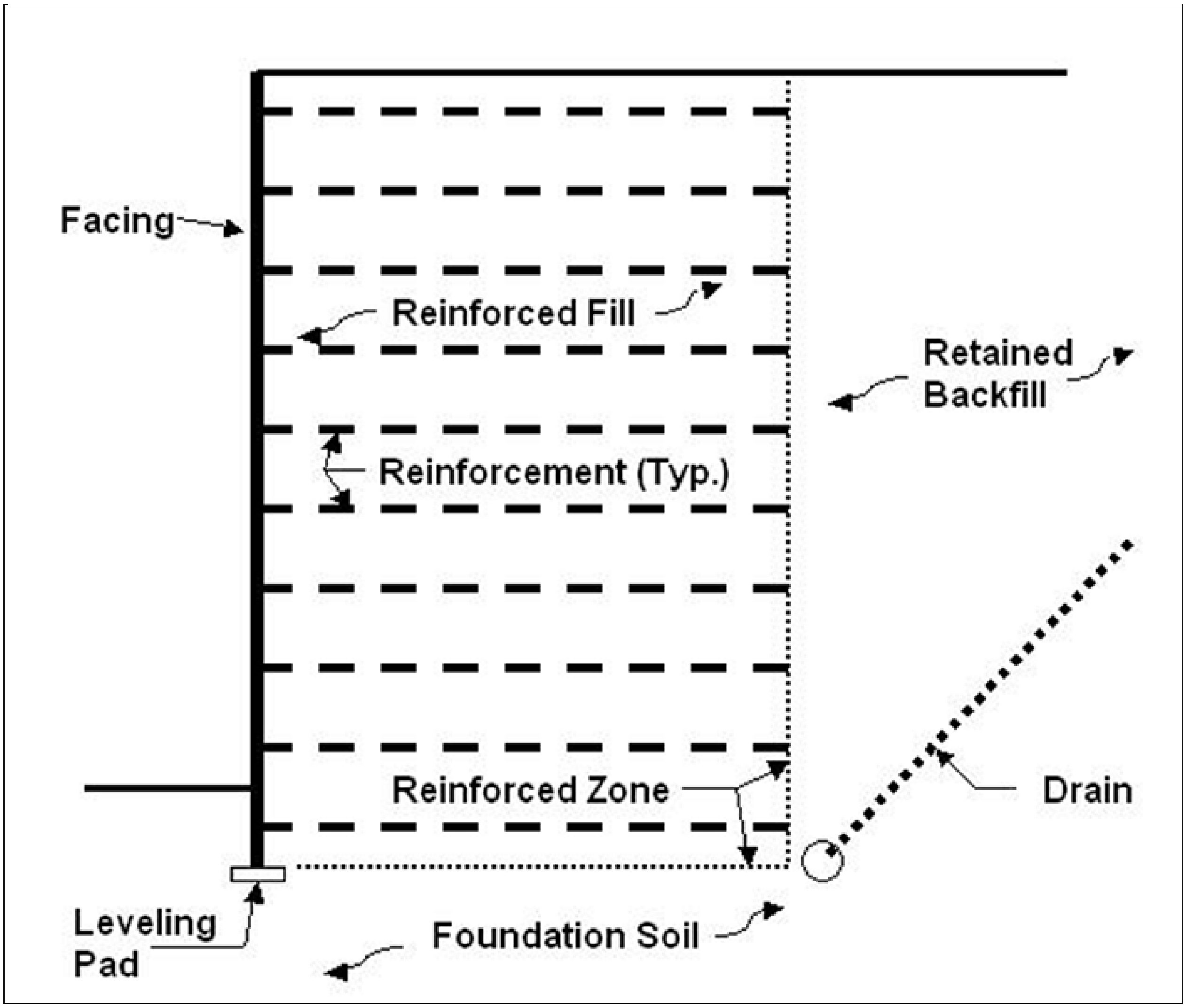

FIGURE 35 SCHEMATIC OF A GENERIC MSE WALL. TAKEN FROM (BERG ET AL., 2009)

While the economic savings of MSE walls compared to traditional concrete retaining walls are significantly better at heights greater than 10 feet, even short MSE walls can be constructed economically. For shallow walls the less expensive option is usually modular block facing, as opposed to precast concrete or metal sheet (Elias et al., 2001). Consider using good quality, especially for high walls, although shorter walls can more easily tolerate poorer quality soils.

Call out box:

> *"[The most cost-effective road slope stabilization technique is] shallow MSE walls, by far and away, because you use native materials and you don't need specialized contractors to do it. We got away from steel strip reinforcement a long time ago. Now we mostly use welded wire because it's easy to install." (S. Romero,personal communication, May 11, 2011)*

Additional Resources for MSE walls

Berg, R. R., B. R. Christopher and N. C. Samtani. 2009. Design of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes—Volume II. Federal Highway Administration Report FHWA-NHI-10-025.

Berg, R., B. Christorpher and N. Samtani. 2010. FHWA GEOTECHNICAL ENGINEERING CIRCULAR NO. 11: Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, Volumes II. 2010. Federal Highway Administration Reports FHWA-NHI-10-024 and FHWA-NHI-10-025.

Elias, V., B. Christopher and R. Berg. 2001. Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines. Federal Highway Administration Report FHWA-NHI-00-043.

5.2.2. Geotextile Walls

Geotextile-wrapped walls, sometimes called burrito walls, were developed by the U.S. Forest Service in the Pacific Northwest as a low-cost alternative to walls requiring facing elements. Geotextile walls are used to stabilize the fill slope by placing sheets of geotextile between layers of soil (pit run or road base) that are usually 6–18 inches (15–50 cm) thick (Figure 36). The geotextile is wrapped at the face, temporary forms or careful compaction can be used before flipping the geotextile over the soil (Powell et al., 1999). Figure 5 shows two examples of geotextile walls. The geotextile face can degrade from sunlight and UV radiation, consider protecting the geotextile unless the wall is constructed as a temporary structure (service life of about three years or less). A layer of gunite (mixture of cement, sand and water) or asphalt emulsion can provide adequate protection (Powell et al., 1999). Vegetation can also shade the geotextile sufficiently. To vegetate a geotextile wall, seeds are sown on the outer face of the soil before wrapping the front with the geotextile; cuttings are also placed in the thin soil layer between sheets of reinforcement (Shah, 2008).

FIGURE 36 EARLY WORK BY A CONTRACTOR CREATING A GEOTEXTILE WALL IN ALASKA, AND GEOTEXTILE WALL ON FILL SLOPE OF ROAD IN KLAMATH NATIONAL FOREST IN CALIFORNIA. PHOTOS PROVIDED BY J. CURREY AND G. KELLER.

Useful Points

- There is a learning curve to creating these the first time and without forms. Using a contractor who has experience in the technique of building a geotextile wall will help. (J. Currey, personal communication, April, 15, 2011)

Additional Resources for Geotextile Walls

Elias, V., B. Christopher and R. Berg. 2001 Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines. Federal Highway Administration Report FHWA-NHI-00-043.

Keller, G. and J. Sherar. 2003. Low-Volume Roads Engineering—Best Management Practices Field Guide. USDA Forest Service, Office of International Programs and U.S. Agency for International Development, Washington, DC. (http://www.fs.fed.us/global/topic/welcome.htm#12).

Powell, W., G. R. Keller and B. Brunette. 1999. "Applications for Geosynthetics on Forest Service Low-Volume Roads." *Transportation Research Record* 1652:113–120.

Shah, B. H. 2008. *Field Manual of Slope Stabilization*. United Nations Development Program, Pakistan. September.

5.2.3. Reinforced Soil Slopes

Reinforced soil slopes (RSSs) are usually steep slopes that are stable because sheets of geosynthetics (geogrids and geotextiles are both common) are used in their construction. The design methods for RSSs are conservative, so they are more stable than flatter slopes designed to the same safety factor (Elias et al., 2001) RSSs offer several advantages over MSE walls: backfill soil requirements are usually less restrictive, the structure is more tolerant to differential settlement, no facing element is required so they are typically less costly, erosion protection vegetation can be incorporated into the face of the slope.

Useful Points

- When using geosynthetics for reinforced soil slopes you need to match the type with the site-specific parameters. (K. Mohamed, personal communication, April 26, 2011)

Additional Resources for Reinforced Soil Slopes

Elias, V., B. Christopher and R. Berg. 2001 Mechanically Stabilized Earth Walls and Reinforced Soil Slopes Design and Construction Guidelines. Federal Highway Administration Report FHWA-NHI-00-043.

Berg, R. R., B. R. Christopher and N. C. Samtani. 2009. Design of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes—Volume II. Federal Highway Administration Report FHWA-NHI-10-025.

Berg, R., B. Christorpher and N. Samtani. 2010. FHWA GEOTECHNICAL ENGINEERING CIRCULAR NO. 11: Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil Slopes, Volumes I and II. Federal Highway Administration Reports FHWA-NHI-10-024 and FHWA-NHI-10-025.

5.2.4. Deep Patch Embankment Repair

The deep patch embankment repair is similar to a reinforced soil slope except the repair is limited to the top of the fill slope instead of reinforcing the entire slope. It is commonly used on paved forest roads with recurring cracks and settlement in the outer portion of road. A deep patch repair involves excavating 3–8 feet (1–2.5 meters) deep and reconstructing with compacted, granular soil and geogrids. Drainage is usually incorporated in the repair. Vertical spacing for geogrid is 1 foot (30 cm), so a 6-foot-deep (2 meter) repair would need six layers of geogrid. The depth, width, and length of the deep patch depend on the location of the cracks. For cracks near the outer edge of the road, a 3-foot-deep (1 meter) repair is usually fine. For cracks near the centerline, especially with greater settlement (vertical displacement), a deeper repair is needed. The length of the repair should extend at least 5 feet (1.5 meters) beyond the ends of the crack. Deep patches have been as short as 20 feet (6 meters) and as long as 800 feet (25 meters), although repairs 50–150 feet (15–45 meters) long are more common. The width of the deep patch needs to extend beyond the crack so the repair is “anchored” into the stable portion of the slope. A good rule-of-thumb is to extend the patch 5 feet (1.5 meters) behind the crack, although an analysis of pullout failure should be performed. Photos of a deep patch in Gifford Pinchot National Forest in Washington during and after construction are shown in Figure 37.

FIGURE 37 DEEP PATCH DURING AND AFTER CONSTRUCTION IN GIFFORD PINCHOT NATIONAL FOREST IN WASHINGTON. PHOTOS PROVIDED BY B. COLLINS.

Additional Resources

Wilson-Musser, S. and C. Denning. 2005. Deep Patch Road Embankment Repair Application Guide. USDA Forest Service. October (http://www.fs.fed.us/t-d/pubs/pdf/05771204.pdf).

Cuelho, E.V., S. Perkins and M.R. Akin. 2011. Evaluation and Revision of Deep Patch Design Method. Western Federal Lands Highway Division Report FHWA-WFL

5.2.5. Tire Walls

Tire walls have been used as retaining structures, for erosion control and to stabilize slopes (USFS., 1992; Retterer, 2000) (Figure 38). The tires can be used as facing or for reinforcing backfill soil. Tire reinforced walls can made from whole tires or bales of compressed tires (Retterer, 2000). Tire walls can be constructed up to 10 ft in height. There are many ways to construct tire walls using varying soil and rock fill types and geosynthetics (Garga and O'Shaughnessy, 2000a; Retterer, 2000). To ensure stability and strength of the tire wall connect the tires together appropriately (Garga and O'Shaughnessy, 2000b).

