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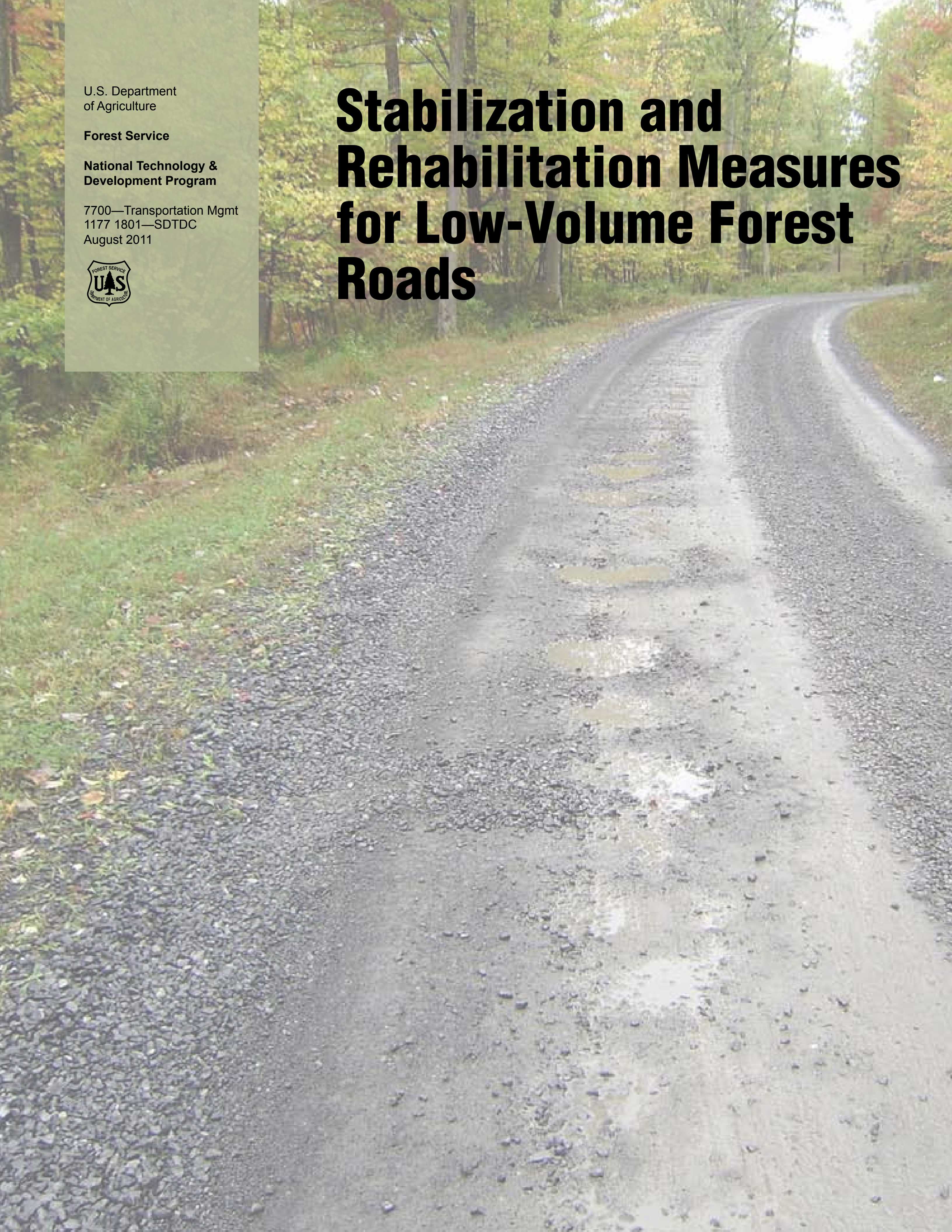
Stabilization and Rehabilitation Measures for Low-Volume Forest Roads



Stabilization and Rehabilitation Measures for Low-Volume Forest Roads

By:

***Gordon Keller**, P. E., Geotechnical Engineer*
U.S. Forest Service, Pacific Southwest Region,
Plumas National Forest

***Sandra Wilson-Musser**, Geotechnical Engineer*
U.S. Forest Service, Pacific Northwest Region

***Pete Bolander**, P. E., Geotechnical/Pavement Engineer*
U.S. Forest Service, Pacific Northwest Region

***Vincent Barandino, Jr.**, Civil Engineer*
U.S. Forest Service, San Dimas Technology and
Development Center

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EXECUTIVE SUMMARY

This low-volume road stabilization and rehabilitation guide has been developed to provide guidance and techniques for the many types of repairs and improvements made to forest roads. Since most of the low-volume road network already exists throughout the United States, emphasis is on stabilization, rehabilitation, and repair measures rather than new construction. However, a great many of the design principles and techniques used for a road's design apply to and are needed in road rehabilitation and repair projects.

This guide has been written relying upon the working knowledge of many road engineers with many years of experience to present a wide range of available rehabilitation practices. Every road project is unique, so application of this information should be tempered and augmented with local, on-the-ground working experience to adapt these ideas and techniques to the given local situation. Also, every project should strive for consistency with adjacent road design standards, but also should conform to appropriate design standards. These standards vary from very low requirements on low-use forest roads to moderately high standards on improved, surfaced collector roads.

Road safety is an ongoing issue and needs to be incorporated into our designs and work operations, particularly on low-volume roads where drivers often are not thinking about traffic and safety. Last, protection of the environment is a must, both required by laws and to be good stewards of the land. Thus, Best Management Practices (BMPs) should be followed in most phases and types of work to guarantee a certain degree of quality and environmental protection in our work.

There are many aspects of road engineering that are encountered and need to be considered in a rehabilitation or repair project. Organization of this document follows an Introduction, with a discussion of the many types of road repair and rehabilitation **problems** presented in section 2. Section 3 discusses the wide variety of **solutions** commonly available to help resolve the specific road problems. Problems and solutions discussed generally deal with these major themes:

- ❑ Erosion Control.
- ❑ Slope Stabilization.
- ❑ Roadway Surface and Subgrade Stabilization.
- ❑ Road Surface and Subsurface Drainage.
- ❑ Stream and Wet Area Crossings.

Erosion Control

There are many ways to control erosion, but the two most fundamental requirements are to control surface water flow and to provide protection and cover for the ground. Ground cover and other erosion control methods are addressed under section 3.1. Surface drainage issues and ways to prevent concentration of water flow are addressed in section 3.4. Erosion control methods include use of vegetation and soil bioengineering; on-grade treatments; use of seed, fertilizer, and soil amendments; mulches and rolled erosion control products, often with stabilizers and tackifiers; and hard armoring.

Slope Stabilization

While erosion can be a pervasive nonpoint source of pollution, slope instability can be a major point source of sediment as well as close the road and be costly to repair. Landslides are a naturally occurring feature, but most road instability problems are related to cut-and-fill slope failures. However, if a road is impacted, all types of instability have to be addressed. The first approach is to construct or reconstruct slopes to a stable slope angle, and incorporate drainage as needed. For specific slide problems, a wide variety of solutions exist including the use of buttresses, retaining structures, reinforced fills, and soil nails and anchors. Today, mechanically stabilized earth (MSE) walls and reinforced fills, typically using geosynthetic reinforcement, are common because of their relatively low cost and ease of construction in rural areas. Other treatments, such as deep patch, lightweight fills, launched soil nails, or shifts in grade and alignment can offer cost-effective solutions. On all slide stabilization projects, use of drainage and use of vegetation should be considered and used if possible.

Roadway Surface and Subgrade Stabilization

Surface and subgrade stabilization issues affect the road’s riding comfort, its ability to support traffic loads, its ability to drain water properly, and its need for maintenance. Thus the road surface is where most common road maintenance practices occur. It is also where up to half the cost of the road can be if an aggregate surfacing, seal coat, or pavement is added to the road. A road cannot be kept in good condition if the road surface is not strong and durable. Key repair issues include removing or preventing surface defects such as ruts, potholes, and washboarding; use and design of aggregate surfacing; dust prevention; freeze thaw problems; subgrade stabilization; and asphalt repairs.

Road Surface and Subsurface Drainage

The majority of road problems are related to poor drainage either on the road surface or subsurface! Most instability problems are caused by ground water. Frequent road maintenance is needed as a consequence of poor surface drainage. Thus roadway drainage and attention to many drainage details are critical for the function and proper rehabilitation and repair of a road. Surface drainage issues include the shape of the road surface (insloping, outsloping, or crown), ditches, cross drains, and the use of leadoff ditches, berms, and waterbars and rolling dips. Subsurface drainage typically is accomplished using underdrains, drainage blankets, or horizontal drains.

Stream and Wet Area Crossings

Stream crossings are critical structures; they are where a road crosses a water course. These crossings can be a major source of sedimentation if not built properly, and significant costs are involved in culverts, bridges, or low-water crossings. Thus these crossing sites have critical structures. Problematic sites can impact road use, stream function, and aquatic organism and fish passage. Culvert design, repair, and rehabilitation information is included, as well as key design and repair considerations for bridges and fords. Scour issues are discussed, as well as other related streambank stabilization measures, using traditional and biotechnical stabilization treatments.

Geosynthetics are used today in all aspects of road design and repair on high standard and low-volume roads. These uses include proper filtration and drainage for underdrains, subgrade reinforcement and separation for aggregates over soft soils, reinforcement in retaining structures, soft subgrade stabilization, or erosion control applications. A brief summary of these uses is presented in appendix A.

Only a brief discussion of each topic is presented herein. A great deal of additional useful information is found in the literature, but it is spread out in many sources. Thus many useful references are listed or linked to find amplifying information on each topic throughout the document. Literature cited is in appendix B.

The authors hope that this information will be useful as a guide and information source for the many types of repair and rehabilitation measures periodically needed in low-volume road projects.

Many Forest Service, U.S. Department of Agriculture (USDA), roads have exceeded their design life and are showing the effects of age, lack of maintenance, poor construction, severe storms, and climate change. As these roads deteriorate, instabilities occur as a result of external and internal factors, such as gravity, concentration of water, temperature variations, scour by wind and water, the action of ice, erosion, and change or loss of vegetation. As fill materials deteriorate, fills settle, creep, and sometimes slide; pavements crack; and culverts corrode, leak, and separate. The Forest Service decommissions unneeded and problematic roads as funding permits, but most roads are still required for access and forest management. Most forests work independently with their available resources to stabilize and rehabilitate their roads.

The primary purpose of this document is to assist the Forest Service and other Federal, State, and local land management agencies road managers, transportation engineers, equipment operators, resource specialists, field personnel, and others who are involved in rehabilitation and stabilization of low-volume roads. This guide was developed by obtaining information that contains methodologies and project-specific data from national forests throughout the country. The problems that require rehabilitation work are defined in section 2. A range of recommended treatments with appropriate rehabilitation methods is listed in section 3. The emphasis is on describing available solutions with corresponding sources of information. Solutions should adhere to acceptable or approved design standards, they must meet and comply with best management practices (BMPs), and they should provide reasonable safety for the road user and worker.

Five major problem areas and solutions are addressed in this document. These areas, with corresponding solutions, are found in the following sections:

1. Techniques to treat erosion problems (section 3.1).
2. Road-related slope stabilization treatments (section 3.2).
3. Road surface and subgrade stabilization methods (section 3.3).
4. Roadway surface and subsurface drainage solutions (section 3.4).
5. Stream and wet area crossing solutions (section 3.5).

Each problem area may create traffic safety concerns, road maintenance and reconstruction expenses, and environmental or resource damage. Fortunately solutions exist to address the problems. The goal is to apply solutions that are appropriate, cost effective, and do not harm the environment. Section 4 is a document summary. Appendix A discusses geosynthetics and their use in repair and stabilization of low-volume roads. Additional references and links on stabilization and rehabilitation methods for low-volume roads are found throughout the document, and are listed in appendix B.

Design Standards

Any road project, whether it involves new construction, road reconstruction or rehabilitation, or local repairs, must adhere to and meet acceptable design standards. Local work also should conform to the road's standards around that zone, for sake of consistency, but keeping in mind normal design requirements. The Forest Service has design standards and requirements defined in its Forest Service Manual (FSM) and Handbook (FSH). Particularly relevant are the 7000 Series of the FSM, FSH 7709.56, and FSH 7709.56b.

Another key reference associated with low-volume roads is the American Association of State Highway and Transportation Officials (AASHTO) (2001) publication on the geometric design of very low-volume local roads. Though many very low standard forest roads do not meet these geometric design standards, most moderate-use low-volume roads do. This guide is widely used by most public agencies to define their road standards. The document may be ordered at <https://bookstore.transportation.org/Item_details.aspx?id=157>.

Best Management Practices (BMPs)

BMPs are a product of many environmental laws and regulations, including the Clean Water Act. The Forest Service and other Federal agencies must use nonpoint source controls, such as BMPs, to meet the intent of these laws. Many States and agencies have developed their own BMPs to guide their operations.

Activities associated with road management include planning, locating, designing, constructing, operating, maintaining, reconstructing, and decommissioning. BMPs control these activities to prevent nonpoint source pollution. BMPs are described for most aspects of road management; particularly those involving ground disturbance, earthwork, and associated potential erosion, and work in or around water, such as at stream crossings.

BMPs used by the Forest Service represent a list of recommended practices and techniques that practitioners can prescribe to meet BMP objectives, particularly with regard to control of nonpoint source pollution and protecting water quality. The Forest Service National Core BMPs “Nonpoint Source Pollution Control for Water Quality Management on NFS Lands” is in the review process as this document goes to press. It should be finalized during FY2011. Section 12.21 of the U.S. Department of Agriculture, Forest Service (2000) document on BMPs for water quality management for Forest Service lands in California pertains to road construction practices, and is available at <http://www.fs.fed.us/r5/publications/water_resources/waterquality/>.

The U.S. Environmental Protection Agency (EPA) has best practices manuals and references on the prevention of nonpoint source pollution relevant to road, highway, and bridge construction and rehabilitation. These are found on their Web site <http://www.epa.gov/owow/nps/roadshwys.html>.

Road Safety

Road safety, for the road user and for the construction or maintenance worker, is important on any road rehabilitation or repair project. Most roads, open to the public in a standard passenger car, are subject to the Highway Safety Act. This act authorizes agencies to design and maintain roads in accordance with appropriate safety standards. FSM 7733.03 and FSH 7709.59, chapter 40, specifically address road safety. Statistically, low-volume roads have more accidents per mile driven than higher standard roads. One is roughly twice as likely to have an accident on a low-volume rural or collector road as on a high standard road (Ron Eck, personal communication). Considering this and the litigious world we live in today, traffic and worker safety has to be an integral part of any road project, during construction or repairs, and in the final repair design.

Safety items or issues commonly considered include vertical and horizontal alignment, adequate road width, shoulders, dust control, clearing and sight distance, road work advisories, proper signing, object markers on stream crossing structures, and many other details. Figure 1-1 shows several key safety issues needed on low-volume roads. The AASHTO Highway Safety Manual (2010) is a comprehensive publication on all aspects of road safety.

Figure 1-1—Low-volume road safety items, such as (a) road work signs to warn traffic of activities ahead and (b) warning signs for a single-lane bridge on a two-lane road.