Significant settlement of tire walls has been observed in field applications (USFS, 2000). Tire walls are considered by some to be visually unappealing. Vegetation, geotextile, shotcrete, concrete blocks, etc. can be used to cover the tires wall surface. Tire walls can be less costly than other retaining wall structures, but cost savings will vary based on location and availability of materials. In general tire walls can be constructed without skilled labor or special equipment (Retterer, 2000).

FIGURE 38 TIRE WALL AND CONSTRUCTION. PHOTOS PROVIDED BY G. KELLER.

Additional Resources for Tire Walls

Garga, V.K. and V. O'Shaughnessy. 2000a. Tire-reinforced earthfill. Part 1: Construction of a test fill, performance, and retaining wall design. Canadian Geotechnical Journal, 37(1): 75-79.

Garga, V.K. and V. O'Shaughnessy. 2000b. Tire-reinforced earthfill. Part 2: Pull-out behavior and reinforced slope design. Canadian Geotechnical Journal, 37(1): 97-116.

Garga, V.K. and V. O'Shaughnessy. 2000c. Tire-reinforced earthfill. Part 3: Environmental Assessment. Canadian Geotechnical Journal, 37(1): 117-131.

Retterer, T.A. 200. Gravity and Mechanically Stabilized Earth Walls Using Whole Scrap Tires. Masters Thesis. Texas Tech University. May.

U.S. Forest Service (USFS). 1992. Engineering Field Notes, Engineering Technical Information System. Volume 24. Washington, DC. Setpember-October.

5.3. In-Situ Soil Reinforcement

In-situ soil reinforcement involves repairing instabilities with minimal to no excavation by inserting reinforcing elements into the soil. While fibers can be used as soil reinforcement (Park and Tan, 2005), they are currently considered too expensive unless more low-cost fibers (e.g., recycled fibers) of high quality become available for slope stabilization applications. Similarly, the use of lime piles ("holes in the ground filled with lime") has been reported to be successful for "in situ treatment of failing clay slopes" (Rogers and Glendinning, 1996) but not widely implemented for roadside slope stabilization, likely for cost reasons. Three cost-effective techniques were identified and are described below: launched soil nails, pin piles, and plate piles.

5.3.1. Launched Soil Nails

Shallow instabilities can be repaired by launching an array of soil nails (also referred to as ballistic soil nailing) through the ground surface deep enough to penetrate into a stable region. The technique was developed in the United Kingdom to avoid the need to excavate and construct a working platform from which traditional soil nails could be drilled and grouted in place. As illustrated in Figure 39, an excavator with a hydraulic boom is used to install soil nails between 5 and 35 feet (1.5 and 10 meters) above and below its position on the road. This technique can be used for instabilities as deep as 15 feet (4.5 meters) from the surface, in which case 20-foot-long (6 meters) nails with a diameter of 1.5 inches (3.8 cm) would be used. For shallower instabilities, shorter nails are used and/or the portion of the nail protruding from the ground is cut off at the ground surface (USDA Forest Service, 1994). Originally solid nails were used, but now hollow galvanized steel or fiberglass tubes are much more common (Barrett and Lobato, 2011). This technique can be used in sands, gravels, silts, clays, and soils with only a few cobbles and boulders. Too many cobbles or boulders would reduce the penetration depth of the nails. Design charts and design examples are available in a USDA Forest Service application guide (1994).

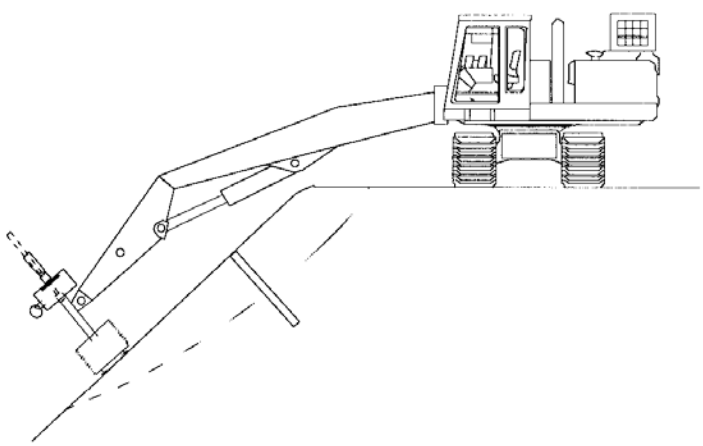

FIGURE 39 A SOIL NAIL LAUNCHER MOUNTED ON AN EXCAVATOR INSTALLING NAILS ON AN UNSTABLE FILL SLOPE BELOW A ROAD. TAKEN FROM (USDA FOREST SERVICE, 1994).

Additional Resources Launched Soil Nails

Barrett, C. E. and S. C. Devin. 2011. “Shallow Landslide Repair Analysis Using Ballistic Soil Nails: Translating Simple Sliding Wedge Analysis into PC-Based Limit Equilibrium Models.” In the Proceedings *Geo-Frontiers 2011 Conference*.

Steward, J. E. and J. M Ribera. 1995. “Launched soil nails: New method for rapid low-impact slope repairs.” In *Proceeding of the Sixth International Conference on Low-Volume Roads.* Minneapolis, MN, June 25-29.

Application Guide for Launched Soil Nails. 1994. USDA Forest Service. Report EM 7170-12A

(www.fs.fed.us/eng/pubs/pdf/em7170_12a.pdf).

5.3.2. Pin Piles (Micropiles)

Pin piles (also known as micropiles) are more commonly used for foundations than slope stabilization (Pearlman, 2001; Tarquinio and Pearlman, 1999). In 2000 when FHWA published design and construction guidelines for micropiles, the chapter devoted to applications for slope stabilization was left out due to a lack of consensus on design procedures. Even in 2008 use of the technique was noted to be limited (Loehr and Brown, 2008). Most references to pin piles or micropiles for slope stabilization are for repairs to deep-seated failures and involve driving (or drilling and casting) long piles at various angles to form “a monolithic block of reinforced soil” (Holtz and Schuster, 1996). However, anecdotal evidence of shallow repair failures 5–10 feet deep (1.5 to 3 meters) using recycled railroad rails was found during the interviews, although performance and design information was not identified.

When asked to provide an example of an underutilized tool, technique or method, Pete Bolander (personal communication, May 2, 2011)replied:

> *Possibly the use of pin piles to stabilize shallow fill slope failures, some forests in Idaho and Montana have been using railroad rails (steel, long rectangular cross section) as pin piles and have had some success. There are a couple (of) techniques. In the east coast they’ve taken these piles (steel or wood) and driven them in the top of the fill slope to reduce the fill slope settlement – intended to be a shallow repair (maybe anywhere from 5 to 10 ft deep).*

5.3.3. Plate Piles

Plate piles are a relatively new slope stabilization technology; the method and device was patented in 2006. As illustrated in Figure 8, an array of plate piles is driven into the soil to prevent shallow slope creep or landslides. A typical galvanized steel plate pile consists of a 2.5-inch (6 cm) L-shaped stem that is 6 feet (1.8 meters) long with a 2-foot-by-1-foot (30 by 60 cm) rectangular plate attached near the top. Typical spacing is 4 feet (1.2 meter) between piles within a row and 10 feet (3 meter) between rows (Figure 40). Other sizes are available depending on site requirements. Successful full-scale field tests and demonstration projects have been reported (Short and Collins, 2006; McCormick and Short, 2006; personal communication Y. Prashar). Ideally the plate piles would be driven through shallow, unstable fill 2–3 feet thick (0.6–1 meter) and into a more competent stratum (e.g., claystone or weak sandstone).

FIGURE 40 6-FOOT PLATE PILES (LEFT) AND PLATE PILE INSTALLATION (RIGHT) USING AN EXCAVATOR WITH A HYDRAULIC HAMMER. PHOTOS PROVIDED BY Y. PRASHAR.

Additional Resources for Plate Piles

McCormick, W. and R. Short. 2006. “Cost-Effective Stabilization of Clay Slopes and Failures Using Plate Piles.” In *Proceedings of the 10th IAEG International Congress*, Nottingham, United Kingdom, September 6–10.

McCormick, W. 2011. “Platepiles: Caltrans experiments with the next generation slope repair alternative.” *AEG News* 54(1), March.

Platepile Slope Stabilization Design Guidelines Second Edition. 2011. Slope Reinforcement Technology, LLC.

Short, R. D. and Y. Prashar. 2011. “Modeling a full scale slide test.” In *Proceedings of Geo-Frontiers 2011 Conference*. March 13-16. Dallas, Texas.

Titi, H. and S. Helwany. 2007. Investigation of Vertical Members to Resist Surficial Slope Instabilities. Wisconsin Highway Research. SPR# 0092-05-09 (http://minds.wisconsin.edu/handle/1793/53953).

6. Earthwork Techniques

This section summarizes literature and interview results on earthwork techniques. Earthwork techniques involve the physical movement of soil, rock, and/or vegetation for the purpose of erosion control and slope stabilization. As part of construction site planning and management, earthwork techniques can be employed to reshape the ground surface to planned grades and to "control surface runoff, soil erosion, and sedimentation during and after construction" (EPA, 2008). For instance, land grading can be used to treat sites with uneven or steep topography or easily erodible soils so as to stabilize slopes, while gradient terraces can be used to reduce sediment-laden runoff by "slowing, collecting and redistributing surface runoff to stable outlets" (EPA, 2008).

Similar to other slope stabilization techniques, the implementation of earthwork techniques can benefit greatly from good planning that tailors the solution(s) to specific site challenges and constraints. The planning should consider whether a specific tool is suitable for the site (e.g., "gradient terraces are inappropriate for use on sandy or shallow soils, or on steep slopes"), the proper selection of site areas to be graded and the proper spacing and grading of slopes or terraces, the drainage patterns, acceptable outlets of re-directed runoff, the timing of earthwork, the handling of excess or borrowed materials, and maintenance considerations (e.g., inspection after heavy rainfalls) (EPA, 2008). For instance, it is crucial to conduct engineering geological mapping in the early stage of construction to minimize the risk of plane failure when man-made cut slopes are to be constructed (Yue and Lee, 2002). It is cautioned that existing drainage patterns should be maintained wherever possible and measures should be taken to minimize disturbed areas and exposed soils and to minimize possible erosion, sedimentation and dust from exposed soils (EPA, 20008).

Useful Points

- Avoid burying stumps, logs, slash or organic debris in the fill material or in the road prism (Keller and Sherar, 2003).

Additional Resources for Earthwork Techniques

Boaze, P. and B. Wiggins. 2000. "Building a Major Highway in Mountainous East Tennessee: Environmental Impacts." *Land and Water* 44(4):20–23.

U.S. Environmental Protection Agency (EPA). 1992. *Stormwater Management for Industrial Activities: Developing Pollution Prevention Plans and Best Management Practices*. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

EPA. 1993. *Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal Waters*. EPA 840-B-92-002. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

EPA. 2004. *Development Document for Final Action for Effluent Guidelines and Standards for the Construction and Development Category.* EPA-821-B-04-001. Washington, DC.

EPA. 2008. National Pollutant Discharge Elimination System: National Menu of Stormwater Best

Management Practices. Stormwater Best Management Practices (http://cfpub1.epa.gov/npdes/stormwater/menuofbmps/index.cfm).

Keller, G and J. Sherar. 2003. Low-Volume Roads Engineering—Best Management Practices Field Guide. USDA Forest Service, Office of International Programs and U.S. Agency for International Development, Washington, DC. (http://www.fs.fed.us/global/topic/welcome.htm#12).

Long, M. T. 1994. *Horizontal Drains, Application and Design*, Section 6D, in The Slope Stability Reference Guide for National Forests in the United States, USDA, Forest Service, Engineering Staff, Washington D.C. (http://www.fs.fed.us/rm/pubs_other/wo_em7170_13/wo_em7170_13_vol3.pdf).

State of Delaware. 1989. *Delaware Erosion and Sediment Control Handbook for Development.* Department of Natural Resources and Environmental Control, Division of Water Conservation.

State of North Carolina. 1988. *Erosion and Sediment Control Planning and Design Manual.* North Carolina Sedimentation Control Commission and North Carolina Department of Natural Resources and Community Development, Raleigh, NC.

6.1. Benched Slopes

Many types of slope modifications include terraces, benches, steps, and serrations that are used to minimize erosion and control runoff (TIRRS, 2001) (Figure 41). Slope shaping can also provide sites for vegetation to establish. Benches, terraces, steps or serrations are mainly distinguished by size (TIRRS, 2001). Slope shaping is well suited for large cut-and-fill slopes. The size of the bench to be installed is determined by the length and degree of the slope (Table 5). For example, long or steep slopes may require many short benches, while less steep slopes may be stabilized with steps or serrations (TIRRS, 2001). When creating these feature on a slope it is important not to leave the surface too smooth but to allow for microtopography—small uneven bumps and ridges that will collect moisture and seeds and improve chances for successful vegetation (Goldman et al., 1986; TIRRS, 2001).

TABLE 5 EXAMPLES OF SLOPE MODIFICATION TECHNIQUES AND THE GENERAL PARAMETERS USED TO CREATE THEM. TAKEN FROM (TIRRS, 2001).

Slope Modification Techniques	Design Parameters
Benches or terraces	4 to 10 feet (1.2 to 3 meters) wide horizontally, level or slightly sloping toward the slope (reverse sloping)
Steps	1 to 4 feet (0.3 to 1.2 meters) wide, usually horizontal
Serrations	~ 10 inches (25 cm) wide, cut by a serrated wing blade

Two main advantages of benched cut slopes, from a stability point of view, is their ability to slow down the rate of surface runoff, and the fact that shallow failures are usually limited to one bench at a time (Hearn and Weeks, 1997). The steps on a benched cut slope should slope into the hillside and have a drainage system installed. Vegetation is more difficult to establish on the steeper riser slopes than on a uniform slope profile. Benches provide an area for vegetation to grow, catch falling material, and break up the areas of drainage, etc. (Hearn and Weekes, 1997).

FIGURE 41 CONSTRUCTED TERRACES ON EXPOSED SLOPES IN ERITREA AND PAKISTAN. PHOTOS PROVIDED BY A. FAIZ.

Maintenance of benches includes periodic inspection for damage from runoff (TIRRS, 2001). If not repaired, rills and gullies may develop. Accumulated sediment may also need to be removed to prevent blockage of drains. Maintenance activities have potential for increasing erosion; therefore limit site disturbances as much as possible.

Building terraces does not work well on decomposed granitic soils or in areas with high groundwater tables (TIRRS, 2001).

Additional Resources for Benched Slopes

Abramson, L. W., T. S. Lee, S. Sharma, G. M. Boyce. 2002. *Slope Stability and Stabilization Methods*. New York: John Wiley & Sons.

Goldman, S., K. Jackson and T. A. Bursztynsky. 1986. *Erosion and Sediment Control Handbook*. New York: McGraw Hill.

Hearn, G. J. and R. W. Weekes. 1997. Principles of low-cost road engineering in mountainous regions. Transport Research Laboratory, Overseas Road Note 16.

Tahoe Interagency Roadway Runoff Subcommittee (TIRRS). 2001. Planning Guidance for Implementing Permanent Storm Water Best Management Practices in the Lake Tahoe Basin, Chapter 6. Slope Stabilization Techniques.

6.2. Soil Roughening

Soil roughening is a temporary erosion control measure that is often performed in conjunction with grading of slopes (EPA, 2008). Soil roughening involves increasing the relief of a bare soil surface with horizontal grooves by either running a piece of equipment parallel to the contour of the slope, or using equipment to track the surface, like a *sheep's foot* attachment. As a general practice slopes are not finely graded, but instead left in a roughened condition (Figure 42). Avoid compacting the soil with heavy equipment, specifically on clay-rich soils.

FIGURE 42 ROUGHENED SOIL AND TRACKWALKING WITH HEAVY EQUIPMENT. PHOTO PROVIDED BY G. KELLER

Soil roughening reduces runoff velocity, increases infiltration rates, reduces erosion, traps sediment and prepares soil for seeding and planting by giving seeds an opportunity to take hold and grow. Soil roughening is inexpensive, but heavy equipment is needed.

Soil roughening can be used on all graded slopes, specifically slopes great than 3:1, excavated soils, and highly erodible soils (EPA, 2008). Soil roughening should occur as soon as vegetation has been removed, or as soon as grading work is completed. Seeding, planting or mulching can then be used to further stabilize the slope.

Soil roughening does not work well on rocky slopes and is only effective under moderate to light precipitation events. If heavy precipitation occurs, re-tracking may be needed. Roughened slopes should be monitored for rills, and if found the slope section should be regraded and reseeded.

Additional Resources for Soil Roughening

EPA. 1992. *Stormwater Management for Industrial Activities: Developing Pollution Prevention Plans and Best Management Practices*. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

EPA. 1993. *Guidance Specifying Management Measures for Sources of Nonpoint Pollution in Coastal*

Waters. EPA 840-B-92-002. U.S. Environmental Protection Agency, Office of Water, Washington, DC.

EPA. 2008. National Pollutant Discharge Elimination System: National Menu of Stormwater Best Management Practices. Stormwater Best Management Practices (http://cfpub1.epa.gov/npdes/stormwater/menuofbmps/index.cfm).

Goldman, S., K. Jackson and T. A. Bursztynsky. 1986. *Erosion and Sediment Control Handbook*. New York: McGraw Hill.

Smolen, M. D., D. W. Miller, L. C. Wyatt, J. Lichthardt, and A. L. Lanier. 1988. Erosion and Sediment Control Planning and Design Manual. North Carolina Sedimentation Control Commission; North Carolina Department of Environment, Health, and Natural Resources; and Division of Land Resources, Land Quality Section, Raleigh, NC.

6.2.1. Extreme Roughening

Extreme soil roughening is similar to soil roughening mentioned in the previous section except instead of creating microtopography you are creating basins. A backhoe or trackhoe shovel is used to create basins for extreme surface roughening. The trackhoe shovel is used to dig, poke, or push basins with a minimum depth of 18 inches (0.5 meter). These basins should be 1.5–2 feet (0.5 meter) deep and have the width of the bucket, up to 4 feet (1.2 meters) wide. The most common construction method is to dig a bucket load of soil and then drop it 2–3 feet (0.6–1 meter) above the excavated soil surface. Repeat this process in a random and overlapping pattern, making it impossible for water to flow down slope. Finished roughened soils should be difficult to walk over. On poor, rocky sites, basins can fill with soil within a short time period. For this reason the basins should be made as large as possible. Conversely, on sites with adhesive soils, the basins should not be too large because they do not fill in with sediment over time. Surface erosion control measures should be used. For example, straw can be spread during roughening and anchored to the soil surface by jabbing the materials into the soil surface or tacking them with hydromulch slurry.

Consider broadcast seeding on extreme roughened slopes. In areas with extremely dry and loose soil, it may be advantageous to wait until the soil has settled before starting the seeding process. One method is to broadcast half the seed immediately and broadcast half the seed after the soil settles.

Problems may occur if:

- Basins are made when the soil is wet, causing hard, compacted soils to form in the depressions when dry.
- There is too much space between basins. Basins need to be overlapping.
- Basins are not large enough, making them susceptible to filling in with sediment prior to vegetation establishment.
- Soil roughening is a temporary erosion control measure.

Additional Resources

Wright, A. (Ed.). The practical guide to reclamation in Utah. Utah Oil Gas and Mining.

(https://fs.ogm.utah.gov/PUB/MINES/Coal_Related/RecMan/Reclamation_Manual.pdf).

6.2.2. Ripping of Soil Surface

Ripping breaks up compacted layers of soil. Ripping is used as a soil roughening technique in areas too large to economically roughen with a backhoe. Seed can be simultaneously spread with the ripping operation if a broadcast seeder is attached to the ripping equipment. Soil amendments or surface mulch should be incorporated into the soil during the ripping operation or anchored with non-surface disturbing methods such as tackifier or netting. Rip soils when they are dry to permit shattering beneath the surface.

Ripping guidelines:

- Rip to a depth of 2–3 feet (0.6–1 meter) and at similar intervals.
- Rip on contour to the slope.
- Rip 10–20 feet (3–6 meters) and then start again, this will reduce long water pathways.

Additional Resources for Ripping of Soil Surface

Wright, A. (Ed.) The practical guide to reclamation in Utah. Utah Oil Gas and Mining (https://fs.ogm.utah.gov/PUB/MINES/Coal_Related/RecMan/Reclamation_Manual.pdf).

6.3. Flattening Slopes

Flattening over-steep slopes or slope re-profiling is a technique used to trim slopes back to a gentler slope angle (Hearn and Weekes, 1997). To re-profile the slope, material is unloaded from the head, or top of the slope, and/or material is placed at the base of the slope (also called toe weighting). Slope re-profiling generally increases slope stability, but is not feasible to do over large areas. Other disadvantages of flattening slopes are that acquiring additional right-of-way may be necessary, there may be a need to dispose of excess soil (often more is removed than replaced), and it can be difficult to "[find] a practical place to start the excavation" (Abramson et al., 1996). In any case, slope re-profiling is one of the most widely applied and economical methods for improving slope stability (Lee et al., 2002).

Additional Resources for Flattening Slopes

Abramson, L. W., T. S. Lee, S. Sharma, G. M. Boyce. 2002. *Slope Stability and Stabilization Methods*. New York: John Wiley & Sons.

Hearn, G. J. and R. W. Weekes. 1997. Principles of low-cost road engineering in mountainous regions. Transport Research Laboratory, Overseas Road Note 16.

6.4. Landforming, Geomorphic Modification

Landforming, or landform grading, aims to preserve the underlying landform through replication of geomorphology and associated vegetation, and to recreate or mimic stable natural slopes using a wide variety of slope elements and forms (Schor and Gray, 2007) (Figure 43). This varies greatly from the traditional methods of slope grading used in housing developments where linear flat pads and slopes are created. While landform grading by itself will not prevent all erosion from occurring, the technique creates slope shapes that are less likely to suffer erosion and overall creates more stable slopes.