1.1. PROCEDURE FOR REHABILITATION/STABILIZATION OF ROADS

1.1.1. Long-term Need for Road and Project Assessment

Determine the long-term uses and road user's needs prior to selecting rehabilitation techniques. First, decide on the road's future; sometimes the best alternative is to decommission or obliterate an obsolete road rather than damage resources and incur costs that are economically infeasible. If a road is to be retained, first determine traffic type, volume, and timing (for example: automobiles versus 4-wheel-drive vehicles, log trucks versus low-boys, all-weather traffic versus dry-weather only, and high volume versus low volume). Next, evaluate the road's effects on the landscape as well as the influence of the landscape on the road.

Use the formal area planning process to evaluate the variables, such as watershed analysis, roads analysis, and/or access and travel management. These are Forest Service efforts to evaluate its transportation-network needs and road-segment impacts on landscapes as well as effects of the geologic setting on the roads. In addition to helping an agency decide on retention or removal of a road or road segment, the processes can guide the intensity and treatment for road repair and stabilization.

1.1.2. Road Objective and Assessment

Assessment or evaluation of the specific road project is necessary to select and engineer appropriate designs. The first step is to know the project's objectives, such as repair or stabilize the road to maintain the current standard, reduce the standard, or increase the standard; these objectives provide sideboards for the design. Ultimately, the objective may be to stabilize and decommission the road.

Staff should address the following parameters when conducting a project area assessment:

- ❑ Landscape
  - ▲ Geology
    - ❇ Does road cross landslide terrain; are cutslopes in soil or rock; if rock, does it dip into or away from the roadbed; are slopes stable?
  - ▲ Soils
    - ❇ Are soils erodible or nonerodible; what is their character?
  - ▲ Terrain Features
    - ❇ What are the geomorphic features; steepness of slopes above and below the roadway?

- Setting
    - Near streams, wet areas, ecologically sensitive areas; position on hillslope (toe, midslope, ridgetop); stream threatening the road?

- Water
    - Drainage
        - Include ditches, cross-drain structures, road surface sheet flow, inlets and outlets of drainage structures; intercepted ground water.
    - Road-Stream Crossings
        - Is there stream constriction; history of overtopping; history of or potential for debris flows above the crossing; aquatic or terrestrial organisms, sediment, or wood debris passage issues; potential changes in management upstream that might affect flows or transported debris; downstream development that could be affected by changes in the crossing?
- Ground water
    - Is there ground water that the road is intercepting or may intercept; is the road fill interrupting ground water or surface water flow, such as across meadows or flood plains?
- Road Character
    - Interaction of road geometry with the terrain and intended traffic (width, horizontal and vertical curves, grades, shape [crown, outsloped, insloped], drainage structures)?
    - Road surfacing or intended surfacing (aggregate, native, bituminous surface treatment, asphalt/concrete, other; condition, dust)?
    - Traffic (type of design and critical vehicles, volume, and timing of traffic)?

CHAPTER TWO
Types of Problems That Require Rehabilitation Work

2.1. EROSION ISSUES

Erosion is a process of soil and rock-particle detachment and transport over an area by wind, water, gravity, ice, and chemical action. Erosion is a naturally occurring process that is accelerated by earth-disturbing projects, such as road work and maintenance. Erosion from these activities may damage the ecosystem and visual environment, increase maintenance costs, degrade water quality, increase water treatment costs, and leave the land susceptible to noxious weeds. Understanding erosion processes is important for selecting the most appropriate erosion control treatments. Because of the strong connection with road management and erosion control, the focus of this section is on road-erosion problems associated with water, gravity, wind, ice, and chemicals.

2.1.1. Water-Caused Erosion

Interrill. Interrill (splash) erosion occurs where rain hits bare soil causing surface soils to dislodge and move. This splash also can create a crust seal on the soil that makes it less permeable (surface sealing). The second part of interrill erosion occurs when water forms very shallow surface flow (sheet erosion). Interrill erosion can occur on any soil that is impacted by water drops and where water begins to flow over the soil surface (figure 2-1). The occurrence and severity of interrill erosion depends on the soil characteristics, slope length and angle, storm duration, and types and density of vegetative cover.

Rill. A rill is erosion by water in small microchannels, typically 0.2- to 1.2-inch (0.5 to 30 mm) wide and up to 3 inches (75 mm) deep. Rills occur where rain contacts bare soil for durations long enough for the water to develop microchannels. Rill erosion depends on the soil characteristics, slope length and angle, storm duration and intensity, and type and density of vegetative cover. This type of erosion can occur on any slope with erodible soils that lack protective vegetative cover, but it is more severe on moderate-to-steep slopes (figure 2-2). It is common on unprotected cutslopes and fillslopes. The volume of eroded material increases as the number of rills increases.

Figure 2-1—Interill (sheet) erosion with rills and gullies forming.

Figure 2-2—Rills formed primarily by surface runoff.

Gully. Untreated rills on slopes may develop into V-shaped gullies. Dimensions range from tens of inches to several feet. Gully erosion is a significant problem on steep forested areas and is a common problem in the southwest and anywhere with noncohesive soils and sparse vegetation. It often occurs where concentrated flow begins on relatively steep long slopes with erodible soils lacking protective vegetation cover. Gully erosion processes may be similar to channels and can be complex (figure 2-3).

Gullies may be caused by concentrated water leaving a road, or roads may be damaged by gullies crossing them (figure 2-4). Water funneled from upslope gullies can cut across a road; downslope gullies can undermine a road.

Figure 2-3—Typical upslope gully erosion.

Figure 2-4—Typical gully erosion on a road.

2.1.2. Other Forms of Erosion

Gravity-Caused Erosion

Dry-ravel erosion removes and transports soil particles down a slope by gravity after the particle loses its cohesion from exposure to the elements, typically by losing soil moisture. Dry-ravel erosion is often recognized by the lack of rills and other water-erosion features and large amounts of particles deposited at the base of the slope. In cutslopes with granular soils, such as decomposed granite, the ravel is a constant source of material on the road and is maintenance intensive. Also, maintenance personnel must locate a disposal site that accepts loose material.

Wind-Caused Erosion

Wind erosion is the detachment and transport of soil particles by wind where particles move suspended in air (suspension), bounce (saltation), or roll (surface creep). In dry climates, or windward facing slopes with frequent high winds, wind erosion can be a more significant source of erosion than water.

Figure 2-5 illustrates the types of erosion encountered along a road and how rills and gullies are formed.

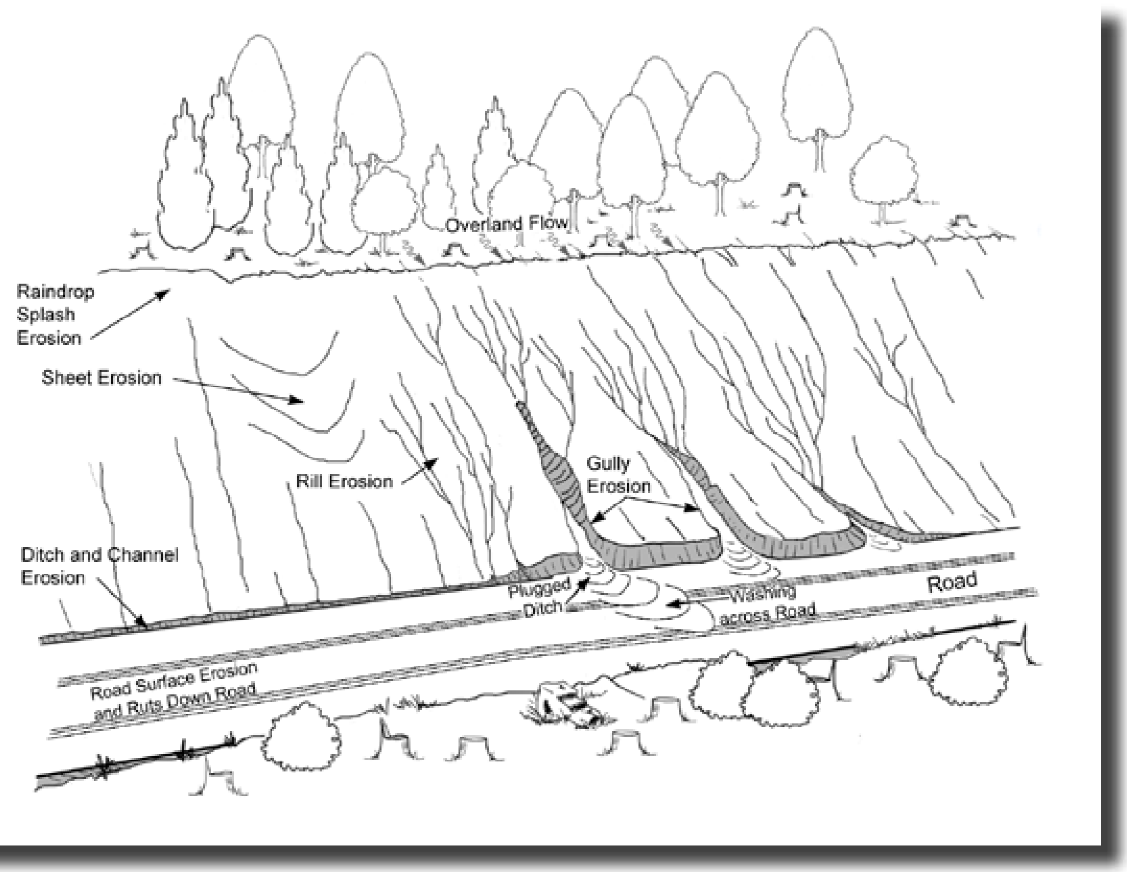


Figure 2-5—Types of roadway erosion and how rills and gullies are formed along a road.

Ice-Caused Erosion

Freeze/Thaw Erosion. Freeze/thaw erosion occurs during the expansion of freezing water and the contraction of thawing ice. It requires freezing temperatures, time for ice to form, soil moisture, and frost-susceptible soils. It can loosen and remove rock and soil and displace seeds and new plants in fine-textured soil. Generally fine-grain soils, such as silt with 3 percent or more (by weight) finer than 0.0008 inch (0.02 millimeter (mm)) are frost susceptible. Gravel with grain size 1.5 to 3 percent finer than 0.0008 inch (0.02 mm) may be frost susceptible.

Glacier (Moving-Ice) Erosion. Glacier (moving-ice) erosion occurs when large amounts of ice entrap, grind, and move soil and rock. It can move soil and rock many miles from its origin. This publication does not discuss the problem directly.

Chemical-Caused Erosion

Chemical erosion is the transport of rock and soil and/or its transformation into another substance through chemical processes. Chemical reactions may transform and weather rock and soil into another substance and the new substance subsequently is removed. In addition, rock and soil may be dissolved and transported by another substance, such as water. Chemical-caused erosion can be significant and complex, such as sink holes forming in limestone. This form of erosion is not addressed specifically.

2.1.3. Problems with Erosion and Impacts on Roads

Much of the Forest Service infrastructure is located in areas with relatively steep slopes that are sometimes unstable, and in areas of highly erodible soil. Erosion is a naturally occurring process that often is accelerated by human projects and earth-disturbing activities. Erosion from these activities may damage the ecosystem; increase road maintenance costs; put sediment into water courses and degrade water quality; increase water treatment costs; contribute to loss of soil, vegetation, and land fertility; and promote the spread of noxious weeds. Effective erosion control may help reduce the spread of invasive plant species.

In addition to mitigating the negative impacts of erosion, control is often needed to satisfy Federal, State, and local laws and policies, the FSM, and environmental documents for original construction. Earth disturbing forest and road projects can be a significant source of erosion that is challenging and sometimes expensive, but necessary to control. Cost-effective erosion control on Forest Service lands is needed to mitigate the impacts of erosion as part of caring for the land.

Soil erosion and water quality and quantity are major concerns in land management. Special attention has been given to nonpoint source pollution, including soil erosion from low-volume roads. Erosion is an intrinsic natural process; however, in many places it is increased by human land use. For example, accelerated erosion can result from land management activities. Sediments carried from forest roads can account for as much as 90 percent of all sediment emanating from forest lands, which has a potential for significant detrimental impacts (Grace 2000), particularly on water quality. Thus road systems, consisting of Federal, State, industry, and private roads can and do present a serious national erosion problem.

Water affects the entire function of a road. Too much water in the base material weakens the road. Water allowed to remain on the top of the road weakens the surface and, when combined with traffic, causes rutting, potholing, and cracking pavements. Where concentrated on the road surface or concentrated and improperly channeled off the road, water causes erosion and deepens ruts, as well as washing off expensive surfacing aggregate. Thus, the road is damaged and sediment from the eroded soil can damage local water quality.

Soil texture, organic matter content, structure, and permeability influence erodibility. Soil texture is the proportions of sand, silt, and clay particles. Soil organic matter, composed mainly of decaying plant leaves, stems, and roots, tends to cement soil particles together and improve soil fertility. Soil structure, the arrangement of soil particles into aggregates, decreases surface water runoff and may increase the capacity of soil to hold water (Lewis et al. 2003). Soil permeability enhances water penetration, thereby reducing surface water runoff that may cause soil erosion along roads.

Topography, slope length, and steepness are keys to erosion potential. Sheet erosion occurs on flatter slopes; steeper slopes tend to have rill and gully erosion. Slope aspect, or exposure direction relative to the sun, affects soil temperature and soil moisture conditions that in turn determine vegetation type and its ability to grow. In addition, the size, shape, elevation, and slope of the drainage upslope affect erosion potential.

Steep road grades cause surface and ditch water to move rapidly, making surface drainage difficult to control. This condition accelerates erosion unless surfaces are armored or water is dispersed or removed frequently. The road surface and adjacent areas, including shoulders and cuts and fills, are a relatively large surface area that has the potential to erode and produce significant amounts of sediment.

Direct human activities, such as channel confinement, local realignment of the streamflow, and damage to or removal of vegetation, are major factors in streambank erosion. Streambank erosion also may be caused by geologic, climatic, and hydraulic factors. Land-use changes or natural disturbances can cause the frequency and magnitude of water forces to increase. Loss of streamside vegetation can reduce resisting forces, making streambanks more susceptible to erosion. Channel realignment often increases stream power and may cause streambeds and banks to erode. Drainage crossing structures, such as culverts, fords, and bridges, can be impacted or damaged significantly by channel erosion or scour near the structure.

2.2. SLOPE STABILIZATION ISSUES

The stability of natural slopes and constructed cuts and fills is very important when trying to reduce a road's maintenance costs and its environmental impacts. An improperly constructed cut or fill can produce more sediment than the erosion from the road surface in a given area. Slides in cuts and fills can divert or plug roadway surface drainage, causing gullying downslope. Slides can close the road or reduce its width, which may cause traffic delays and increase maintenance costs. Slope instability often occurs as a result of excavation and earthwork with some combination of excessively high slopes, excessively steep slopes, poorly compacted soils, plains of weakness in rock, or ground water. Slides may occur in constructed slopes and fills or in naturally occurring slopes, particularly if they have been modified, oversteepened, undercut, or poorly drained (figure 2-6).