Call out box:

> *"Landform grading provides a cost-effective, attractive, and environmentally compatible way to construct slopes and landforms that are superior in the long run in terms of resistance to surficial erosion and mass wasting." – Landforming (Schor and Gray, 2007)*

The traditional, "engineered" approach to slope design is characterized by linear, horizontal alignments, planar surfaces of a uniform slope ratio with a sheet flow run-off pattern and uniform plantings, and often an abrupt transition between manmade and natural slopes. The shape of traditionally engineered slopes and other manmade creations do not typically exist in the natural topography. Landform slope design is based on the various typical natural slope elements identified and is characterized by concave and convex shapes, variable slope ratios and diverse run-off patterns that encourage diverse re-vegetation patterns, as well as a more gentle transition between manmade and natural slopes (personal communication with B. Schor).

While it is believed that landforming techniques will translate to roadway environments, the authors feel that landforming may not be feasible in all highway situations because of restrictions or creative limitations presented in typical linear right-of-ways adjacent to roads (personal communication with B. Schor).

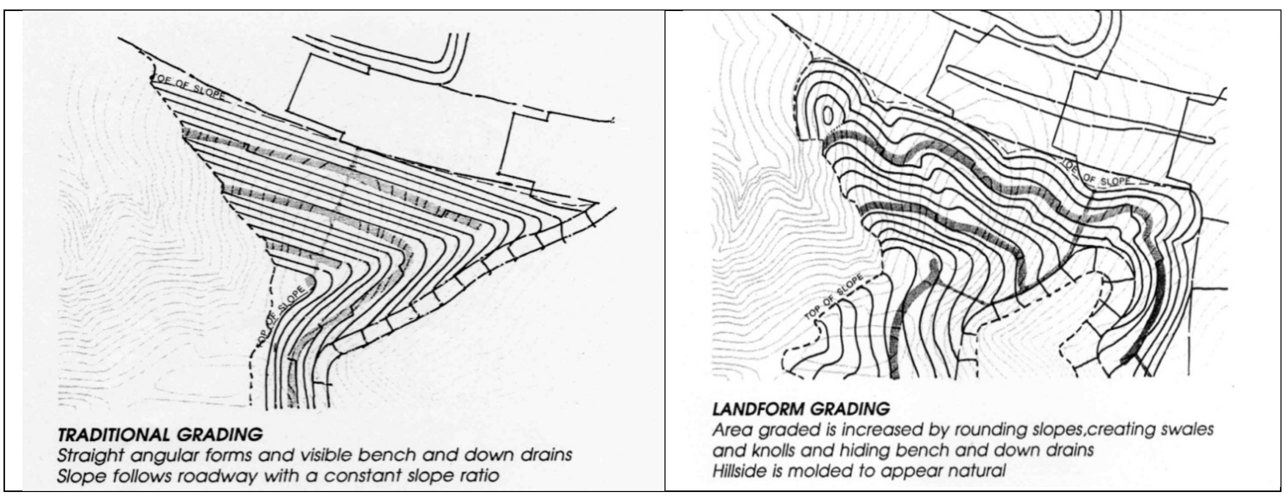

FIGURE 43 TRADITIONAL GRADING VERSUS LANDFORM GRADING. FIGURES PROVIDED BY D. GRAY.

Landform grading was originally developed as an alternative to traditional grading; it has been used in many other applications since its inception such as watershed restoration and mine reclamation. In a project conducted in 2004, landform grading was used in conjunction with traditional low-cost and environmentally friendly slope stabilization techniques at Nichols Arboretum in School Girl's Glen in Ann Arbor, Michigan (Gray et al., 2004). Landform grading was used to create stepped pools to handle unmitigated on-site water flow. Traditional slope stabilization techniques used were stone weirs, live staking and native plants, gabion check dams and root-wad revetment, and boulder cascades.

Additional Resources for Landforming

Schor, B. and D. H. Gray. 2007. *Landforming: An environmental approach to hillside development, mine reclamation and watershed restoration.* Hoboken, N.J.: John Wiley & Sons.

7. Conclusions

This report presented information on cost-effective and sustainable road slope stabilization techniques, with a focus on shallow or near-surface slope stabilization and related erosion control methods used on low-volume roads. To document the state of the practice, a comprehensive literature review was conducted, followed by a survey and interviews. The key findings from each section are presented below.

Information was presented on how to plan for success, including the importance of creating a work plan, project timing, identifying necessary preliminary work, using a multi-disciplinary approach and, once completed, how to perform a site assessment and/or necessary maintenance.

The role of soil type and soil mechanics in slope stability was reviewed. Including the importance of understanding what soil types are present, how they will behave under stress or saturated with water, and the mechanism by which they could fail. Understanding these concepts will aid in the selection of appropriate slope stabilization techniques and vegetation to most effectively stabilize the slope.

Appropriate water management may be the key to preventing slope failures. Developing a water management plan that identifies where the water is coming from, how the water interacts with soil and topography of the site, where the water will go, and how much water is on site are critical. When designing and building roads using well-draining materials and incorporating surface and sub-surface drainage where appropriate is critical.

Use of mulch and soil amendments (e.g., compost) can help onsite vegetation to stabilize a slope. In many cases, the soil that is exposed when cut-and-fill slopes are created along roadways is not suitable for plant growth. Soil amendments with fertilizer, compost, mulch or the addition of topsoil may be necessary. Sustainable practices include saving and reusing topsoil and mulching with onsite materials.

Erosion control is the proactive use of products and techniques to prevent soil from eroding from slopes. A summary of cost-effective and sustainable erosion control products and techniques is provided in Table 6. Erosion control products should be considered for use at every site on any disturbed soil surface. It is much easier to prevent erosion than to fix a slope that has eroded. Methods used to control surface erosion presented here can be used alone or as a component of a system. This is also true for the other slope stabilization techniques presented in this document. One special note is that the implementation of these techniques should pay close attention to ecological considerations so as to minimize any possible disturbance to the local ecosystem.

TABLE 6 SUMMARY OF EROSION CONTROL TECHNIQUES.

Treatment Component		Stabilization	Pros	Cons
Grass	Hand seeding	Shallow	No equipment required	
	Hydroseeding	Shallow	High success rate	Lack of available of equipment, limited application distance
	Sod	Shallow	High success rate	
	Slips	Shallow	Can be used to create drainage channels	Hand planting takes time
Mulching	Wood, leaf litter, straw, bark, stone	Surface	Keeps soil moist and cool, protects surface from erosion	If mulching with wood chips, nutrients may be removed from soil
Blankets and Mats	Jute, geo-synthetics, rock	Surface	Keeps soil moist and cool, protects surface from erosion. Aids in revegetation of steep slopes and where revegetation may be difficult	Non-biodegradable products should be cleaned from the site
Check Dams	Inert (stone, wood, concrete)	Concentrate and control surface water flow	Reduces suspended solids in runoff	Maintenance may be required to clean out deposited sediment
	Live (vegetated)	Concentrate and control surface water flow	Reduces suspended solids in runoff; Roots increase slope stabilization; Modifies shallow slope hydrology	Maintenance may be required to clean out deposited sediment
Wattles and Rolls	Inert (geosynthetic, straw, coir, pine needle)	Protect against sheet flow, reduces surface water velocity by breaking up the slope	Reduces suspended solids in runoff	Maintenance may be required to clean out deposited sediment, restake and replacement may be necessary; Non-biodegradable products need to be cleaned from the site
	Live (vegetated)	Protects against sheet flow, reduces surface water velocity by breaking up the slope	Reduces suspended solids in runoff; Modifies shallow slope hydrology	Maintenance may be required to clean out deposited sediment, restaking and replacement may be necessary.
Straw Bale Barriers		Slows surface flow	Reduces suspended solids in runoff; Can be used at base of slopes and around drains	Wet bales can be heavy and difficult to move; Bailing material may need to be removed from site if non-biodegradable
Silt Fences		Reduces surface flow	Reduces suspended solids in runoff; Can be used at base of slopes and around drains	Difficult to construct and maintain; Need to be removed from the site

Soil bioengineering and biotechnical slope stabilization is the use of vegetation and structural elements to stabilize slopes and can be both cost-effective and sustainable. A summary of the techniques discussed in the section are provided in Table 7.

TABLE 7 SUMMARY OF SOIL BIOENGINEERING AND BIOTECHNICAL STABILIZATION TECHNIQUES.

Treatment	Component	Stabilization	Pros	Cons
Crib Walls	Inert (wood, concrete)	Shallow; used at base of slope	Reduces steepness, prevents shallow slope failures, works where space is limited	Does not work for large lateral stresses; Maximum height 6-10 ft (2-3 m)
	Live (vegetated)	Shallow, used at base of slope	Modifies shallow slope hydrology; Reduces steepness, prevents shallow slope failures, works where space is limited; Vegetation provides flexible binding	Does not work for large lateral stresses; Maximum height 6-10 ft (2-3 m)
Stakes		Shallow, slump or slips	Work well for projects with limited construction time; Can be used to pin or anchor erosion control materials; Modify shallow slope hydrology	Cuttings should be harvested within a day of planting
Fascines		Shallow; Protect against sheet flow, reduce surface water velocity by breaking up the slope	Modify shallow slope hydrology; Reduce suspended solids in runoff; Well suited for steep, rocky slopes; Can be use to create drainage channels	Maintenance may include thinning vegetation
Brush Layering and Palisades		Shallow; Protect against sheet flow, reduce surface water velocity by breaking up the slope; Armor the slope	Modify shallow slope hydrology; Reduce suspended solids in runoff; Can be used to create drainage channels	Maintenance may include thinning of vegetation
Branch Packing		Shallow; Used for small localized slumps, embankments or holes.	Modify shallow slope hydrology	Does not work on slumps greater than 4 ft (1.2 m) deep or 5 ft (1.5 m) wide; Maintenance may include thinning of vegetation
Rock Joint Planting		Shallow	Modify shallow slope hydrology	Maintenance may include thinning of vegetation
Gabion	Rock or earth filled, vegetated	Shallow, used at base of slope	Modify shallow slope hydrology; Reduce steepness, prevent shallow slope failures, works where space is limited; Vegetation provides flexible binding	Maintenance may include thinning of vegetation
	Soft, vegetated	Shallow, used at base of slope	Modify shallow slope hydrology; Reduce steepness, prevent shallow slope failures, works where space is limited; Vegetation provides flexible binding; Can be used when rock is not available	Maintenance may include thinning of vegetation
Rock Wall	Vegetated	Shallow, used at base of slope	Modify shallow slope hydrology; Reduce steepness, prevent shallow slope failures, works where space is limited; Vegetation provides flexible binding; Can be built against undisturbed slopes	Maintenance may include thinning of vegetation; Boulders or large rock is required

In addition to soil bioengineering, there are many other cost-effective and sustainable slope stabilization techniques that do not necessarily incorporate vegetation and these are grouped in the reinforced soil slope section. This section covers the use of retaining walls, geosynthetics and other artificial and/or non-biodegradable slope stabilizers. A summary of the techniques and products discussed in this section is provided in Table 8.

TABLE 8 SUMMARY OF MECHANICAL STABILIZATION TECHNIQUES

Treatment Component		Stabilization	Pros	Cons
Walls	Masonry (rock, concrete)	Shallow to deep; Protect against toe scour and undermining of cut slopes	Reduce steepness above wall, prevent shallow slope failures, work where space is limited; Provide extra space for a road shoulder; Built external to slope; Easily conforms to slope shape	Does not tolerate settlement or movement; Require a drainage system behind the wall
	Gabion	Shallow to deep; At base of slope	Reduce steepness, prevent shallow slope failures, work where space is limited; Provide extra space for a road shoulder; Can accommodate slope movement; Allow for water drainage	May require the use of an experienced contractor; Baskets are rigid and can be restrictive in building
Mechanically Stabilized Earth and Geosynthetic Reinforced Soil	MSE Walls (reinforcement: metal strips, welded wire, or geosynthetics facing: concrete panels, concrete blocks, metal sheets, gabion baskets, etc.)	Shallow to deep	Reduce steepness, prevent shallow slope failures, work where space is limited; Provide extra space for a road shoulder; Easily conforms to slope shape; Can accommodate complex geometries; Simple and fast construction; Somewhat tolerant of settlement	Good quality backfill should be used
	Geotextile Walls	Shallow to deep; Protect against toe scour and undermining of cut slopes	Reduce steepness, prevent shallow slope failures, work where space is limited; Provide extra space for a road shoulder; Built within the slope; Tolerant of settlement; Can incorporate vegetation	May require the use of an experienced contractor; Geotextile surface must be protected from UV light
	Reinforced Soil Slopes	Shallow to deep	Can provide extra space for a road shoulder; Tolerant of differential settling; Less restrictive soil type criteria; Can incorporate vegetation	Require extensive excavation for deeper instabilities
	Deep Patch Embankment Repair	Shallow	Less excavation than if repairing full depth of slope	Only applicable to failures in fill slope
	Tire Walls	Shallow	No skilled labor or special equipment required.	Settlement occurs. Visually unappealing.
In Situ Reinforcement	Launched Soil Nails	Shallow	Little to no excavation required and little disturbance to existing vegetation	Need to catch problem before slope has failed
	Pin Piles (Micropiles)	Shallow or deep	Works with shallow and deep instabilities	No accepted standard design; More difficult installation than launched soil nails
	Plate Piles	Shallow	Promising new technique	New technique - more case studies need to be documented

Earthwork techniques involve the physical movement of soil, rock and/or vegetation for the purpose of erosion control and slope stabilization. Grading work is done as part of the original road building project but can also be used to prepare a slope for a stabilization treatment. Earthwork techniques discussed in this section are presented in Table 9.

TABLE 9 SUMMARY OF EARTHWORK TECHNIQUES.

Treatment Component		Stabilization	Pros	Cons
Benched Slopes	Benches, terraces, steps, serrations	Surface to shallow; Reduce surface water velocity by breaking up the slope	Shallow failures are limited to one bench at a time, Reduce suspended solids in runoff	Does not work well on decomposed granite or slopes with high water tables; Maintenance may include removal of accumulated sediment
Soil Roughening	Microtopography, ripping, extreme roughening	Surface to shallow; Reduces surface water velocity by breaking up the slope	Increase infiltration rates; Reduce sediment loss	Temporary; Require the use of heavy equipment; Does not work well on rocky slopes; Re-grading may be necessary if heavy precipitation occurs
Flattening Over-steepened Slopes		Shallow to deep	Increase slope stability	Additional right-of-way may be required; Finding a location for soil disposal; Determining a practical place to start excavating
Landforming or Geomorphic Modification		Shallow to deep	Slopes less likely to erode; Overall slopes are more stable; Can be used over large or small areas.	Requires the use of heavy equipment

In summary, here a few key findings to consider when planning for the road slope stabilization project:

- Plan ahead
- Know your site conditions—water, soil, topography
- Consider current and future user needs of a road
- Consider using cost-effective and sustainable treatments

8. Knowledge Gaps

There is a significant body of information about erosion control and near-surface slope stabilization available in the published domain and in the experiences of practitioners. Knowledge gaps that still remain were compiled from review of the literature and the results of the interviews. Further research areas to address these gaps may include the following:

- Methods to determine when a slope is on the verge of failure are needed because preventive action is more cost-effective than reactive measures.
- An understanding of how soils develop on over-disturbed sites.
- A cost/benefit analysis, predictive models, and performance evaluation criteria for each technique.
- Defining life expectancy of each technique and actual capability of products.
- A complete record of root establishment timing, spatial distribution, and contribution to slope stability for different climates and soil compositions. Some of this information is available, but the record is incomplete.
- Compatibility between mechanical and vegetative components of slope stabilization techniques.
- Independent testing of the effectiveness of erosion-control products.
- Independent testing of the effectiveness and appropriate applications for geogrids and geotextiles.
- Analysis techniques and understanding of pin piles.
- The carbon sequestration potential of vegetative solutions and the contribution of these techniques on soil and water conservation.
- The effects of over-digging.
- How cut slopes behave in frozen soils and freeze/thaw issues on new slopes.
- Mandates for the inclusion of erosion control and slope stabilization on all projects.
- Definitive standards or specifications for civil engineers who have little knowledge and training in soil science and plant science.
- Tailoring the solution for the specific site—too often the chosen technique is based on a narrow field of candidates and without considering all possible alternatives.
- Viewing highway slopes as part of an ecosystem that may require restoration based on the need for increased safety, stability, and/or maintaining roadside ecology.
- Encouraging widespread practice of proper soil analyses in the planning stages of projects.
- Increasing the dissemination of information and training.
- Developing a single source of good information—a one-stop-shop toolbox and/or a glove box field guide.
- Implementing site specific warning systems for travelers domestically and internationally.
- Develop a suite of standard test methods for erosion-control products.
- Identify the current knowledge base of vegetation root behavior and then fill in the gaps with laboratory and field studies.
- Evaluation of erosion prediction models.

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Appendix A – Survey Questions and Responses

A survey was developed to gather additional information from practitioners, scientists, contractors and vendors on current practices, best practices, and emerging solutions that are used regionally, nationally, or internationally. The survey was created in Survey Monkey (http://www.surveymonkey.com/), an Internet-based survey tool that allows survey respondents to answer questions online. The survey asked participants to provide identifying information, followed by eight questions requesting information on the respondents' direct experience with erosion control and slope stabilization techniques. The survey was distributed electronically via email to individuals identified in the literature review and by project panel members. Information identified in the survey that was incorporated into this report includes resources, references, erosion control and slope stabilization techniques and tools, best management practices, useful points, photographs, etc. Survey responses aided in focusing the synthesis on the most frequently used road slope stabilization techniques that are cost-effective and sustainable.

Survey Questions

1.Please provide the following information:

Name
Company/Agency
Address
City/Town
State/Province
Zip/Postal Code
Country
Email address
Phone Number

2. How frequently do you use shallow or near surface road slope stabilization and/or erosion control measures in you job?

Always
Frequently
Occasionally
Never (If never please describe you experience with road slope stabilization and erosion control below).

3. Please check the road slope stabilization and/or erosion control measures you have used.

Water Management Plan
Soil Bioengineering
Reinforced Soil Slopes
Biotechnical Slope Stabilization
Structural Stabilization
Surface and Subsurface Water Drainage
Erosion Control Mats/Treatments

Flattening Failing/Over-Steep Slopes
Shallow Structures
Earthwork and/or Terracing
Shallow Anchors
Anchored Wire or Mesh
Pins and/or Posts
Buttresses or Low-Cost Retaining Structures
Brush Layering
Live Stakes
Vegetated Walls
Vegetated Reinforced Soil Slopes
Geotextile (burrito) Walls
Low Gabion Walls
Deep Patch Geosynthetic Road Shoulder Reinforcement
Hydro seeding
Hand seeding
Other (please specify)
4.Where do you use road slope stabilization measures?
Embankments
Road cut and fill slopes
Culverts
Bridges
Other Slopes
Ditch Cleaning or Reshaping
Other (please specify)

5. When considering a road slope stabilization or erosion control measure how important is cost?

- Initial/short term- extremely important, important, somewhat important, not important at all
- Longterm (including maintenance)- extremely important, important, somewhat important, not important at all
- Both short and long term considered together- extremely important, important, somewhat important, not important at all

6.When considering a road slope stabilization or erosion control measure how do you factor in how environmentally friendly or sustainable it is in your decision making process?

Always
Frequently
Occasionally
Never
If considered please describe why (i.e. state mandate, etc.)

7.Can you provide examples of successful road slope stabilization measures you have used that were sustainable, environmentally friendly, and/or low cost? (If so do you have drawings, sketches or photos of these?)

Yes
No
If Yes please provide up to 3 examples below.

8.If you answered yes to the previous question may we contact you for additional information and a possible follow-up interview?

Yes
No
Contact information for follow-up interview (if you did not provide it initially).

9.Please point us to 1-2 relevant documents/publications or professionals that can benefit this project.

Survey Results

A survey was developed by project researchers to gain information on low-cost solutions to road slope stabilization. The survey sought information on treatments currently used by practitioners, the importance of cost and environmental factors when choosing a treatment, and additional resources and people to contact for follow-up information. The following section describes the survey responses.

Survey responses from 81 respondents were received from the following countries: Australia (n=1), Canada (n=3), China (n=2), Ethiopia (n=1), New Zealand (n=1), and U.S.A. (n=63). Nine survey respondents chose not to provide any identifying information.

Figure 44 shows the location and numbers of U.S. respondents.