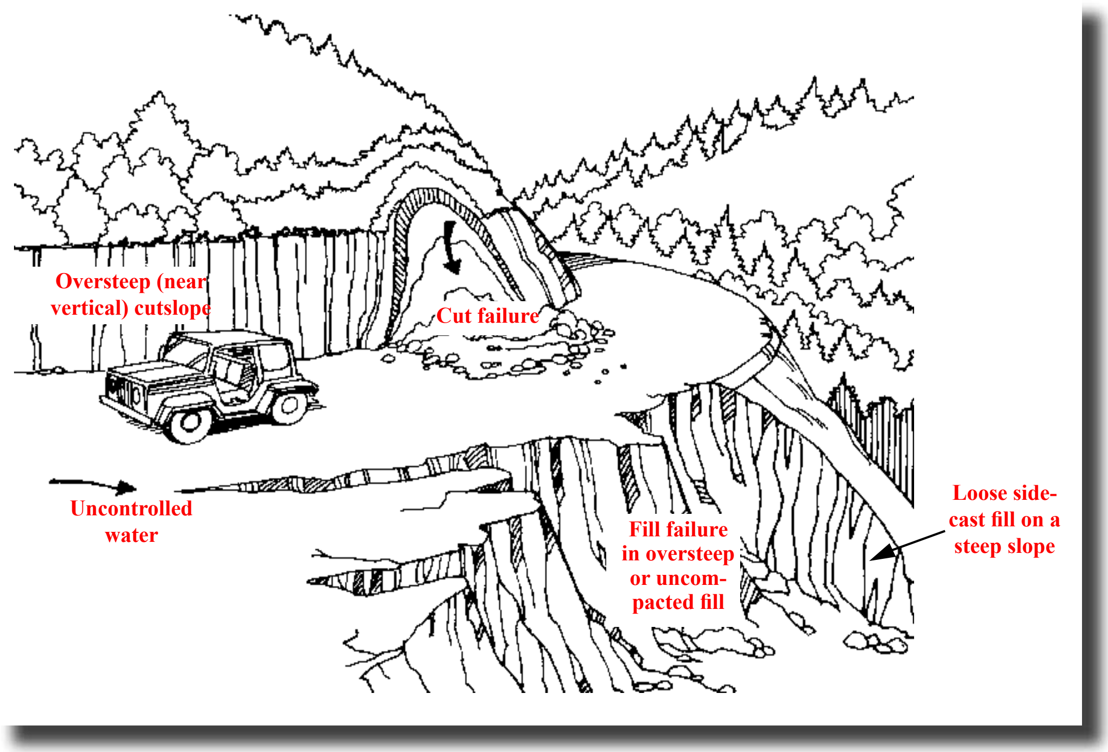


Figure 2-6—Common slope stabilization problems.

Whether naturally occurring or human induced, slides can add major costs to the construction or maintenance of a road. They may cause significant adverse environmental impacts from sediment production, may damage natural resources or downslope infrastructure, impact road surface drainage or cause significant traffic delays or road closures (figure 2-7).

Figure 2-7—A cutslope slide closing the road.

The stability of natural slopes, cutslopes, and fillslopes varies depending on many factors. These include:

- Inherent strength of unweathered rock.
- Degree of decomposition of the rock body.
- Degree of fracturing, faulting, and folding of the rock body.
- Depth and strength properties of the soil.
- Height, shape, and steepness of the cut or fill.
- Effects of ground water pore pressure.
- Effects of surface water and drainage patterns.
- Effects of drainage structures.
- Erosion potential of the soils involved.
- Construction/compaction quality control methods.
- Soil reinforcement (via root systems) and surface protection provided by vegetation.

Common causes of slope instability along roads are:

- Over-steepened cut and fillslope.
- Construction over wet areas.
- Roads built across existing unstable ground.
- Excessive weight from fills on the road shoulder.
- Rotting logs buried in the fill.
- Uncontrolled water or concentrated road surface drainage.
- Undercutting rock dipping parallel to the slope.
- Ground water.
- Uncompacted fills.

The current slope condition is often an indicator of what can be expected in the future. Engineers can study stable slopes to determine stable material types and slope angles. Defining what construction and drainage techniques have worked successfully in the past, particularly in a local area, is valuable input for slope design. Interpreting the slope form, or morphology, can help engineers define areas subject to future instability and cut/fillslope angles that have remained stable over time.

Many landslide types exist in nature and most of them can adversely affect a road in some way. On roads, the most common problems are simple slumps, or shallow cutslope and fillslope failures. These failures may be caused for many reasons based on the factors listed above. Landslides include rockfalls, debris slides, earth flows, and rotational or rotational-translational slides, as seen in figure 2-8.

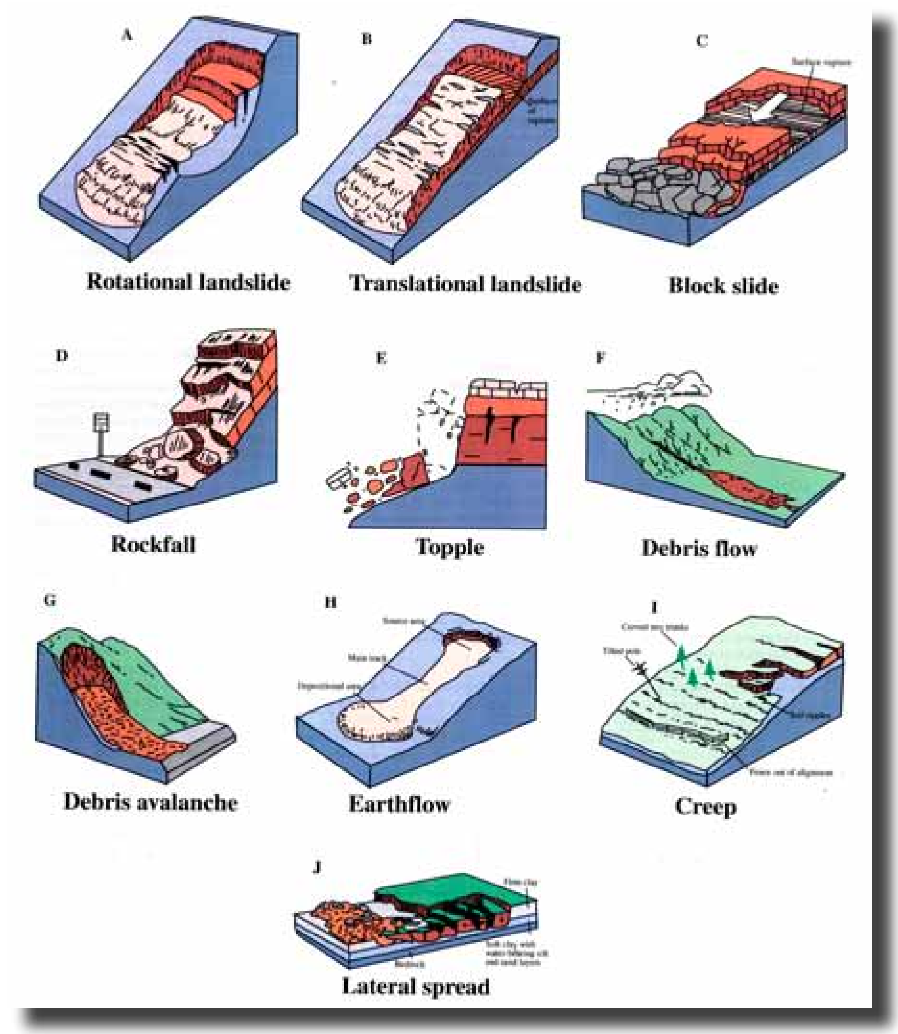


Figure 2-8—Common types of landslides (from U.S.Geological Survey).

Figure 2-9 shows more detail of a rotational-translational slide and a debris slide that impact roads in upland topography.

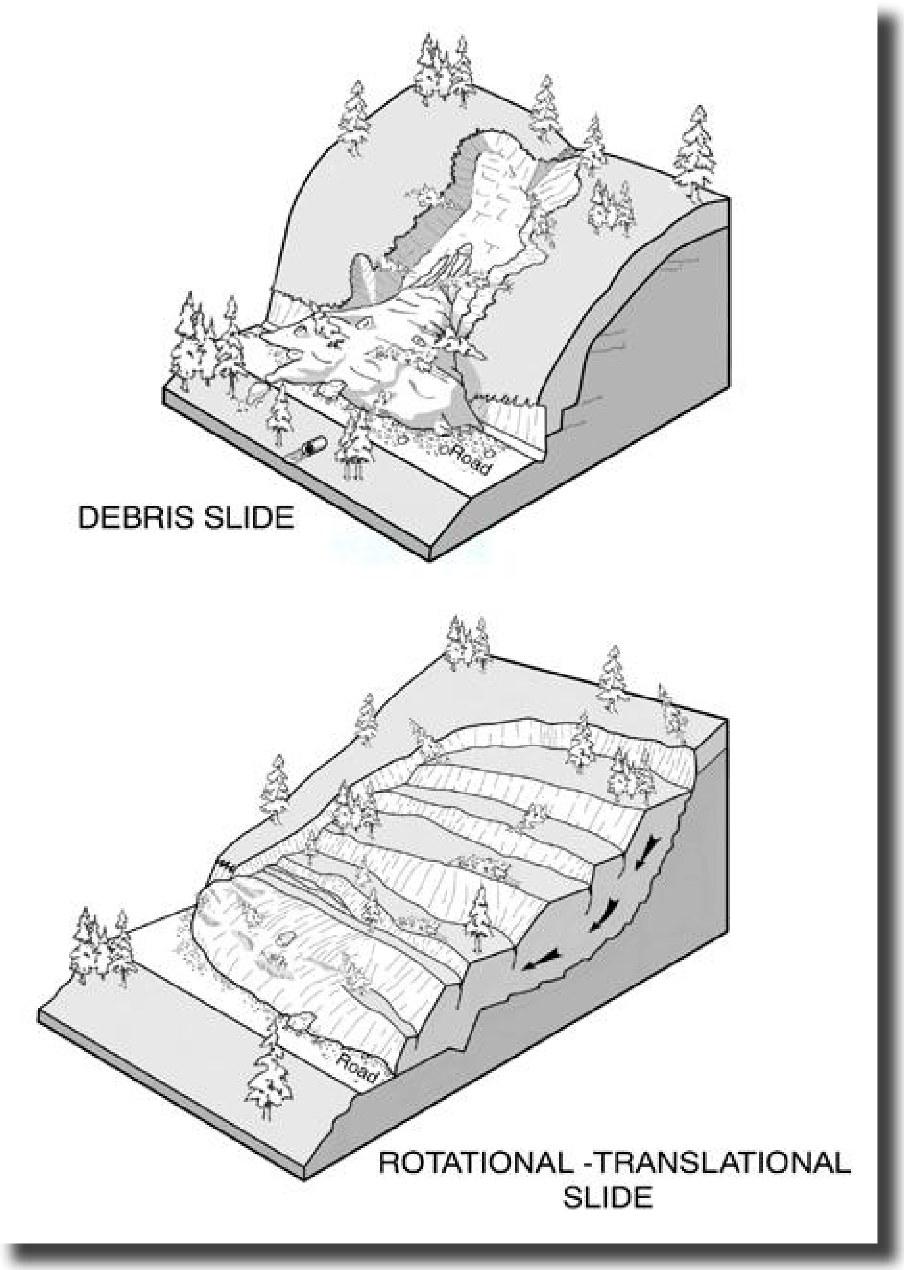


Figure 2-9—Rotational-translational and debris slides (adapted from Royster 1982).

2.2.1. Mass Movement (cut-and-fill failures, settlement, downslope creep)

Mass movement is rock, debris, or earth moving down a slope. Examples include landslides and debris flows. They can be complicated and sometimes expensive to control, or with maintenance, crews can remove the material from the road. Section 3.2 discusses mass-movement treatments.

Past design methods for roads across hillslopes emphasized achieving road width with balanced earthwork (equalizing cut-and-fill quantities). Typically, constructors removed material from the hillside (cut) and placed it along the outside edge of the road (fill or sidecast) with minimal keying or benching, or controlled compaction.

Settlement or consolidation of the inadequately compacted fill material and/or downslope fill creep often caused subsidence and cracking. In addition, woody debris from the clearing and grubbing operation went into the sidecast fills. In some cases, logs and stumps supported the toe of the fills. The woody debris initially acted as reinforcement and probably improved the slope stability. Over time however, the decomposing debris led to subsidence or to total fill failure.

Other areas have been built with excessively steep cutslopes, a common practice to minimize the volume of earthwork. These overly steep slopes occasionally lead to slope failures, particularly in locally weak soil areas or areas where ground water is encountered. Failures then lead to slope stabilization measures or additional road maintenance (figure 2-10). In the meantime, the road may be closed and the ditch drainage system blocked.

On low-volume roads with relatively small cuts and fills, shallow slumps (a localized shallow cut or fillslope failure) or surficial instability problems occur in some areas. One can consider a shallow or surficial instability problem a slide with a depth of only a few feet, often 2 to 5 feet (0.6 to 1.5 meters (m)). The depth of sliding typically is small compared to the slide's length. These failures often occur in fine-grained soils, such as silty clays with a shallow rotational failure, or in silty-sandy soils as a shallow infinite slope failure. Failure typically is caused by a prolonged heavy rain, a rain-on-snow event, or a spring thaw that saturates the slope. Additionally, slopes may have variable soil layers that can perch water or loose topsoil that promote failures. Section 3.2.1.5 presents a range of solutions. Consult a geotechnical engineer regarding which solution to use after a site evaluation determines the cause of the failure, and which fix will be most appropriate and cost effective.

Figure 2-10—A fillslope settling or beginning to fail, and a failed roadway fill.

2.2.2. Rockfall

Rockfall instability on roads typically results from excessively steep and high cutbanks in fractured or loose rock. It also is aggravated by external and internal factors, such as ice, temperature variation, thermal expansion, hydrostatic pressure, residual geological stresses within the rock, seismic action, and vibration from vehicular traffic. All create conditions suitable for rockfalls, sliding, or toppling. Rockfall consequences include increased road damage and maintenance costs, traffic delays, traffic hazards, and driver safety (figure 2-11). Periodically, people are killed or injured by rocks and or boulders falling on to roads, even on low-volume roads.

Section 3.2.3 discusses rockfall prevention measures, such as scaling loose rock, netting, terracing, and so forth. Using these prevention measures typically depends on the site's risk as a function of rockfall frequency, cut height, and traffic.

Figure 2-11—Rockfall blocking a road.

2.3. ROAD SURFACE STABILIZATION ISSUES

2.3.1. Unbound Surface Ruts, Washboards, Potholes, and Soft Soils

Road surface problems typically are caused by poor road surface drainage combined with weak subgrade soils. Ruts, washboards, and potholes in the road surface pond water, weaken the roadway structural section, accelerate surface damage, and make driving difficult. Heavy rainstorms are a major contributing factor, combined with inherently poor or weak soils and poor surface drainage to remove the water off the road surface. Blocked ditches aggravate the situation by ponding the water in the ditch, saturating the subgrade soil, or causing water to flow across the road surface.

Poor subgrade soils or marginal, fines-rich surfacing materials rut (figure 2-12) when wet and under traffic loads, damaging the road surface, making driving difficult and creating additional road-maintenance needs. Further damage is caused by the ruts that form. The new rutting causes further drainage problems by channelizing water along the road, and creating new erosion problems. In very weak saturated soils, the road may become impassable and vehicles get stuck.

Figure 2-12—Ruts in soft soil road surfaces.

Potholes (figure 2-13) and washboarding are products of traffic on the road surface aggravated by poor drainage and improperly graded road-surfacing materials. Potholes form by having soft spots in the road surface, which get depressed or lose material, pond water, and subsequently get deeper and larger with traffic. Washboarding forms with traffic on loose, noncohesive raveling material (figure 2-14). With time and traffic, the washboarding becomes deeper and more accentuated. A poorly graded material washboards more quickly than a dense, well-graded surfacing material, but, without periodic maintenance, eventually most roadway surfacing materials form washboards. The solutions discussed in section 3.3 typically include increasing road maintenance, adding aggregate surfacing and improving aggregate quality, improving drainage, improving the in-place soil with soil stabilization, or staying off the road when wet. Try using wood chips for surfacing and reducing vehicle tire pressure to control damage.

Figure 2-13—Potholes in the road surface. These potholes pond water, weaken the roadway structural section, accelerate surface damage, and make driving difficult.

Figure 2-14—Washboarding forming in a gravel road surface.

2.3.2. Dust

Dust is created from vehicles driving on a dry road surface with fine-grained soils, or on an aggregate with a high percentage of fines. Dust from unpaved roads is not only a nuisance but creates a safety hazard by reducing the driver's visibility (figure 2-15). Dust also affects road-user health, increases vehicle wear and tear, and damages vegetation along the road. Dust always is an intruder at campsites and picnic areas. In some areas there are regulations that limit the amount of particulate allowed in the atmosphere.

Fine particles, including dust, act to help hold the unpaved road surface together. With a loss of fine particles from the roadway, surface raveling and maintenance costs increase. These fines are smaller than what the eye can see and pass through the 75 micrometer (No. 200) sieve (Bolander 1999). There are many measures and dust palliative products available to suppress dust on roads. Section 3.3.2 discusses the options.

Figure 2-15—Dust from unpaved roads is not only a nuisance but creates a safety hazard by reducing the driver's visibility.

2.3.3. Freeze-Thaw Problem

Major highways are designed to withstand heavy vehicles and high traffic volumes year round. Typically low-volume roads are not designed to accommodate heavy traffic year round. However, low-volume roads in seasonal frost areas are extremely susceptible to damage from trafficking by heavy vehicles during spring and midwinter thaws. As a result, the maintenance-free life of a low-volume road in a seasonal frost area averages less than half that of a similar road in a nonfrost area.

Freeze-thaw-related erosion happens primarily during spring thaw as a result of channelized water flow in the ruts that are caused by springtime trafficking on soft, thaw-weakened, damage-susceptible materials. The combination of subfreezing temperatures, soil moisture, and frost-susceptible soils must all be present for frost action to occur. During the winter, the pavement structure freezes from the top downward, and ice lenses form as moisture is drawn toward the freezing front. As thawing commences, ice lenses melt, and water becomes trapped in the unconsolidated, undrained soil above still frozen underlying layers. This makes the road highly susceptible to damage from traffic. Note the rapid rate of damage and relatively short duration over which damage occurs, coinciding with the spring thawing period (figure 2-16).

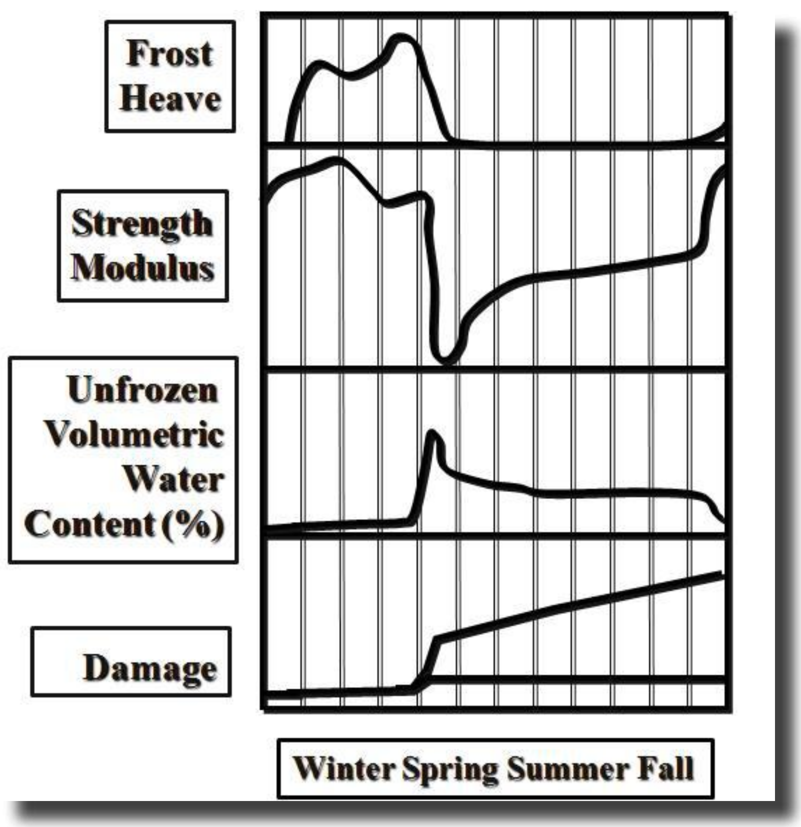


Figure 2-16—Relationship between spring thaw, road stiffness, moisture content, and damage.

Generally, soils with 3 percent or more (by weight) finer than 0.0008 inch (0.02 mm) are frost susceptible. Gravel with 1.5 to 3 percent finer than 0.0008 inch (0.02 mm) may be frost susceptible. However, uniform sands can have up to 10 percent finer than 0.0008 inch (0.02 mm) without being frost susceptible (Kestler 2003).

Freeze-thaw problems are common in fine-grained particularly silty soils in northern regions in the spring. However, it also can be a problem at marginally high elevations in many forests during a typical midwinter thaw periods. For additional information see section 3.3.3.

2.3.4. Asphalt Concrete Pavement and Bituminous Surface Treatment Road Surface Distresses

Many asphalt concrete (AC) pavements and bituminous surface treatments (BST) on forest roads are old and have far exceeded their design life or were marginally structurally adequate in the first place. Thus, many paved roads are showing their age, or deteriorating in a number of ways. First, for discussion purposes an asphalt concrete pavement is a road that is surfaced with either a mix of hot asphalt cement and aggregate (hot mix asphalt concrete (HMAC)) or a mix of either liquid asphalt or asphalt emulsion and aggregate (cold mix asphalt concrete (CMAC)). These pavements typically have an asphalt mat thickness greater than 1inch (25 mm) and may have a seal coat on the top surface. BST is a series of sprayed seal coats, placed on an aggregate base, using one of a variety of asphalt types and aggregate; the asphalt mat is usually less than 1-inch (25 mm) thick. Common BSTs are single- and double-chip seals.

Common ways asphalt surface shows its age is through asphalt surface distress. These distresses include but are not limited to the following:

- Cracking
    - Alligator/Fatigue Cracking
    - Block Cracking
    - Edge Cracking
    - Longitudinal Cracking
    - Transverse Cracking

- Patching and Potholes
  - Patch Deterioration
  - Potholes
- Surface Deformation
  - Depressions/Distortions
  - Rutting
  - Shoving
- Surface Defects
  - Bleeding
  - Polished Aggregate
  - Raveling
  - Loss of Cover Aggregate
  - Longitudinal Streaking
- Miscellaneous Distresses
  - Water Bleeding and Pumping

Traffic, drainage, pavement structure, construction conditions, and climatic extremes all affect the field performance of an asphalt surface and each can cause a unique asphalt pavement distress. The most common distress is fatigue from repeated loading over time, particularly for relatively thin pavements. The second most common distress is raveling and/or cracking due to climatic extremes.

A common practice is to design an asphalt concrete surface for 15 to 20 years of traffic and climate and a BST typically for 7 to 12 years. As noted above many Forest Service asphalt pavement surfaces have been in service for over 20 years and many pavement distresses have become so extensive that just patching or spot repairs have become difficult or no longer are a reasonable option. Figure 2-17 shows typical damaged BST surfaces after many years of traffic.

Section 3.3.4 discusses common maintenance treatments for asphalt distresses as well as some nontraditional treatments that might extend the life of the asphalt pavement. Possible reconstruction alternatives also are discussed providing the reader with a broader idea of what rehabilitation options might be practical when looking at various maintenance and reconstruction strategies.

Figure 2-17—Bituminous surface treatment failures on old chip seal road surfaces.

2.4. ROAD SURFACE AND SUBSURFACE DRAINAGE ISSUES

Drainage is the single most important aspect of road design, construction, and maintenance. Practitioners can relate a vast majority of road problems to excess water or poor drainage. Too much water in any part of a road's structure can weaken it, leading to failure. Improperly designed roadway surface-drainage measures or natural drainage crossings can lead to major failures, high maintenance or repair costs, and extensive environmental damage. It is commonly said that the three most important aspects of road design are drainage, drainage, and drainage.

Road location and drainage, construction areas, and other areas of activity are the most significant factors that can affect water quality, erosion, and cost. Drainage issues include controlling surface water, removing or addressing subsurface water as needed, and adequately passing water under roads in natural channels.

Heavy rainstorms are a major contributing factor that causes cutslope failures that block ditches, cause water flow on the road surface, and erode the roadway surface and fillslopes. Debris moving down natural channels during heavy rains can block drainage structures, causing water to overtop and damage the road and the fillslopes. Good drainage is particularly important (and obvious) during major rainstorms.

2.4.1. Surface Drainage

Water affects the entire function of a road. Road surface-drainage problems can occur on the road surface, in the ditches, at the inlet and outlet of cross-drain pipes, or beyond the road. Too much water in the base material weakens the road. Water allowed to remain on the top of the road weakens the surface and, when combined with traffic causes ruts, potholes, gullies, and cracks. Where concentrated on the road surface or concentrated and improperly channeled off the road, water causes erosion and deepens ruts, as well as washing off expensive surfacing aggregate. Concentrated water leaving the road surface or roadway ditches can further create gully erosion beyond the roadway.

Steep road grades cause surface and ditch water to move rapidly, and make surface drainage difficult to control. Road grades over 12 to 15 percent can be very difficult to drain properly. This condition accelerates erosion unless surfaces are armored or water is dispersed or removed frequently. The road surface and adjacent areas, including shoulders and cuts and fills, are a relatively large surface area that has the potential to erode and produce significant amounts of sediment from concentrated water flow (figure 2-18).

Figure 2-18—Examples of poor surface drainage causing erosion and damaging the road surface.

2.4.2. Subsurface Drainage

Subsurface water (ground water) may come from fissures or fractures in rock, fault zones, buried alluvial strata, and so forth. It may be naturally occurring; it may be the result of a new roadway cut, or the modification of ground water flow patterns caused by filling over an area.

The road subgrade gets saturated and soft when there is significant ground water, and the potential exists for pore-pressure buildup. This typically occurs in a local seepage or spring area where ground water is present under the road. Without proper drainage, subsurface water weakens the soils, particularly in clay or silt-rich soils, causing deformation in the road. This can result in local failures, ruts, loss of subgrade strength, and erosion. Moisture pumps to the surface under repeated loading from traffic and reduces the structural capacity of even relatively good soils. Subsurface water also may lead to cut and fillslope instability problems.

At times the roadway surface can be strengthened with aggregate or other structural-section material, but typically it is most cost effective to remove the water with a subsurface drainage measure described in section 3.4.2. In meadow crossings where a high ground water table needs to be maintained, additional surface drainage is needed in conjunction with an elevated structural section. This topic is discussed in section 3.5.5.

2.5. STREAM AND WET AREA CROSSING ISSUES

2.5.1. Culvert Failures (plugging, scour, lack of capacity, fish barriers)

Culverts are used as cross drains for ditch relief and to pass water under a road at natural drainage and stream crossings. In either case, they need to be sized and installed properly, and protected from erosion, scour, and plugging. Natural drainages need to have pipes large enough to pass the expected design flow plus extra capacity to pass debris without plugging, which can cause road failure and stream damage. Small culvert pipes are particularly susceptible to plugging and require cleaning and maintenance.

Culverts fail for a variety of reasons, but the two principal reasons are (1) they lack sufficient hydraulic capacity to pass the flow from a major storm event, and (2) they plug with sediment and debris. Other reasons for failure include loss of capacity due to a damaged pipe, a piping failure in the bedding material under the pipe, poor compaction and settlement around the pipe, improper bands at the union of separate pipe sections, or pipe deterioration due to old age, abrasion, or corrosion. Figure 2-19 shows a pipe failure due to plugging while figure 2-20 shows a pipe failing due to piping and water running under the pipe.

Other significant problems with culverts are the impacts they can have on the stream itself and on aquatic organism or fish passage. Most culvert pipes accelerate the water velocity flowing through them, often causing scour and streambank instability particularly at the pipe outlet. Culverts are a common barrier to fish and other aquatic organisms for a variety of reasons, including forming a barrier, flowing too fast or too shallow, or no resting areas or natural substrait, as seen in figure 2-21.

Figure 2-19—Failed culverts probably caused by plugging.

Figure 2-20—Piping failures underneath culverts.

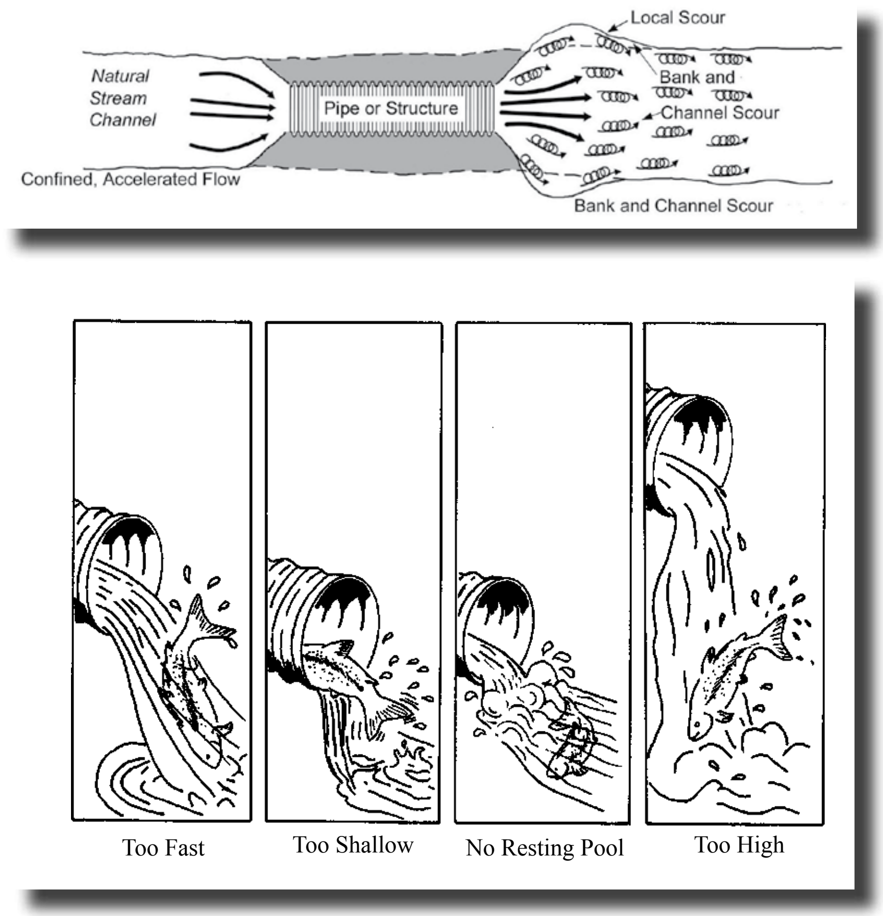


Figure 2-21—Poorly designed or installed culverts with (a) flow contraction that accelerates flow velocity and causes scour, and (b) fish barriers that prevent fish and other aquatic organism passage (redrawn from Evans and Johnston 1980).