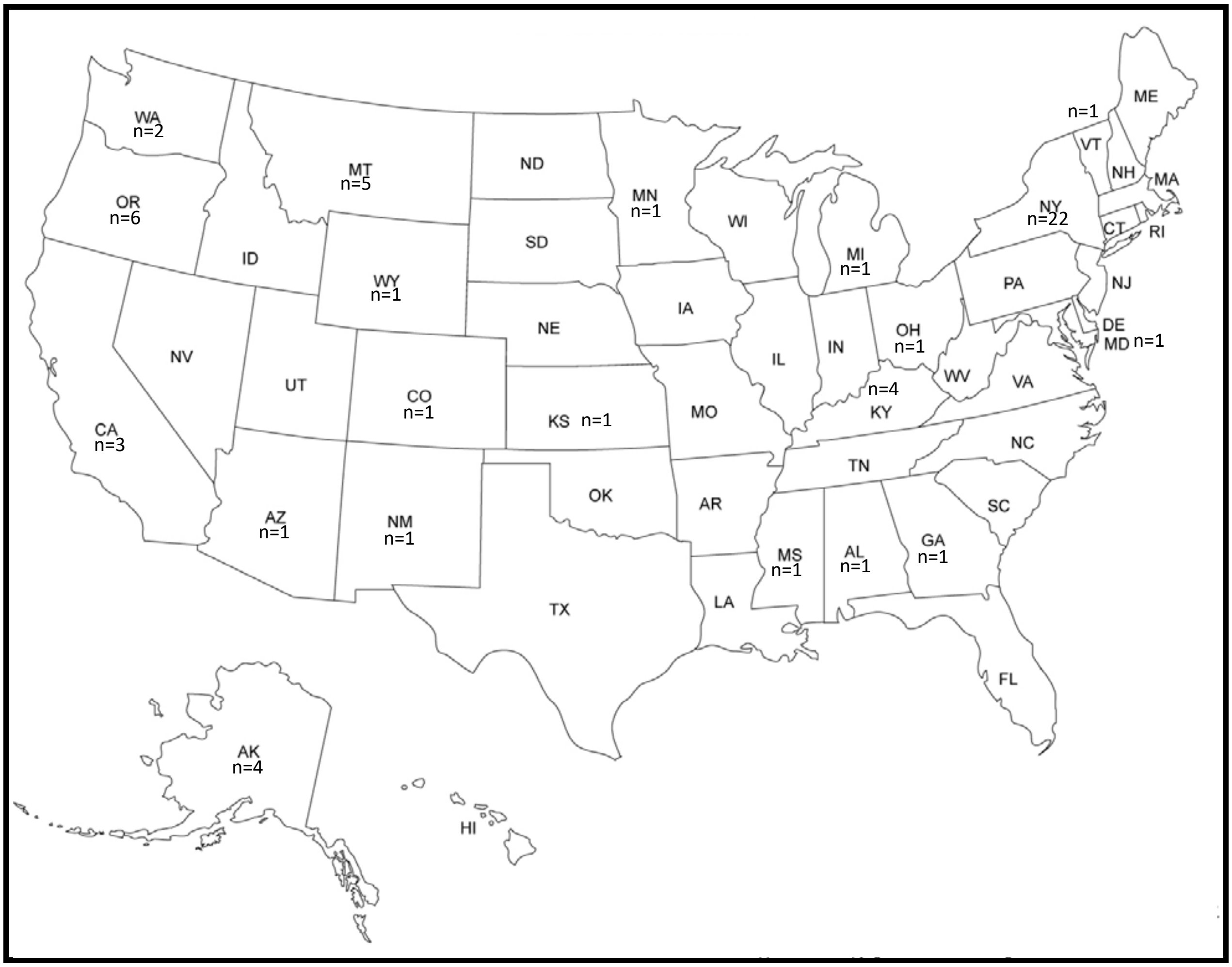

FIGURE 44 MAP OF THE U.S. SHOWING STATES REPRESENTED IN THE SURVEY WITH THE NUMBER OF RESPONDENTS FROM THAT STATE.

Survey respondents were asked how frequently they use shallow or near-surface road slope stabilization and/or erosion-control measures in their job. Responses indicated that only 14 percent of survey respondents *always* use road slope stabilization and/or erosion control measures in their job, while the larger percentage of respondents 38 and 34 percent *occasionally* or *frequently* use road slope stabilization and/or erosion control measures in their job, respectively (Figure 45).

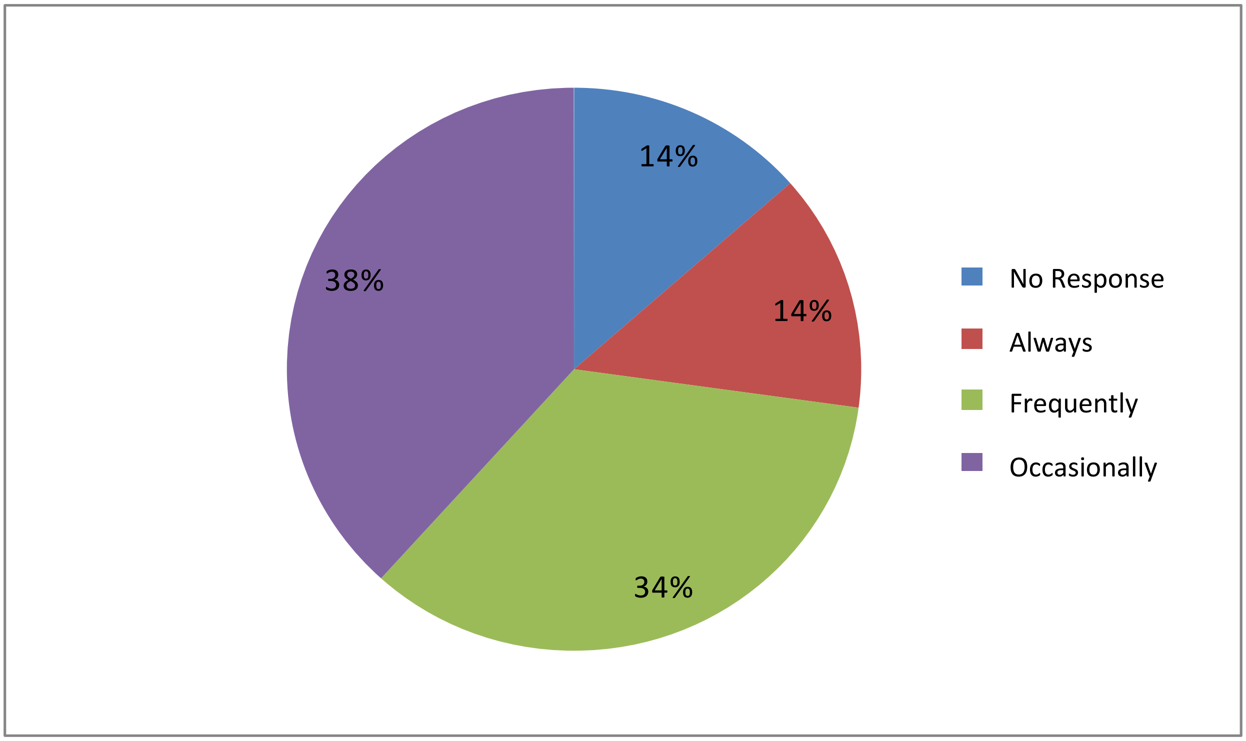

FIGURE 45 FREQUENCY OF USE OF NEAR-SURFACE ROAD SLOPE STABILIZATION MEASURES BY SURVEY RESPONDENTS.

Survey respondents who did not respond to this question, 14 percent of respondents, commented that:

- "I provide training in erosion and sediment control."
- "The only control we use is rocks and natural vegetation."
- "Our organization has researched full depth soil stabilization for expedient airfield construction. This requires heavy dosages of stabilizers to support aircraft loads. We do not have much experience with shallow depth stabilization or erosion control."
- "The Vetiver Network International promotes the Vetiver System for road slope stabilization in tropical and subtropical climates. The system is becoming common practice in some countries. On this basis I will complete the questionnaire."
- "I am a researcher and advisor and not involved with construction."

Survey respondents were then asked which road slope stabilization and/or erosion control measures they have used. Respondents indicated that they used the following road slope stabilization techniques (Table 10)

TABLE 10 ROAD SLOPE STABILIZATION AND/OR EROSION CONTROL MEASURES USED BY SURVEY RESPONDENTS.

Road Slope Stabilization Technique	Number of Respondents who indicated they have used this technique
Hand seeding	47
Surface and Subsurface Water Drainage	44
Hydroseeding	42
Erosion Control Mats/Treatments	37
Structural Stabilization	36
Reinforced Soil Slopes	35
Earthwork and/or Terracing	27
Low Gabion Walls	24
Flattening of Failing/Over-Steep Slopes	23
Vegetated Reinforced Soil Slopes	22
Buttresses or Low-Cost Retaining Structures	22
Biotechnical Slope Stabilization	20
Water Management Plan	19
Vegetated Walls	18
Soil Bioengineering	18
Live Stakes	16
Geotextile Walls	16
Anchored Wire or Mesh	16
Compost/Soil Amendments	15
Brush Layering	11
Shallow Structures	9
Shallow Anchors	8
Deep Patch Geosynthetic Road Shoulder Reinforcement	8
"Burrito" Walls	7
Pins and/or Posts	2

Survey respondents were asked to provide examples of other road slope stabilization and/or erosion control measures they have used that were not listed in the question. They provided the following examples:

- Cement-sand mixture bags
- Fascines, wattles, pole drains, vegetated rip-rap, launched soil nails
- Chemical stabilization and erosion control
- Straw mulch
- Ground up right-of-way, material is passed through a 3-inch screen and blown on cuts and fills after we have placed seed down. We apply with a mulch blower or an adapted manure spreader that one of our contractors developed. Mulch is placed on slopes 0.8 to 1 inch depth.

- Rip rap
- Rough and loose for erosion control

Responses to this question were used as a starting point for information provided in the body of the report.

Survey respondents were then asked where they use road slope stabilization techniques. Survey respondents indicated they commonly use road slope stabilization and/or erosion control measures on embankments, cut and fill slopes, culverts, ditches, bridges and other slopes (Table 11).

TABLE 11 FREQUENCY OF WHERE SURVEY RESPONDENTS USE ROAD SLOPE AND/OR EROSION CONTROL MEASURES.

Embankments	58
Road Cut and Fill Slopes	54
Culverts	46
Ditch Cleaning and Reshaping	41
Bridges	29
Other Slopes	17

Survey respondents were also asked to provide examples of where road slope stabilization and/or erosion control measures were used in addition to the six listed above. One example was provided:

- Sinkholes within the roadway slopes or ditch line.

Survey respondents were asked how important short- or long-term costs were when deciding on a road slope stabilization treatment. The majority of survey respondents indicated that both short- and long-term costs were important when considering road slope stabilization (Figure 46).

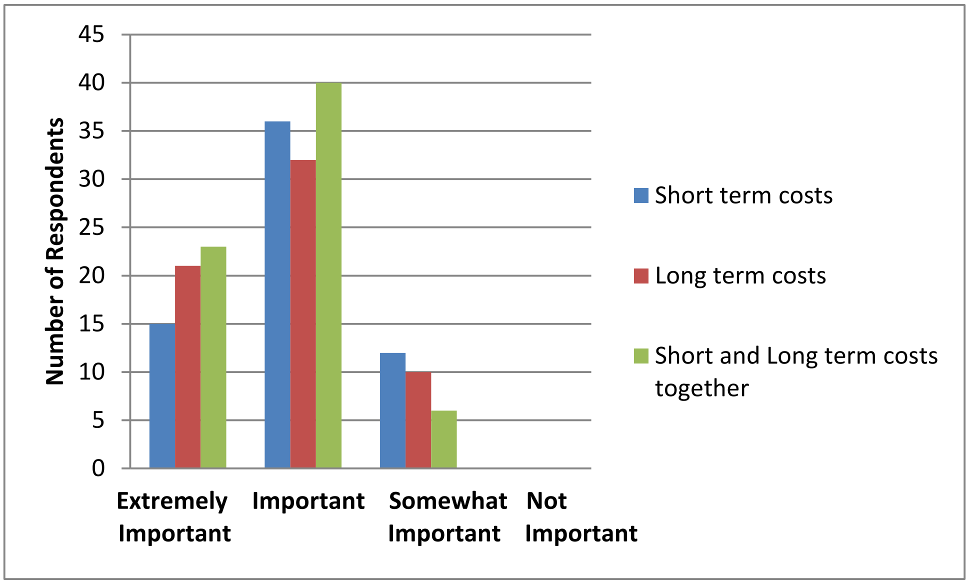

FIGURE 46 EFFECT OF SHORT- AND LONG-TERM COSTS ON DECISIONS TO EMPLOY ROAD SLOPE STABILIZATION TREATMENTS.

Survey respondents were then asked how often they factor in how environmentally friendly or sustainable the measure is when considering a specific road slope stabilization technique. Figure 47 shows that the majority, 76 percent, of survey respondents indicated they *always* or *frequently* factor in the sustainability of road slopes stabilization techniques.