One can minimize problems and the probability of failure in many ways. A culvert sized and aligned with the upstream channel and with an efficient transition has the least chance of plugging with debris. Damage or failures can be minimized with appropriate flood and debris capacity and culvert height, a spillway for overtopping, or additional flood capacity through other structures in the floodway, etc. Stream simulation is the ideal way to provide for aquatic organism passage in culverts. Section 3.5 discusses solutions for stream-crossing structures.

2.5.2. Low-Water Crossings Problems

Low-water crossings, or fords, are desirable alternatives to culverts and bridges for stream crossings on low-volume roads where road use is low and streamflow conditions are appropriate. Like other hydraulic structures for stream crossings, low-water crossings require specific site considerations and specific hydrologic, hydraulic, and biotic analyses. Also like many hydraulic structures, occasionally they have failed, needed repairs, or caused damage to the stream.

Common issues for low-water crossings are turbidity, pollution, and formation of barriers to aquatic organism passage. Low-water crossings have failed or performed poorly for many reasons. Also the many crossing types and designs have led to problems. These problems include scour under the slab or structure (figure 2-22), an inadequate foundation, end-run flow around the structure, backing water into other structures, channel aggradation (sedimentation) or degradation, fish barriers, traffic delays, etc. A failed crossing can be a major source of sediment, can create significant traffic delays, can close the road, and can be expensive to repair or replace.

Figure 2-22—Low-water crossing structures damaged after a storm from scour moving materials beneath the concrete planks or concrete slab.

2.5.3. Bridge Problems

Bridges are expensive to build and maintain, but often are the most desirable stream-crossing structure because they can be constructed outside of the stream channel and thus minimize channel changes, excavation, or placement of fill in the natural channel. They minimize disturbance of the natural stream bottom and they do not require traffic delays once constructed. They are ideal for fish passage. They do require detailed site considerations, specific hydraulic analyses, and structural design. Bridges must be maintained periodically. Lack of maintenance can lead to a shorter design life and failure of the bridge can cause significant expense and traffic delays (Kattell et al. 1988).

Many of the problems described below are particularly problematic with bridges, but the problems also can apply to some box culverts and vented fords.

General Scour

Scour, defined as the erosion or removal of streambed or bank material from bridge foundations due to flowing water, is the most common cause of highway bridge failures in the United States. The Forest Service administers 7,650 bridges on National Forest System lands and virtually all of them are over water. Scour also is the single most common cause for bridge damage. Many bridges experience floods, which can cause damage each year. It is important to assess bridges as to their vulnerability to scour and then take appropriate mitigation or repair measures.

Contraction Scour

Contraction scour occurs when a channel narrows and stream velocities increase (figure 2-23). Many Forest Service bridge spans, as well as culverts, are undersized by today's standards and contraction scour is present. If a stream channel cross section is reduced one half by a structure, then the velocity must double to pass the same flow, and typically some backwater condition develops, creating other problems.

Figure 2-23—A bridge abutment washout due to contraction scour on a short span bridge (one-half of the span of the natural channel).

Abutment Scour

Abutment scour is known as local scour. Local scour involves removal of material from specific areas caused by an acceleration of flow past an obstruction and the subsequent turbulent water (vortices) around the obstruction, such as a midchannel pier (figure 2-24). Local scour is accentuated by debris buildup or stream instability that shifts the stream towards one abutment or changes the angle of attack. The most common locations for local scour on a typical low-volume road single-span bridge with vertical wall abutments are adjacent to the upstream and downstream corners intersecting the wingwalls, as seen in figure 2-25.

Figure 2-24—Bridge scour at a midchannel pier.

Figure 2-25—Bridge abutment undermined by scour.

Debris

Debris can have a significant impact on bridge scour in a number of ways:

- A buildup of debris can reduce a bridge's waterway opening causing contraction scour of the channel.
- A buildup of debris can increase the obstruction area of a pier or abutment and increase local scour.
- Debris can deflect the flow of the water, which changes the angle of attack and increases local scour or shifts the entire channel around the bridge altogether.
- Action of water against debris can place a substantial lateral force on the bridge, and at times has pushed the bridge superstructure off its abutments.

Stream Channel Instability

Stream channel instability is a problem associated with braiding streams. Many Forest Service roads are located adjacent to larger rivers, and thus, many Forest Service bridges cross the tributaries. Many of these tributaries have grade changes as they approach the flood plain of the larger rivers, and have braiding characteristics and experience shifting and lateral migration. Bank erosion and changing angles of attack of the stream to the bridge cause local scour problems.

Aggradation

Mountainous streams generally have variable grades. Many have steep grades, yet flatten out substantially within a short distance of their confluence with a larger river. Aggradation within this flatter stream section can be a problem as the stream transports bedload off the steeper grades and deposits it as velocities slow along the flatter grades. High flows in a larger river where a smaller tributary joins can cause backwater in the smaller tributary, which can also cause aggradation. Over time, the aggradation may be balanced by isolated storm events that flushes (downgrade) out the tributary stream section. However, in the short term, this aggradation can be a problem to bridges. Continued aggradation can minimize clearance for debris passage, reduce the open area and hydraulic capacity of the bridge, or cause overtopping or scour damage to the bridge and approach roadways.

Long-Term Degradation

Long-term degradation is another characteristic of mountainous streams. Steep, incised channels will experience long-term degradation. When evaluating bridges for scour vulnerability, long-term degradation should be a factor. Many Forest Service bridges were built on spread footings with an embedment depth of only a few feet. Today, many of these bridges are of the age in which these footings will be exposed or undermined, mainly due to long-term channel degradation.

Abutment Fill Failures

During many flood events, the structure and foundations of the bridge will not be damaged, but the fill behind an abutment scours (figure 2-26). This occurs on a typical Forest Service single-span bridge with vertical wall abutments. Streams have a natural tendency to meander or change their channel-flow patterns, particularly in relatively flat, low-gradient areas. Local scour occurs around the wingwalls or undermines the abutment footing and subsequently scours away the approach fill. To a user on the road, an abutment fill failure can be just as hazardous as a bridge failure. For this reason, abutment fill failures (due to scour) should be included in determining the bridge's scour vulnerability.

Figure 2-26—Abutment fill scour due to a shifting channel and streambank scour (with little damage to the bridge itself).

2.5.4. Streambank Instability

Direct human activities, such as channel confinement, local realignment of the streamflow, and damage to or removal of vegetation, are major factors in streambank erosion. Streambank erosion also may be caused by geologic, climatic, and hydraulic factors. Land-use changes or natural disturbances can cause the frequency and magnitude of water forces to increase. Loss of streamside vegetation can reduce resisting forces, thus streambanks become more susceptible to erosion where the sediment directly enters into the water course, resulting in water-quality degradation (figure 2-27).

Figure 2-27—Streambank erosion.

Channel realignment or straightening often increases stream power and may cause streambeds and banks to erode, which can cause damage to structures or the roadway platform unless streambank stabilization measures are built. Conversely, stream-channel modifications to accommodate structures, such as bridges and culverts, can lead to upstream or downstream streambank instability and subsequent water-quality degradation.

A stream cutbank is an erosional feature of streams (as well as a road feature). Cutbanks are found in abundance along mature or meandering streams, they are located on the outside of a stream bend, known as a meander. They are shaped much like a small cliff, and are formed by the erosion of soil as the stream collides with the riverbank. Typically, cutbanks are nearly vertical and often expose the roots of nearby plant life. Often, during periods of high rainfall and higher-than-average water levels, trees and poorly placed structures can become undermined and fall into the stream due to mass wasting events. Given enough time, the combination of erosion along cutbanks and deposition along point bars can lead to the formation of an oxbow lake in very flat terrain.

2.5.5. Meadow and Wet Area Crossings

Wet meadow areas perform a variety of hydrologic functions operating through physical, chemical, and biological processes. Primary among these functions are flow dispersal and energy dissipation, sediment detention, toxicant retention, ground water discharge, ground water recharge, and down-channel runoff. Thus, these areas are very important to the forest environment.

Damage has frequently been done to meadows by building roads across them. Single (or a few) culverts used to drain the meadow have concentrated the flow, caused gullies and headcutting, lowered the water table, and dried up areas of the meadow (figure 2-28). Drying the meadow has resulted in changes within the plant community and often erosion and other degradation.

Headcutting removes fine-textured surface soils, creating a gully and lowering the water table. When the rate of erosion exceeds deposition, a meadow's ability to detain and store water diminishes and it begins to dry. As the meadow dries, the dense stands of riparian vegetation decrease, exposing the fine-textured soils to erosion. As channel incision and gully formation worsen, periodic surface flooding no longer occurs and riparian vegetation disappears leaving only remnant areas of formerly hydric soils as evidence of site potential (Zeedyk 1996).

The best way to protect meadows and wetlands is to avoid crossing them. If this is not feasible, minimize and mitigate impacts of any crossing, as discussed in section 3.5.5.

Figure 2-28—A headcut caused by a road crossing, moving upslope in a meadow area.

2.5.6. Temporary Wet Area Crossings

Removing wood products from the forest requires access systems, such as truck roads and skid trails. Roads and trails must often cross streams. The construction and use of access roads and trails in the forest has the potential to negatively impact streams and wetlands directly by soil compaction, ruts, or the placement of fills. Streams and wetlands also can be impacted indirectly by funneling the movement of sediment, debris, and nutrients into the water body or by causing changes in hydrologic flows across the area.

Temporary wet area crossings commonly are used for temporary roads and logging roads as a way to minimize impacts and cost. The best way to protect the meadows and wetlands is to avoid crossing them. If this is not feasible, try to minimize and mitigate impacts of any crossing. For any particular application, selecting a crossing option that is cost effective for the contractor and/or landowner, that adequately addresses the environment concerns of society, and that satisfies the wide range of regulatory constraints is becoming increasingly difficult (Blinn et al. 1998).

3.1. EROSION CONTROL

Erosion control on roads is fundamental to protect water quality. Soil stabilization and erosion control practices are needed and should be used in areas where soil is exposed and natural vegetation has been disturbed or is inadequate. Bare ground should be covered with some form of matting or mulch to reduce initial erosion and promote long-term stabilization with growth from grass seed or other types of vegetation (ideally native). Use vegetation as the primary form of erosion control. This helps prevent long-term erosion and subsequent movement of sediment into streams, lakes, and wetlands.

Sediment movement can occur during and after road construction, after road maintenance, during logging or mining activities, as the road is being used, if a road is closed but not stabilized, or from poor land management practices near the road. Roughly half of the erosion from a logging operation, for instance, comes from the associated roads and skid trails. Mass erosion rates from roads are typically one to several orders of magnitude higher than from other land uses, based on unit area. Surface erosion from road surfaces, shoulders, and cuts and fills is significant. (Gucinski et al. 2001)

Also, most erosion occurs during the first rainy season after construction. Erosion control measures need to be implemented prior to, during, and immediately following construction and every time an area is disturbed. Soil erosion prediction models such as the Water Erosion Prediction Project (WEPP) or Revised Unified Soil Loss Equation (RUSLE) can be used to quantify erosion and compare the effectiveness of various erosion control measures. Concentrated water flow can begin as minor sheet flow, produce rills, and eventually result in major gully formation.

USLE: <http://fargo.nserl.purdue.edu/rusle2_dataweb/RUSLE2_Index.htm>.

WEPP: <http://forest.moscowfsl.wsu.edu/engr/software.html>.

The Geomorphic Roads Analysis and Inventory Package (GRAIP), developed by the Forest Service, Utah State University, and the EPA, is a tool to predict the impacts of roads or a road segment and prioritize where reconstruction work is needed most. It uses resource data and field road inventory data in an ARC-GIS platform to predict and quantify sediment production, diversion potential, or slope stability risks. Information on this analysis method is available at <http://www.fs.fed.us/GRAIP/index.shtm>.

BMPs are a tool used to guide the quality and care of construction and other activities to prevent erosion and protect water quality. Currently, the Forest Service is using the California BMP, U.S. Department of Agriculture, Forest Service (2000). The BMPs are available at <http://www.fs.fed.us/r5/publications/water_resources/waterquality/>.

3.1.1. Factors Affecting Erosion

Erosion processes are a function of climate, soil, topography, and vegetation cover. First, climate involves the frequency of intense rainfalls as well as the presence of conditions moist enough to support a relatively complete vegetation cover. Seasonality is also important; for instance, so that construction work is done when stream ecosystems are least damaged and so that vegetation establishment avoids dry or cold seasons (Forman, R. et al. 2003).

Second, soil texture, organic matter content, structure, and permeability influence erodibility. Soil texture refers to the proportions of sand, silt, and clay particles. Soil organic matter, composed mainly of decaying plant leaves, stems, and roots, tends to hold soil particles together and improve soil fertility as well as reduce erosion. Soil permeability enhances water penetration, thus reducing surface water runoff that may cause soil erosion along roads (Lewis et al. 2003).

Third, for topography, slope length and steepness are keys to erosion potential. Flatter slopes tend to maintain sheet erosion, whereas steeper slopes tend to have rill and gully erosion. Slope aspect (exposure direction relative to the sun) affects soil temperature and soil moisture conditions that in turn determine vegetation establishment. In addition, the size, shape, elevation, and slope of the drainage upslope affect erosion potential.

Finally, vegetation cover is the most critical factor influencing erosion. Vegetation provides seven major benefits. It:

1. Reduces raindrop impact via top growth and leaf litter.
2. Reduces runoff velocity via increased roughness from growing plants and leaf litter.
3. Provides, via the root system, structural integrity (reinforcement) of the soil.
4. Filters chemical pollutants and sediments from runoff.
5. Increases water infiltration into the soil.
6. Increases percolation through the soil (lateral movement of water in the soil).
7. Increases evapotranspiration (vertical movement of water to the air).

These benefits are easy to visualize. Raindrop impact is reduced by the cover of foliage and leaf litter on the ground. Runoff velocity and sediment transport decrease with stem density and litter cover. Mechanical strengthening and structural integrity of the soil is enhanced by a mixture of species, which provide shallow and deep dense root networks. Pollutant filtering increases with more organic matter (hydric soils), assuming that water infiltrates into the soil. Infiltration and percolation increases with lower runoff velocity and an abundance of soil pores produced by soil animals, such as insects, ground squirrels, and earthworms. Evapotranspiration pumps out more water vertically as plant density and vegetation cover increase. Diverse human-related activities tend to accelerate erosion, primarily by altering or removing the vegetation cover.