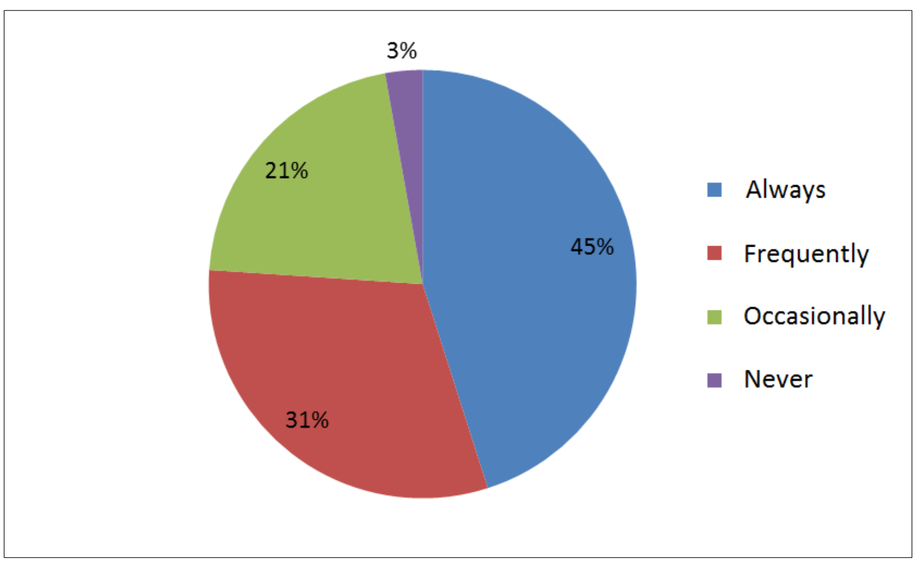

FIGURE 47 IMPORTANCE OF ENVIRONMENTAL FRIENDLINESS OR SUSTAINABILITY ON DECISION MAKING.

The survey respondents who indicated they *always* consider environmental friendliness or sustainability when deciding on road slope stabilization measures provided the following comments:

- “Working in NYC watershed”
- “Agency has strong environmental ethic”
- “State mandate, complying with EPA Consent Decree”
- “It is the World Bank's policy to minimize the negative environmental impact on our projects therefore environmental impacts are very important.”
- “Professional responsibility”
- “The Department has committed to an Environmental Management System which mandates the ‘environment' be considered in all our decisions.”
- “Liability”
- “We always consider possible erosion factors and determine what is necessary. Slope slants range due to individual conditions.”
- “To meet storm water management plans or requirements by Army Corps”
- “Concerned about invasive species (Federal and State), use of native species, chemistry of products, life of system and cost to maintain/replace.”
- “Always considered because of State laws especially near waters”
- “All measures have to be something that would meet our environmental standards or be acceptable to specialists in an Environmental Analysis.”
- “Slope treatments are part of ecological restoration so they must integrate with the restoration of the site, leading to re-establishment of natural successional trajectories.”
- “Because that is very important”

Survey respondents who indicated they *frequently* consider environmental friendliness or sustainability when deciding on road slope stabilization measures provided the following comments:

- “Have less complaints later about the material effect on environment.”
- “Policies and environmental consciousness”
- “Bare ground is the least sustainable practice since it leads to erosion and sedimentation of surface water, but also the lack of vegetation is also analogous to a lack of capacity to sequester CO2. Carbon belongs in the soil, not the atmosphere.”
- “Because I had some experience in the slope bioengineering in China, and others know me from some papers.”
- “Both aspects tend to also reduce future maintenance. Also, with several trout streams in the county, those methods are more easily accepted by natural resources and public.”
- “State and federal water quality requirements. Impacts to maintenance and aesthetics for state forces and the public (yards, parking areas, etc.)”

Survey respondents who indicated that they *occasionally* consider environmental friendliness or sustainability when deciding on road slope stabilization measures provided the following comments:

- “Forest certification plays a role here.”
- “Specifications, Permits”

- “Limited selection of varying measures is possible within state materials allowable.”

No comments were provided by survey respondents who indicated they never consider environmental friendliness or sustainability when deciding on road slope stabilization measures.

Survey respondents were asked to provide examples of cost effective and/or environmentally friendly road slope stabilization measures they have employed. They provided the following examples:

- “-wire basket gabions -jute stabilization bank stabilization mats -heavy stone fill”
- “360 foot parallel culvert to mitigate 4' deep erosion ditch 600 foot parallel culvert to mitigate 3' deep erosion ditch and sheer bank, and to widen unpaved road Gabion baskets used as slope protection”
- “1.) Placement of filter cloth, rip rap , and fine topsoil, geo mat topsoil, grass seed on steep slope to create a reinforced vegetative fabric to stop erosion. 2.) Placement of filter cloth and large rip rap to reinforce culvert inlets and outlets 3.) gabions at pipe inlet/outlet, geo mat, top soil, seed 4.) installation of headwalls to stop erosion at pipe inlets and outlets 5.) seeding drainage swales and ditches after retrenching to stem erosion”
- ”Hydro seeding at the end of the day after digging a ditch. The ditch is stabilized quicker and looks nicer for the public”
- ”Planting trees, Grass, and or placing stones both large and small.”
- ”In 2010, we experienced Emergency level rain/flooding on the Taylor Highway, a primitive gravel road that serves a remote community and travel between Alaska and Dawson City, Yukon Territory, Canada. We used ‘Deep Patch’ type RSS to repair local landslides with failure surface through the travelled way, when final slope was ~1.5:1 or flatter. We used geotextile ‘wrapped face’ walls to repair local landslides where the final slope was steeper than 1.5:1. In some cases, oversteepened final slopes as steep as 0.5:1 were successfully reconstructed. We also used riprap to reconstruct the lower portion of washed-out road embankments. The riprap was placed at slopes approaching 1:1, allowing us to regain road width without exceeding the original road footprint.”
- ”Saco-cretos (cement and sand mixture bags) used in Nicaragua Road Rehabilitation and Maintenance Project in place of the much more expensive gabions. These are placed in a terraced manner, and then covered with vegetative soil, and grass is planted.”
- ”Compost blanket application of 1-3 cm is very environmentally friendly in terms of reusing waste (feedstocks for compost manufacturing), returning and environmental benefit (erosion control and vegetation establishment). The costs associated with these treatments range from low to high depending on the site specific characteristics (compost procurement cost, transportation cost, method of application, etc.). Compost can be considered high cost compared to leaving bare soil in an eroded condition, but I take the position that bare and erosive transportation corridors are unacceptable. If that is true the alternative to compost application is topsoil replacement in areas where topsoil is extremely limited. In the Northern Rocky Mountains DOTs have elected to not replace topsoil on several projects I am familiar with due to local topsoil unavailability/cost with severe consequences in terms of erosion. I have many photos. A second low cost technique I am familiar with is in Yellowstone Park where road widening has resulted in disturbances of soil vegetation. Their low cost technique is on-site tree chipping as mulch for placement on bare soil. It is modestly effective in erosion control. My preference would be to introduce a small amount on compost to this work for the sake of plant available nitrogen to increase the establishment of grasses for erosion control. I believe a

research opportunity exists to develop a continuum of compost and wood waste formulations for roadside revegetation ranging from high nitrogen compost for use in grassland ecotypes to woodier low-med nitrogen compost for use in forest ecotypes. The Yellowstone example was a great low cost method, but somewhat short on effectiveness. This technique was also used in Teton National Park. I have photos. A companion approach is being developed by the Forest Service in Missoula using shredded wood fibers for similar work on forest roads. I have contact names, CDs of research, etc   A third low cost technique that is highly effective and underutilized is native grass sod lined ditches. Several companies are developing native grass sod in rolls up to 4 feet wide. It can easily be installed in ditches or in areas of concentrated flow around culverts, bridge abutments, etc. Sod is 'expensive' compared to seed, but it is inexpensive compared to fabric lined channels and much more effective. Much of the erosion control fabric work done is modestly effective and strongly reflects the quality of the underlying soil. Revegetation by broadcast seeding is inexpensive and effective when applied over good soil and inexpensive and ineffective when applied over poor soil. There tend to be few erosion issues when good soil is used, so the issues are associated with difficult sites. So in a comparison of low cost alternatives I would be inclined to filter out broadcast seeding. hydroseeding on difficult sites because it doesn't work unless there is adequate soil quality. The lowest cost technique is natural recovery by seed rain from adjacent land, but that is impractical since it takes 500-1000 years per inch of soil formation on level ground."

- "Hyroseeding or hand seeding is the most practical and economical and adaptable method and is commonly used. Geotextiles are a little more expensive depending on the fabric selection. Compost blankets are more expensive and more suited to difficult terrain."
- "Please visit TVNI website at: http://www.vetiver.org/ http://www.vetiver.org/g/slope_protection.htm https://picasaweb.google.com/VetiverNetwork   https://picasaweb.google.com/VetiverClients"
- "Freeway Projects   Northern Hume Alliance   Ballina Bypass"
- "Sinks Canyon project WY DOT 2004 and revist again in 2007 Bufflo Fork River WY DOT 2007 Canyon in Calistoga, CA, in the middle of the Napa Valley 2004"
- "We have done many streambank stabilizations projects that support road embankments, two examples are: Hwy 2:08 Willow Creek project, completed in 2008 Hwy 734:22 Pembina River project, completed in 2006   Depending on your definition of sustainable, environmentally friendly one shallow slide repair method we have used many times is pinning the slope with launched soil nails. An example of a launched soil nail project is: Hwy 575:04 Soil Nail project, completed in 2007"
- "I have hundreds of photos showing examples of many BMPs being used both correctly and unfortunately incorrectly."
- "1. Shrubs planting for slope stabilization in Loess plateau and south of china(esp. Plants screening and establishment in Qinghai, Ningxia, Yunnan and Hubei). 2. Hollow brick planting for geotechnical engineering technique in Hubei province; 3. A L shape planting structure for geotechnical engineering technique in Hubei province"
- "1. Curb & flumes to direct water runoff from eroding top of earth slopes. 2. Permanent seeding utilizing Erosion Control Blanket. 3. Rock embankment, or using rock slope protection."
- "1. Straw bale ditch checks   2. Rock ditch checks   3. Hand seeding followed by straw mulch"
- "Sunriver to Bachelor Highway was a 12 mile FHWA realignment that created around 30 acres of exposed soils. Through bucket imprinting (slight compaction), seeding with native, locally collected seed sources, and applying a surface mulch (from grounded road right-of-way material), we had a very successful establishment of native plants on highly disturbed sites (no

topsoil). Sunriver Interchange and Lava Butte Road projects are Oregon Dept of Transportation projects untilizing the same methods as above plus some areas reapplying topsoil. Blaine Road is a FHWA project where vegetated gabion walls were planted with native shrubs and grasses. Several dozen rip rap culvert outlets were applied with 8 inches of compost and planted with shrubs and trees with good survival. North Bank Lane is a FHWA project on the F&WS Bandon Wildlife refuge where a compost blanket was used on road fills and willow stakes were placed at the bottom of the fills. Next fall the levees will be removed and estuary water will be lapping up on these slopes (we will see how well they hold up with willows and native grasses. We have more projects if you are interested."

- "I understand many other methods are preferred for environmental reasons, but in our area, the rip rap works well and is identified by DEQ as an acceptable product in our type of application."
- "1) Rock and/or vegetation filter zones at the base of tall cuts to prevent sediment from getting to ditches. 2) Using turf reinforcement mats in ditches as a substitute for riprap. 3) Planting woody vegetation on slopes as a means of providing additional soil stabilization."
- "* Compost socks for erosion control * Vegetated geogrid reinforced soil slope * Butresses flushed with No. 57 stone and topsoil and seed."
- "1. Mayflower-Ochoco CERCLA - contractor used a wood mulch, combined with fertilizer and a native seed mix."
- "1) colville national forest (washington) sprayed mixture of crimped synthetic fibers with grass seed and tackifier to mitigate erosion on a steep cutslope (mid 1990's) 2) numerous deep patch applications on forest service land throughout oregon and washington 3) might have a couple reinforced embankments (I would have to check) on the willamette national forest 4) very likely flatten cutslopes, low cost wire mat retaining wall, realignments through the national forests in oregon and washington"
- "Just obtained two additional publications (only available in hard copy) 1. Roadside Bioengineering Site Handbook by John Howell, Department of Roads, Nepal, 2002 2. Roadside Bio-engineering Reference Manual by John Howell, Department of Roads, Nepal. 2002 (has three case studies)."
- "Cut Slopes with hydroseeding, Live stakes in a slide area, Live crib walls, Geosynthetic reinforced retaining walls. I have photos for each, and drawings for the geosynthetic wall."

Survey respondents were also asked to provide one to three names of professionals or relevant documents/publications that could benefit this project. We received the following information:

- "Cornell local roads erosion control"
- "town of Manheim Town of Oppenheim Town of Salisbury"
- "Cornell training manual"
- "APWA reporter Superintendents profile"
- "George Machan, Landslide Technology. We had Landslide Tech under (an unrelated) contract at the time, so we asked him for advice on public safety and repair options."
- "Geohazards management in the transport sector: a World Bank Transport Note"
- "Look at the RRG/WTI compost/steep slope publications on MDT's website. Another useful, but now somewhat dated product I developed for MSU under EPA funding: stormwater.montana.edu. I also have some CD's left of this project"
- "http://www.vetiver.org/ENG_bioengineeringmal.htm

http://www.vetiver.org/ENG_Ecoengineering.htm http://www.vetiver.org/ICV4pdfs/BA03.pdf http://www.vetiver.org/ICV4-ppt/BA03-PP.pdf”

- “USFS Back Country Roads Manual Calif OHMVR Div BMP Manual Calif Soil Conservation Guidelines and Standards”
- “Sediment and Erosion Control on Construction Sites By Jerald Fifield, Ph.D CPESC National Management Measures to control Nonpoint Source Polltion from Urban areas EPA 2006”
- “Alberta Transportation ‘Design Guidelines for Erosion and Sediment Control for Highways’, 2003 Alberta Transportation ‘Field Guide for Erosion and Sediment Control for Highways’, 2003”
- “Stormwater Magazine”
- “Revegetation for side slope protection of Hu-Rong Freeway in Hubei Province”
- “Dave Polster for bioengineering expertise in british Columbia. My Handbook for erosion and sediment control. Gillies, 2007. erosion and sediment control practices for forest roads and stream crossings. fpinnovations. Adv. 9 No. 5.”
- “Local Soil and Water Conservation Districts are helpful.”
- “Road construction/Landscaping construction”
- “Our team (Forest Service R6 Restoration Services Team) developed a manual called ‘Roadside revegetation—an integrated guide approach to establishing native plants’ which you can download from www.nativerevegetation.org. Michael Hogan has written a guide called ‘Sediment source control handbook: an adaptive approach to restoration of disturbed areas’ which you can retrieve at http://www.sbcouncil.org/SSCH”
- “Gray & Sotir, 1995. Biotechnical and Soil Bioengineering Slope Stabilization.”
- “Mounir Abouzakhm”
- “Sandra Wilson Musser (USDA forest service) Gordon Keller (USDA forest service)”
- “Design and Construction of Low Cost Retaining Walls by Jonathan Wu, U. Colorado, Denver and CDOT 1994”

Appendix B – Interview Questions and Responses

Interview questions were developed to gain information not available from the survey responses. A list was compiled of survey respondents who indicated they were willing to participate in follow-up interviews. Interviewees were asked 16 questions and instructed to only provide responses based on their direct experience. Interview responses were recorded with a digital recorder and then transcribed or recorded by hand during the interview process. Thirty individuals were selected and asked to be interviewed based on the information they made available in the survey. A total of 25 interviews were conducted, providing an 83 percent interview response rate. Interviews were conducted over the phone with the exception of two responses received via email, due to interviewees' location and language differences. Information gained from the interviews that was incorporated into this report includes additional resources, references, erosion control and slope stabilization techniques and tools, best management practices, useful points, photographs, knowledge gaps and research needs, etc.

Interview Questions

NCHRP Synthesis Low-Cost Solutions for Road Slope Stabilization and Erosion Control

Please read this paragraph before you begin the interview.

Hello my name is Laura Fay/Michelle Akin from the Western Transportation Institute at Montana State University. In the survey for the NCHRP Synthesis *Low-Cost Solutions for Road Slope Stabilization and Erosion Control*, sponsored by the National Cooperative Highway Research Program under the National Academies, you identified yourself as being willing to participate in a follow-up interview or you were identified by a survey respondent as a potential interviewee. We are seeking your participation in a follow-up interview in which we are compiling information on cost-effective (i.e., low cost), environmentally friendly and sustainable shallow or near-surface slope stabilization and related erosion control treatments used on low volume roads. We are seeking information on current practices, best practices, or emerging solutions that are used regionally, nationally, or internationally.
This interview will take approximately 10–20 minutes of your time and will ask for you to comment on your direct experience on this topic. Participation is voluntary, and you can choose to not answer any question that you do not want to answer, and you can stop at anytime. May I audio record this interview? If not, I will be documenting all of your answers by hand—is that all right with you?

1. Name, title, agency, contact information
2. Please describe your working experience with road slope stabilization.
3. What road slope stabilization technique do you most frequently use?
4. Based on your experience what is the most cost-effective road slope stabilization technique?
5. Have you used this method? If so, do you have information (photos, data, design, cost, benefits, limitations, life expectancy, etc.) from the implementations that you could share?
6. Based on your experience what is the most sustainable/environmentally friendly road slope stabilization technique?
7. Have you used this method? If so do you have information (photos, data, design, cost, benefits, limitations, life expectancy, etc.) from the implementations that you could share?

8. Can you provide us with a description, of up to three, road slope stabilization projects that you have completed that were both low-cost/cost-effective and sustainable/environmentally friendly?
9. Could you tell us about some lessons learned in road slope stabilization related to the examples you have provided?
10. Are there road slope stabilization techniques/treatments you would never try or use again? Why?
11. What do you see as an underutilized tool, material, method, etc. in road slope stabilization?
12. Where do you see gaps in current state of practice of road slope stabilization or do you see any need for additional research?
13. Could you provide a name of an individual that may be willing to be interviewed on this topic or point us to additional resources or case examples?
14. Would you like to receive an email with a link to the final report when it becomes available? If so, please provide the email address you would like the link to the final report to go to.
15. Comments/Suggestions
16. Thank you for your time. May we thank you for your participation by listing your name in our final report?

List of Interviewees

The following individuals were interviewed:

- Vickie Bender, Alaska Road Builders
- Chris Bennett, World Bank
- Pete Bolander, USDA Forest Service
- Chenjianye, China Academy of Transportation Science
- Xueping Chen, China Academy of Transportation Science
- Paul Clark, Valley Hydromulch & Revegetation
- Jeff Currey, Alaska DOT & Public Facilities
- Asif Faiz, World Bank
- Donald Gray, University of Michigan
- Jim Haang, Franklin County, Ottawa, Kansas
- Stuart Jennings, Reclamation Research Group, LLC
- Byron Johnson, Kentucky Transportation Cabinet
- Gordon Keller, USDA Forest Service
- Kathy Kinsella, Town of Rhinebeck Highway Department
- Chris Marr, ESI Resource Services, LLC
- Khalid Mohamed, FHWA Office of Infrastructure
- David Orr, Cornell Local Roads Program
- Dave Polster, Polster Environmental Services, Ltd.

- Skip Ragsdale, Sunshine Supplies, Inc.
- Steve Romero, USDA Forest Service
- Warren Schlatter, Defiance County (Ohio) Engineer's Office
- Roger Skirrow, Alberta Ministry of Transportation
- David Steinfeld, USDA Forest Service
- Bob Vitale, Midwest Industrial Supply, Inc.
- Stan Vitton, Michigan Technological University

Appendix C - Slope Ratio versus Percent Slope Diagram

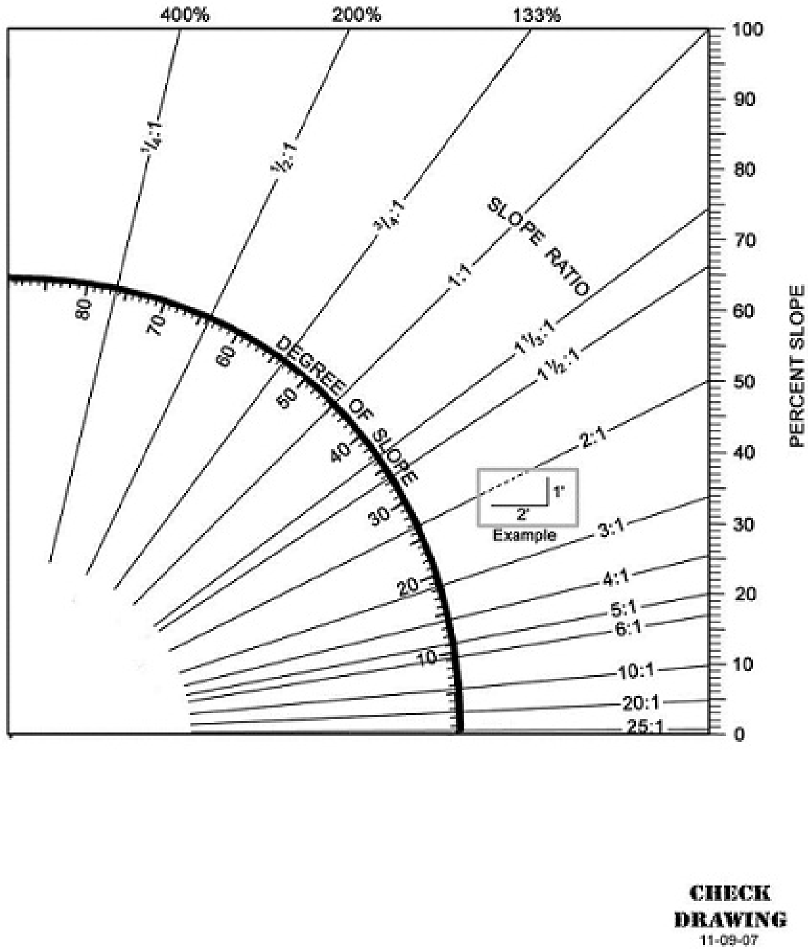

FIGURE 48 DEGREE OF SLOPE AND PERCENT SLOPE TO SLOPE RATIO CHEAT SHEET. PROVIDED BY G. KELLER.