Numerous soil types exist that can be grouped and ranked according to water runoff potential. Low runoff soils have high infiltration rates even when drenched, and are deep and sandy, gravelly, or cobbley. Water readily passes through these well-to-excessively drained soils. At the other end of the continuum are very high runoff soils, which have an extremely slow infiltration rate when saturated. These soils are mainly silt and clay (with a high swelling potential). Water moves slowly through such soils. These concepts are represented in table 3-1.

Table 3-1—Ground water transmission rates (Lewis, et al. 2003)

Soil Textural Category	Transmission Rates
Large stone, cobble, gravel	Rapid
Gravel and sand	Moderate
Fine sand and silt	Moderate
Clay	Slow

Different soil textures also have different erosion potentials and different abilities to support vegetation. Table 3-2 shows the soils most and least susceptible to erosion. Coarse granular soils and most clay soils have a relatively low erosion potential. Fine sands and silts have the highest erosion potential, but fortunately many of these soils also are good at supporting vegetation.

Table 3-2—Erosion potential and plant growth capability of selected soils (from Rivas 2006; based on Gray and Leiser 1982; Gray and Sotir 1996; and Bell 2000)

USDA Soil Texture*	USCS group symbol	USCS Soil Description	Surface Erosion Potential (rill/interrill/wind)	Support of Vegetation Establishment
Gravel	GW	Well-graded gravel	Low to medium	Poor
Gravel	GP	Poorly graded gravel	Low	Very poor
Gravel/silt	GM	Silty gravel	Low to medium	Poor to fair
Gravel/clay	GC	Clayey gravel	Low	Poor to fair
Sand	SW	Well-graded sand	Medium to high	Poor to fair
Sand	SP	Poorly graded sand	Medium to high High wind erosion	Very poor
Loamy sand	SM	Silty sand	Medium to high	Good to very good
Sandy clay loam	SC	Clayey sand	Medium to high	Good to very good
Silt	ML	Silt	High to very high High wind erosion	Good to very good
Clay	CL	Clay	Low to medium	Fair to good
Silt	MH	Silt, high plasticity	Medium	Good
Clay	CH	Clay, high plasticity	Low to medium	Fair to good
Organic Soils	PT OL/OH	Peat/Organic silts/clays	Low to high	Very good

** The USDA soil texture system does not correlate well with some aspects of the Universal Soil Classification System (USCS), especially for gravelly and organic soils.*

3.1.2. Erosion Control Treatments

Erosion control is a two-step process; short-term erosion control generally followed by the establishment of vegetation for long-term erosion control. Sometimes in steep or severe conditions, a structural solution, such as a retaining wall, ground armoring with rock, or a gully plug, is required. The ideal erosion control solution promotes germination, plant growth, and encourages the natural recruitment of the surrounding native plant community while it protects the soil from short-term erosion. There are numerous treatments, combinations of treatments, and emerging products that may be suitable for a site. The following information is a starting point in selecting various treatments. The general erosion-control treatment categories and corresponding tables are:

- Grade related.
- Seed, fertilizer, and soil amendments.
- Soil stabilizers and tackifiers.
- Mulch.
- Rolled erosion control products.
- Hard armor.
- Use of vegetation.
- Soil bioengineering.

Soil bioengineering and biotechnical treatments are very practical, useful, and environmentally desirable techniques for long-term slope stabilization and erosion control. **Soil bioengineering** is a technology that uses integrated ecological principles to assess, design, construct, and maintain living vegetative systems to repair damage caused by erosion and slope failures. It is based upon sound engineering principles (Sotir 2001). It uses specific native live plant materials in various configurations as a shallow structure, erosion control ground cover, or environmental and aesthetic components for protection, enhancement, and restoration.

Biotechnical treatments combine the use of mechanical structures, such as walls, gabions, or reinforced fills in conjunction with vegetation to combine physical structural elements with the advantages and long-term performance and aesthetics of vegetation. Biotechnical stabilization is a specialized field and consultation with experts and other guides is highly recommended. However, many techniques can be readily applied on low-volume road design, maintenance, and rehabilitation projects.

The International Erosion Control Association is the industry representative for the erosion control profession. While it is primarily a products-oriented organization, it is also a good source for information on erosion control technology. Their monthly trade journal "Erosion Control" provides many articles on all aspects of erosion control, evaluation of products, case histories, and vendors. Their Web site is <www.erosioncontrol.com>.

Table 3-3 through table 3-10 address methods common for each erosion control treatment. Figures 3-1 through 3-9 show a variety of erosion control treatments and materials. A description of each method, how it functions, when it typically is used, and its limitations for use are noted. The conditions of use and limitations are those generally found in literature, or in some cases, are based on the author's and reviewers' experience. This information is adapted from "Erosion Control Treatment Selection Guide" (Rivas 2006), which describes the erosion control principles, erosion types, and soil types. The references cited within the tables of Rivas (2006) are not cited individually in this guide. The guide also details erosion control treatments and proper treatment selection for use by engineers and technicians. Link to the document <http://www.fs.fed.us/eng/pubs/pdf/hi_res/06771203hi.pdf>.

Figures 3-1 through 3-9 illustrate erosion control treatments discussed in the tables.

Another useful reference that combines many erosion and sediment control practices in a forest road setting, including drainage control, vegetation, mulch use, biotechnical measures, and various physical structures is Gillies (2007).

3.1.2.1. Grade-related treatments

Table 3-3— Grade-related treatments (Rivas 2006)

Functions	Typical uses	Limitations
Grading and shaping		
❑ Flattens slope for stability. ❑ Modifies soil surface and topography to control runoff and establish vegetation. ❑ Optimizes slope angles and shapes for reduced water erosion and sediment yield.	❑ Use to improve final appearance, improve stability, enhance vegetation establishment, and reduce erosion. ❑ Use to reduce costs and increase effectiveness of treatments.	❑ May reduce vegetation establishment if surface is compacted on sites with high silt and clay content. ❑ May have limited options due to topography. ❑ Final grading should be compatible with the land use objectives. ❑ May open up more surface area for erosion, especially in easily erodible soils. ❑ Requires immediate cover treatment.
Soil roughening		
❑ Reduces and detains runoff and improves vegetation establishment.	❑ Use to loosen the soil for improved soil properties for improved vegetation establishment.	❑ May not be suitable for steep slopes. ❑ May temporarily increase erosion prior to vegetation establishment. ❑ Roughening must be done across slope to discourage rilling. ❑ Requires immediate cover treatment.
Tracking (Tracking cleated construction equipment up and down or across a slope)		
❑ Roughens the soil surface to reduce runoff, increase infiltration, trap sediment, and promote seed germination and growth.	❑ Use to reduce erosion and sediment yield, particularly for sandy slopes, if the cleats are parallel to the contour.	❑ May compact the surface if used on clay and silt soils. ❑ Increases erosion if used with cleats perpendicular to the contour. ❑ May increase time to finish slopes. ❑ May not be suitable for steep slopes.

Table 3-3—Grade-related treatments (Rivas 2006) continued

Terraces (Berm or bench-like earth embankment, with a nearly level plain bounded by rising and falling slopes. Based on slope, terraces are either level (placed on contour) or graded (sloped to drain).		
Functions	**Typical uses**	**Limitations**
❑ Improves infiltration; reduces effects of interrill and rill erosion. ❑ Assists vegetation establishment. ❑ Reduces slope distance by changing a long slope into a series of shorter slopes.	❑ Use on long, steep, stable cut and fillslopes 2H:1V or steeper. ❑ Use to prevent erosion with paved on-contour terrace drainage ditches.	❑ May be susceptible to instability if not well compacted. ❑ May be difficult in rocky, hard soils. ❑ May reduce sediment. ❑ Requires immediate cover treatment on the slopes and on the benches.
Constructed wattles (A constructed linear feature placed in contact with the soil surface, generally on contour, that breaks a longer slope into a series of shorter slopes, such as small rock walls, woven wooden fences, or logs.)		
❑ Retains seeds and soil, slows runoff. ❑ Breaks a long slope into a series of smaller slopes. ❑ Improves conditions for plant establishment immediately upslope of wattle.	❑ Use to shorten slope distance, retain sediment, and reduce rill formation. ❑ Use for long-term protection during and after vegetation establishment. ❑ Use on gentle or steep slopes (up to 1H:1V). ❑ Use in combination with soil bioengineering, such as a bender board fence, live fascines and brush layer to help establish vegetation for steep and dry sites. ❑ Use log wattles (with live stakes and or rooted plants if possible) for fire rehabilitation.	❑ May require maintenance to remain effective particularly without live measures. ❑ Has limited sediment capture capability. ❑ Should not be used on creeping or slumping soils or for high flows. ❑ May be ineffective for interrill erosion. ❑ Requires intimate contact with ground.

Table 3-3—Grade-related treatments (Rivas 2006) continued

Manufactured wattles (Natural plant materials such as coir, rice or wheat straw, or flax encased in tubes of netting and placed securely on the slope, generally on contour, to break a longer slope into a series of shorter slopes.)		
Functions	**Typical uses**	**Limitations**
❑ Retains seeds and soil, slows runoff. ❑ Breaks a long slope into a series of smaller slopes to reduce rill erosion. ❑ Improves conditions for plant establishment immediately upslope of wattle.	❑ Use to shorten slope distance, retain sediment, and reduce rill formation. ❑ Use for temporary 2-3 year protection until plants are established. ❑ Use for quick, relatively easy installation. ❑ Use on gentle or steep slopes (up to 1H:1V).	❑ Requires intimate contact with ground. ❑ May require maintenance to remain effective. ❑ Has limited sediment capture capability. ❑ Should not be used on creeping or slumping soils or for high flows. ❑ May be ineffective for interrill erosion, depending on spacing.

Grading-installation tips

- ❑ Soil surface should be as rough as possible to improve mulch adherence, increase infiltration, reduce runoff velocities, and encourage sedimentation of eroded soil.
- ❑ Overhangs should be removed and top, bottom, and sides of slopes rounded to meet natural ground.
- ❑ Soil surface may need to be smoothed somewhat to eliminate highly erosive rills.
- ❑ Level terraces promote infiltration on dry sites and graded terraces facilitate drainage on wet sites.
- ❑ Terrace horizontal cut to vertical cut of stairs should be less than 1H:1V, with insloping benches.
- ❑ Terrace cuts should not be more than 2 feet (0.6 m) high on soft soils or more than 3 feet (0.9 m) on rocky soils
- ❑ Topsoil or soil amendments, such as organic fertilizers can be placed on terraces to promote vegetation on infertile soils.

3.1.2.2. Seed, Fertilizer and Soil Amendments

Table 3-4—Seed, fertilizer, and soil amendments (Rivas 2006)

(Broadcast of seeds, fertilizer, and or amendments on or into the surface of the soil)

Seed		
Functions	**Typical uses**	**Limitations**
❑ Helps erosion control after germination, and increases performance as plants grow. ❑ Encourages water retention and infiltration, once the seeds have germinated. ❑ Improves aesthetics.	❑ Use of dry seed and fertilizer may be effective on slopes up to 1.5H:1V. ❑ Use seed and mulch to provide adequate vegetation for erosion protection prior to harsh weather conditions. ❑ Use native seed whenever possible; if unavailable use an annual seed.	❑ May be more effective on higher slopes if seed, hydromulch, or straw mulch are used with tackifier. ❑ Often requires additional interim erosion control treatments. ❑ If applied too early, birds and rodents may eat the seeds.
Fertilizer and Soil Amendments		
❑ Provides nutrients and desirable soil properties for vegetation growth.	❑ Use for long-term vegetation establishment by applying to soils lacking nutrients or other desirable properties, such as favorable pH. ❑ Use hydraulically applied composted manure on cutslopes with low nutrient content.	❑ May require hydraulic application on difficult steep slopes.

Figure 3-1—Relatively recent cutslope armored with rock and vegetated with native grasses.

Seeding-installation tips (Oregon Department of Transportation 2000)

- Best time for seeding varies from region to region and by season.
- Place vegetation requiring moisture in concave areas (valleys) collecting runoff and moisture and drought-resistant plants on convex areas (hillslopes) with little runoff or seepage.
- Design seed mix for rapid vegetation establishment.
- Consider growth season, method of natural propagation, and root depths when designing a seed mix. These factors vary by climate.
- Base seeding rate on the pure live seed weight (that portion of the desired seed that is live).
- Verify that the seed purity and quality, inert material, weed seed, other seeds, and hard seed percentages are labeled and total 100 percent.
- Ensure that seed is labeled correctly and backed up with a lab report.
- Double the seeding rate when seed and mulch are applied together.

- ❑ Hard-seed percentage is the viable seed percentage not germinated after the test.
- ❑ Seed-soil contact is the key to germination.
- ❑ Apply seed before mulch, immediately after soil disturbance, while soil is loose and moist and before seasonal rains or freezing temperatures.
- ❑ Using seed and fertilizer without mulch may be ineffective, especially for steep slopes.

Soil amendment installation tips (Norland 2000; Fifield 2001; Harding 1994; Agassi 1992)

- ❑ Application rate is based on dry weight and dilution ratio.
- ❑ Soil moisture is important when applying chemical additives to soils. This affects the dilution and ultimately their performance.
- ❑ Amendments may not perform well if applied during cool weather with high soil moisture.
- ❑ Dilutions that produce runoff should be avoided. Runoff conditions may require an application outside of the hydraulic seeding and mulching operation.
- ❑ Dilution rate, soil properties, climate, and amendments may determine performance.
- ❑ Erosion control performance differences may exist between chemicals applied on different soils.
- ❑ Chemical stabilizers do not appear to have any impact on vegetation establishment on sands in humid climates.
- ❑ Soil stabilizers and mulches together may provide the same protection for less material than either one alone.
- ❑ Chemical tackifiers are applied in solutions to bind mulches together and to the soil.
- ❑ Soil sealants may require permeable soils with voids for effective treatment.
- ❑ Application of polyacrylamide may be more difficult than phosphogypsum due to its higher viscosity and lower dissolution rate.

3.1.2.3. Soil Stabilizers and Tackifiers

Table 3-5—Soil stabilizers and tackifiers (Rivas 2006)

(Organic or inorganic products applied in solution to the soil surface that form a protective surface film or infiltrate and bind the soil particles together or seed and mulch to the surface.)

Functions	Typical uses	Limitations
❑ Aids vegetation establishment while temporarily protecting surface of steep slopes. ❑ Reduces seed loss and evaporation, increases infiltration, moderates soil temperature, and adds nutrients. ❑ Holds mulch fibers in place. ❑ Encourages vegetation establishment in dry climates by preventing soil surface sealing while vegetation develops. ❑ Increases infiltration rate of soils in dry climates (phosphogypsum (PG)).	❑ Use to tack mulches on hard to reach areas and increase mulch durability. ❑ Use alone or with hydraulic mulch to increase vegetation establishment especially for short, high intensity rainfall on sandy loam slopes. ❑ Use polysaccharide (PS) and PG or polyacrylamide (PAM) and PG as very effective treatments in dry climates for slopes up to 1H:1V with no significant difference between the two combinations of treatments. ❑ Use to reduce surface sealing of soil.	❑ May have varied application needs and effectiveness depending on temperature, soil moisture, and dilution. ❑ Will become less effective with time. ❑ May reduce vegetation establishment in some cases. ❑ May be less effective if used on frost-heave susceptible soils or when applied near freezing weather. ❑ May increase soil biological activity and reduce the efficiency of PS in warm weather and moist soil. ❑ May have reduced effectiveness of PG when subject to high intensity storms or applied to long, windward slopes.

3.1.2.4. Mulch

Table 3-6—Mulch (Rivas 2006)

(See original reference for definition and discussion on long-fibered and short-fibered mulch)

General		
Functions	**Typical uses**	**Limitations**
❑ Provides seed coverage and reduces splash erosion. ❑ Improves soil structure and nutrients. ❑ Reduces surface crust formation. ❑ Detains and reduces runoff. ❑ Moderates soil temperature. ❑ Creates a microclimate to enhance seed germination.	❑ Use to establish vegetation at sites with surface erosion, daily temperature fluctuations, lack of available moisture, acidic soils, lack of nutrients, and lack of organic material. ❑ Use as a supplement to other erosion control treatments, such as seeding and soil bioengineering. ❑ Use tackifiers or nettings for steep slopes.	❑ May be ineffective in some applications if used alone. ❑ Will not control concentrated water erosion. ❑ May sometimes increase seedling mortality. ❑ May require addition of nitrogen when straw or wood is used. ❑ Will be most effective in long form; straw or wheat mulch requires hand spreading.
Straw mulch (Typically long-fibered wheat or oat stems, or hay.)		
❑ See general functions above.	❑ See general typical uses above. ❑ Use for relatively inexpensive and readily available mulch. ❑ Use with fertilizer and tackifier up to 1.25H:1V slopes. ❑ Use with netting up to 1H:1V slopes. ❑ Use with pneumatic spreader or hand place.	❑ See general limitations above. ❑ Decomposes rapidly. ❑ May introduce weeds, even when certified weed free. ❑ May be removed by wind and water and require anchoring onto surface.
Pine needle mulch (Mulch made from coniferous tree needles.)		
❑ See general functions above ❑ Forms interlocking matrix that is difficult to move by wind, water, and gravity.	❑ See general typical uses above. ❑ Use for establishing plants, such as conifers, which thrive in acidic soil. ❑ Use on steep slopes up to 1.25H:1V, maybe steeper.	❑ See general limitations above. ❑ May not be readily available in some regions.

Table 3-6—Mulch (Rivas 2006) continued

(See original reference for definition and discussion on long-fibered and short-fibered mulch)

Functions	Typical Uses	Limitations
Wood mulch (Typically wood fibers including wood chips, excelsior, coconut, jute, or burlap.)		
❑ See general functions above. ❑ Hardwood bark is effective due to its weight and interlocking fibers. ❑ Onsite shredded small trees (6 inch) are effective and plentiful in areas being thinned.	❑ See general typical uses above. ❑ Used in rolled erosion control products (RECPs) or applied with hydroseeder, hydromulcher, or pneumatic spreader.	❑ See general limitations above. ❑ May not be as effective as straw or hay. ❑ May reduce vegetation establishment if applied too thick. ❑ May be easily washed or blown away, especially on steep slopes.
Wood strand mulch (Wood manufactured into approximately 1.6 to 6.3 inch strands approximately 0.125 mm thick by 0.24 inches wide.)		
❑ See general functions above. ❑ Forms an interlocking 3-D matrix that is difficult to move by wind, water, and gravity. ❑ Increases overland flow path length. ❑ Reduces rill formation by creating mini-debris dams.	❑ See general typical uses above. ❑ Use to reduce rill formation. ❑ Use as weed- and pesticide-free substitute for straw and pine needle mulch. ❑ Use as possible longer term, allergy friendly, foraging reducing, more wind-resistant alternative to straw mulch.	❑ See general limitations above. ❑ May require advanced planning with manufacturer for availability. ❑ May cost more than straw mulch.
Recycled paper/pulp mulch (May be referred to as cellulose and applied with a hydraulic seeder or hydraulic mulcher.)		
❑ See general functions above.	❑ See general typical uses above. ❑ Use as a less expensive alternative to wood fiber, hay, and straw mulches.	❑ See general limitations above. ❑ Less effective alternative to wood fiber, hay, and straw mulches. ❑ Short fibers are easy to move, even when bonded with a tackifier. ❑ Decomposes quickly. ❑ Ineffective for significant surface runoff.

Table 3-6—Mulch (Rivas 2006) continued

(See original reference for definition and discussion on long-fibered and short-fibered mulch)

Hydraulic mulch (Wood, cellulose, paper pulp, or recycled fibers sprayed on slopes in slurry, typically with seed and fertilizer.)		
Functions	**Typical Uses**	**Limitations**
❑ See general functions above.	❑ See general typical uses above. ❑ Use for one-step application. ❑ Use on steep slopes with tackifier rather than dry loose mulch. ❑ Use on sites inaccessible to loose mulch blowers yet near a water supply and road. ❑ Use as less expensive alternative to RECPs.	❑ See general limitations above. ❑ Less effective on short fibers without tackifier than long fibers. ❑ Long fibers may clog applicators. ❑ Relatively short effectiveness. ❑ Less effective than RECPs for high intensity storms.
Bonded-fiber matrices (BFMs) (Fiber mulch material combined with chemical adhesives or gypsum based compounds that are more resistant to water once cured and dried.)		
❑ Reduces interrill and rill erosion through close ground contact. ❑ Increases strength over mulch from bonding agents, even when wet. ❑ Supplies some soil nutrients. ❑ Holds water well in small pores.	❑ See general typical uses above. ❑ Use on rough, irregular slopes. ❑ Use for high seed retention. ❑ Use to assist vegetation establishment. ❑ Use as more durable alternative to hydraulic mulch.	❑ See general limitations above. ❑ Generally denser and lower tensile strength than erosion control blankets (ECBs). ❑ May have weather-dependant application. ❑ May not perform well under high intensity rainfall.

Figure 3-2—Straw mulch on a road shoulder.

Figure 3-3—Close-up of straw mulch.

Figure 3-4—Close-up of wood mulch.

Mulch-selection tips

- ❑ Supplier reasonably close by reduces haul distance and possibly the cost.
- ❑ Wood-fiber mulch may establish vegetation better on clay soil than recycled fiber/pulp mulch.
- ❑ Long-fibered mulches (e.g., straw, hay, and wood bark) generally last longer and perform better than short-fibered mulches (e.g., hydromulch, wood fibers, cellulose, and paper).
- ❑ Wood fiber, recycled paper/pulp, or seed and fertilizer may encourage vegetation establishment on sandy soils equally well.
- ❑ Wood chips, rock mulches, and hydraulic mulch without tackifier may not be suitable for steep slopes.
- ❑ For dry climates, mulches with lower density but greater thickness may provide better vegetation establishment and reduce runoff more than other mulches.
- ❑ For dry climates, hydraulic mulches deteriorate and release more sediment after 5 months, but treatments may need to last up to 2 years for effective vegetation establishment.
- ❑ Effectiveness of short-fibered mulch improves when tackifier is added.
- ❑ Wood strands and straw may be equally effective at reducing erosion on coarse-textured soils on slopes up to 3H:1V.
- ❑ Wood strands may be more effective than straw on fine-textured soils on slopes up to 3H:1V.
- ❑ Thinner wood strands may speed decomposition, be a more effective aid in vegetation establishment, and decrease application costs than thicker wood strands.

Mulch-installation tips (Yanosek et al. 2006; Norland 2000; ODOT 2000; Fifield 1992; Fifield and Malnor 1990)

- ❑ Use certified weed-free mulch.
- ❑ Apply mulch before active runoff, weed growth, or dry conditions for best results.
- ❑ Ensure that mulch is uniformly distributed at desired rate and depth for effectiveness.
- ❑ Anchor lightweight mulches such as straw, wood cellulose, and wood fiber either manually, mechanically, or chemically.
- ❑ Use mechanical anchoring (crimping) for slopes flatter than 3H:1V, otherwise use manual or chemical anchoring.

- ❑ Apply chemical tackifiers at the same time or just after the mulch.
- ❑ Use native-hay mulch with long fibers and native seeds to help establish vegetation.
- ❑ Use wood-fiber mulch on slopes steeper than 1.5H:1V. Do not use wood bark or woodchips on slopes.
- ❑ Use rotary spreaders for moderately rolling terrain, and pneumatic and hydraulic spreaders on steeper slopes.
- ❑ Use hand spreading for small, hard to reach areas on steep slopes beyond the reach of blowers or sprayers.
- ❑ Use pneumatic spreaders to dispense mulch easily, evenly, and in closer contact to the ground than hand spreading.
- ❑ Use dry blowers to cover large areas quickly and apply a tackifier.
- ❑ Use onsite mulching materials. They may be less expensive for remote sites than imported mulches with high transportation costs.
- ❑ Use less mulch on north-facing slopes than on south-facing slopes.
- ❑ Use less than 2 inches (50 mm) of mulch for large seeds, and less than 0.5 inches (12.5 mm) for small seeds.
- ❑ Use of too much mulch may kill seeds and prevent growth from heat generated during decomposition.
- ❑ Use higher mulch rates for erosion control of silts and clays than sands.
- ❑ Use lower mulch thickness with fine-grained soils so root aeration is not reduced.
- ❑ Use higher mulch rates for woody plant establishment.
- ❑ Use dark colored mulches to warm the soil and light colored mulches to cool the soil.
- ❑ Apply seed and fertilizer before wood mulch on dry sites to help establish vegetation.
- ❑ Realize that woodchips, sawdust, and pine needle mulch may be less desirable. They are lightweight and may float.
- ❑ Use hydraulic spreaders for wood fiber and cellulose and to reach areas inaccessible by other methods. They can only treat a small area with each load. Ensure that a water source is nearby. Filling and transporting water may take time.
- ❑ Use thicker mulch for dry climates to reduce sediment yield.

- ❑ Apply mulch at higher rate to produce better vegetation establishment on sandy soils than seed and fertilizer alone.
- ❑ Add tackifier to improve the effectiveness of short-fibered mulch.
- ❑ Apply typical long-fibred mulches by non-mechanical methods so they don't have to be chopped into smaller pieces for mechanical application.
- ❑ Apply wood strand mulch to obtain about 50-percent surface cover for optimal surface cover in most circumstances.
- ❑ Consider increasing wood strand surface cover for fine-grained soils. It is less likely to have an impact on coarse-grained soils.
- ❑ Apply wood strands by hand or helicopter.
- ❑ Apply wood strands by helicopter higher and faster than aerial straw application.
- ❑ Use a mixture of long strands (about 6.3 inches) (160 mm) with shorter strands (1.6 to 3.1 inches long) (41 to 79 mm) for wood strand mulch to control inter-rill and rill erosion.

Bonded-fiber matrix (BFM)-installation tips (Spittle 2002; Cabalka and Lancaster 1997; Roberts and Bradshaw 1985)

- ❑ BFM with crimped fibers may decrease the density and increase the thickness 50 percent more than other BFMs.
- ❑ BFM may function from 4 to 6 months or, with crimped fibers from 6 to 12 months.
- ❑ BFMs should not be applied to moist soils.
- ❑ Apply seed directly to soil in dry areas. Seeds suspended in the mulch may dry.
- ❑ Quality of BFM material depends on the applicator's skill.
- ❑ Omit chemical stabilizers for better vegetation establishment on sand slopes in humid climates.
- ❑ BFM can be shot up to 225 feet (67 m). A 3-person crew with access to water can cover about 4 acres (1.6 hectares) per day.

3.1.2.5. Rolled Erosion-Control Products

Table 3-7—Rolled erosion control products (Rivas 2006)

Functions	Typical Uses	Limitations
Rolled erosion control products (RECPs) (Flexible organic or synthetic nets, mats or rolls that are rolled out to reduce surface erosion.)		
❑ Reduces splash, sheet, and rill erosion when in contact with the soil, reduces surface sealing, and increases infiltration. ❑ Reduces and detains runoff and lessens erosion if water moves along fibers.	❑ Use for immediate surface erosion protection. ❑ Use to combine long-fibered mulch benefits with the tensile strength of anchoring nets. ❑ Use on steep slopes and low to moderate velocity flow. ❑ Use when ease of handling and storage of materials are important.	❑ Requires intimate contact with the ground. ❑ May fail by soil eroding beneath RECP. ❑ May be lifted off the ground by seedlings. ❑ May be more costly than other surface cover treatments. ❑ Correct installation is critical for success. ❑ Soil surface needs to be graded smooth to establish soil contact. ❑ May be hazardous to wildlife and entrap small animals. Use biodegradable products.
Mulch control nets (MCNs) (A planar woven natural fiber or extruded geosynthetic mesh used as a temporary degradable RECP to anchor loose fiber mulches.)		
❑ Anchors mulch to the slope to provide stronger mulch-soil contact. ❑ Improves erosion control only when combined with mulch.	❑ Use to improve loose mulch performance for moderately steep sites. ❑ Use photodegradable for short-term control. ❑ Use ultraviolet (UV) stabilized for long-term control.	❑ May be internally weaker than glued or mechanically bonded RECPs. ❑ Slopes flatter than 1H:1V. ❑ May be labor intensive to install. ❑ May entrap rodents, birds, and reptiles, especially for synthetic material.

Table 3-7—Rolled erosion control products (Rivas 2006) continued

Functions	Typical Uses	Limitations
Open Weave Textiles (OWTs) (A temporary degradable RECP composed of processed natural or polymer yarns woven into a matrix, used to provide erosion control and facilitate vegetation establishment.)		
❑ Provides erosion protection in combination with mulch or by itself due to the close weave.	❑ Use for higher tensile strength than MCN. ❑ Use as facing for vegetated geotextiles that can be photodegradable or UV stabilized.	❑ Typically for up to 2H:1V slopes. ❑ May entrap rodents, birds, and reptiles.
Erosion control blankets (ECBs) (A temporary degradable RECP composed of processed natural or polymer fibers mechanically, structurally or chemically bound together to form a continuous matrix to provide erosion control and facilitate vegetation establishment.)		
❑ Acts as mulch but is physically connected to an MCN or OWT for greater strength. ❑ May reduce erosion as much as 90 percent.	❑ Use on sites requiring durable, long-lasting, erosion control beyond anchored or unanchored mulch. ❑ Use for erosion control until plant establishment. ❑ Use on steep slopes and/or erodible soils.	❑ May be relatively expensive. ❑ May not be any significant performance difference between different ECBs. ❑ Typically up to 1.5H:1V, maybe up to 1H:1V. ❑ May entrap rodents, birds, and reptiles, especially for synthetic material.
Turf reinforcement mats (TRMs) (A rolled erosion control product composed entirely or mostly of nondegradable synthetic fibers, filaments, nets, wire mesh and/or other elements, processed into a permanent, three-dimensional matrix of sufficient thickness.)		
❑ Retains seeds and soil, stimulates germination, and accelerates growth. ❑ Provides permanent reinforcement for roots. ❑ Provides immediate erosion protection.	❑ Use in channels, ditches, shorelines, or steep slopes where plants need extra long-term reinforcement. ❑ Use as alternative to riprap or other “hard armor” techniques.	❑ May have higher erosion rates initially than bare ground if backfilled. ❑ May be used up to 0.5H:1V with careful installation and anchoring. ❑ Requires a smooth surface for installation.

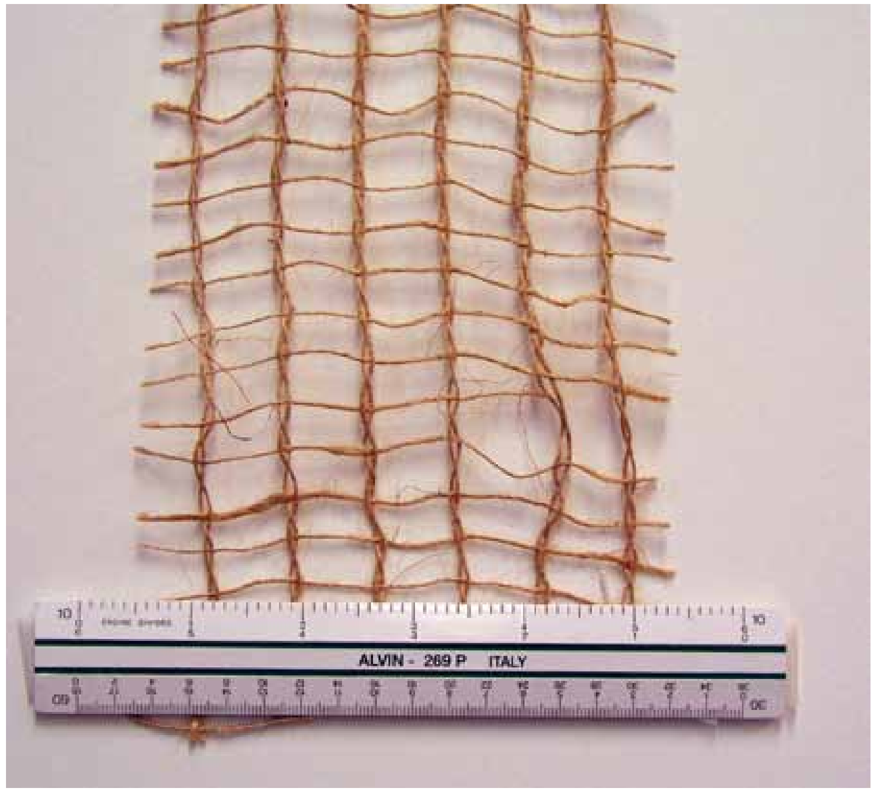


Figure 3-5—Close-up of erosion control net, a natural coir fiber.

Figure 3-6—Erosion control netting over grass and straw mulch on a cutslope.

Figure 3-7—Erosion control blankets (l to r) – straw, excelsior (natural), excelsior (dyed green), coir, and netless wood/synthetic.

Figure 3-8—Erosion control blankets in a field test section to determine the most cost-effective erosion control material for the fillslope.

Rolled erosion control product (RECP) selection tips (Sutherland 1998; Austin and Ward 1996; Gray and Sotir 1996; Baxter 2003; Fifield and Malnor 1990)

- ❑ More effective the shorter the water run-off producing event lasts.
- ❑ Contact with soil and firm attachment is more important than surface-cover percentage.
- ❑ Some natural fibers may shrink (e.g., jute) or expand (e.g., coconut) and may lose contact with the ground.
- ❑ RECP should include high surface coverage and reasonable thickness while still allowing for vegetative growth.

- Erosion rates decrease as surface cover of open-weave RECPs increase.
- Vegetation establishment may be poor for large open-weave RECPs due to sunlight exposure and/or seed displacement.
- RECPs with random fiber orientation and significant three-dimensionality outperform open-weave RECPs.
- Manufacturers provide recommendations based on slope angles and lengths; test results may be available.
- Photodegradable netting on products should not be used for shaded areas.
- Photodegradable netting may leave unsightly netting pieces in various stages of degradation on the ground.
- Crust and rills may form under more rigid synthetic products (dry climates).
- Products often have to be effective for at least 2 years in dry climates to establish long-term vegetation.
- Semiarid-plant establishment (dry climates) depends on increasing thickness of RECPs.
- Natural RECPs appear to increase growth of cool-season grass while synthetic RECPs appear to increase growth of warm-season grass (dry climates).
- Synthetic materials appear to generate more runoff but less sediment than natural materials (dry climates).
- Choose a product that does not retard vegetation growth. Some heavy netting is initially durable but may retard the germination of grass seed.
- Consider product impacts on small wildlife and animals that may get entrapped in netting. Plastic netting can trap frogs in a riparian area.

Rolled erosion control product (RECP) installation tips (Cabalka and Lancaster 1997; Norland 2000; Sutherland 1998b; ODOT 1999; Theisen 1992)

- Apply with skilled installers for effective application. Material quality is consistent, so installation is the key to success.
- Prevent excessive damage from wind and water with proper maintenance.
- Stake RECP and bury edges to prevent wind from lifting RECP off the soil.
- Use fewer seams to reduce erosion.
- Apply seed and fertilizer prior to installation.

- ❑ Add check slots along steep slopes to prevent rilling beneath product.
- ❑ Consider using mulch in combination with jute netting because of its open structure.
- ❑ Ensure that manufacturer's recommendations are followed and the RECP is installed properly.
- ❑ Use mulch, mulch and netting, bonded-fiber matrix, or an erosion control blanket to protect surface from erosion when using a geocellular containment system.

3.1.2.6. Hard Armor

Table 3-8—Hard armor (Rivas 2006)

Functions	Typical uses	Limitations
Geocellular containment systems (GCSs) (Synthetic three-dimensional cells up to 8 inches (206 mm) deep filled with soil, sand, or rock and anchored to the slope.)		
❑ Increases shallow soil strength. ❑ Assists vegetation establishment in cells by providing soil support.	❑ Use on gentle or steep slopes (<1H:1V). ❑ Use to minimize excavation and utilize low quality backfill. ❑ Use to confine cohesionless soil like sand. ❑ Use perforated cells to promote drainage and root growth.	❑ Cell walls limit lateral root growth. ❑ Not for rough, severely rilled, or gullied slopes. ❑ May be undermined on steep slopes or along stream/river banks.
Riprap or rock blankets (Rock placed on ground surface.)		
❑ Protects soil from surface erosion. ❑ Reduces runoff velocities, encouraging infiltration. ❑ May provide shelter for growth of some species of plants on uneven surface. ❑ Reduces seepage erosion when placed upon a filter system.	❑ Use with sites located near quality rock of suitable size and quantity. ❑ Use on dry, difficult to vegetate sites. ❑ Use in conjunction with filter systems to reduce seepage and erosion. ❑ Use with live stakes or plant between riprap stones for improved mechanical/ hydraulic performance and aesthetic benefits.	❑ Quality rock of suitable size needs to be close for economic feasibility. ❑ May not be aesthetically pleasing to some. ❑ Unstable riprap on steep cutslopes can be a safety hazard. ❑ Filter needs to be properly designed. ❑ Planting between rocks can be difficult, especially if the rock is thicker than 18 inches (46 cm).

Figure 3-9—Riprap erosion protection on a cutslope above a retaining wall.

3.1.2.7. Use of Vegetation

One can use vegetative methods for erosion control and soil stabilization in a variety of manners. Some methods have very strong advantages, particularly if used in conjunction with other physical or drainage measures. Vegetative erosion control uses natural materials and relies on the natural ability of vegetation to break up the impact of rain, slowdown water velocities, draw moisture from the soil, maintain soil porosity, and add root strength to the soil, helping it to resist movement. Materials can be relatively inexpensive, cover large areas, look natural, and provide strong soil stabilization. However, some types of erosion control can be labor intensive and require long-term maintenance. Plants require water for initial establishment. Over time, they also may need a minimal amount of fertilizer and maintenance, including replanting.

Ideally, select vegetation for good growth properties, hardiness, canopy form, dense ground cover, and a mixture of deep and expansive root structures for slope stabilization. Use native pioneer species with these properties where possible. Fortunately there are many sources of native seed available today. Figure 3-10 shows cutslopes well vegetated with grass and forbs. The vigor of vegetation, particularly on cutslopes, depends a lot on the site, soil type, amount of rock, and climate. Fillslopes typically are easier to vegetate than cutslopes.

Figure 3-10—Cutslopes well vegetated with grasses and forbs.

Vegetative stabilization includes the use of herbaceous species (grasses and forbs) to cover large areas with a dense mat of vegetation, thus protecting slopes and waterways by slowing the velocity of water over that surface and binding the soil particles together with roots. Figure 3-11 shows a closed road stabilized with a cover of grass. To achieve temporary and permanent erosion control, use brush and trees to absorb the impact of raindrops, slowdown runoff, allow precipitation to enter the soil, remove excess soil moisture, and stabilize a block of ground with roots that are moderately deep. Figure 3-12 shows a brushmattress used in conjunction with live stakes to provide a dense ground cover. Table 3-9 shows a summary of vegetative stabilization applications. Section 3.1.2.8, soil bioengineering, discusses biotechnical methods involving vegetation used as structures and combining vegetation and physical structures.

Figure 3-11—Vegetation (grasses) used to stabilize a closed road.

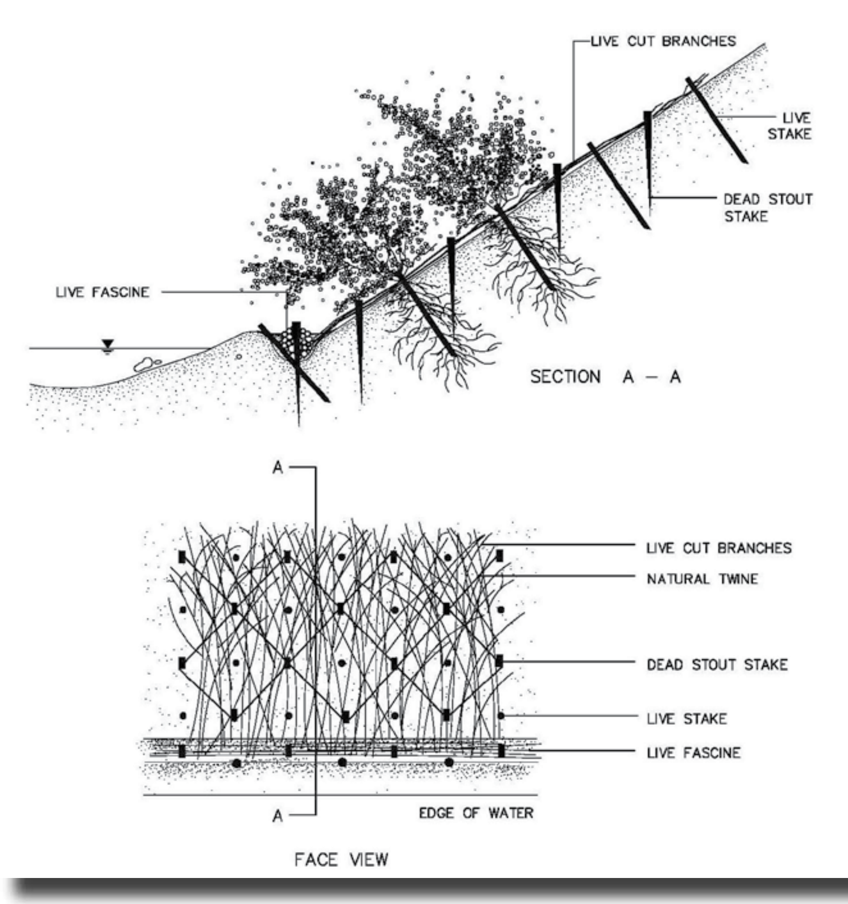


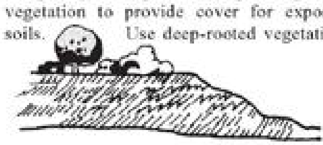
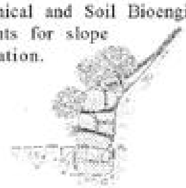
Figure 3-12—Brushmattress used to provide a dense mat of vegetation for ground cover (Courtesy of Robbin B. Sotir & Associates, Inc.).

A key practice for successful vegetative erosion control is to conserve the native organic soil and reuse it onsite where possible. This organic soil can be a principal source of seeds for native vegetation. The use of organic compost as a mulch and fertilizer also greatly improves revegetation results.

Practitioners often use white oats to provide a dense, quick ground cover soon after construction if native grasses are not available. The oats will not regrow the following year and are the least toxic to native plant seed, so they do not compete with long-term native species.

Live barriers or hedgerows of vegetation planted on contour offer another useful application of vegetation for erosion control. The practice is used most on agricultural land as barriers to separate fields or crops and to control erosion on slopes. Place the barriers

Table 3-9—Summary of the applications of vegetative stabilization.

Control Measure	Purpose	Condition needing Control					
		Cut Slopes	Fill Slopes	Denuded Gently sloping or flat area	Eroding streambank	Eroding Swale	Protection of adjacent property
1. Temporary and permanent planting of vegetation to provide cover for exposed soils. Use deep-rooted vegetation. 	To stablize soils by absorbing the impact of raindrops, reducing velocity of runoff, binding soil particles together, and allowing precipitation to enter the soil.	*	*	*			*
2. Temporary and permanent grass protection of waterways, swales, dikes, slopes, and closed roads. 	To protect drainageways and flat surfaces by lowering water velocity over the soil surface and by binding soil particles with roots.				*	*	*
3. Biotechnical and Soil Bioengineering treatments for slope stabilization. 	To combine vegetation with physical structures to create an aesthetic, long lasting, and strong composite structure for slope and streambank stabilization and erosion control.	*	*	A	*	A	

Key: * Preferred control measure A Alternative but less effective control measure

Source: Association of Bay Area Governments, 1981.

on contour to properly disperse water. However their use can easily be applied to any disturbed areas, such as across borrow sites or placed across or at the toe of a fillslope to catch sediment.

Root strength is one of the most valuable contributions from vegetative erosion control measures, particularly for slope stabilization. Intermingled, extensive spreading roots of plants bind the soil together into one solid mass. On slopes, vertical roots can penetrate through the soil mantle into firmer material, pinning the soil to the slope and creating an arching and buttressing effect within the soil mantle. The roots actually mechanically reinforce the soil by transferring shear stresses in the soil to tensile resistance in the roots. Other advantages of the roots include their ability to move moisture out of the soil and, in most situations (on all but very steep slopes), the positive effect of its surcharge on the slope.

Ideally, the care used in planting vegetation for erosion control should be similar to that of a gardener or landscape contractor who is planting flowers and trees or a lawn. The materials and steps in the vegetation or revegatation process should be thought out and implemented carefully, as logical steps of a revegatation plan. The main considerations and components of a revegatation plan are listed below:

- ❑ Choose carefully the type and source of vegetation to best accomplish the specific purpose. Project planning should first assess the problem and then determine the effective solution. Information, such as location, aspect, climate and microclimate, soil type, fertility, time of planting, and subsequent land use are critical factors in making the final design determination. Figure 3-13 shows some of the different forms of root systems and ground cover of vegetation that one should consider in meeting project objectives.
- ❑ Use native species whenever possible for the best adaptation to the site and achieve the best growth. For difficult sites, such as arid environments, set up test plots to determine what species and methods achieve the best results. Consider setting up onsite nurseries to harden and adapt plants to the local project area. In some cases it helps to utilize completed projects as sources for live cut stock on a new project.
- ❑ Consider whether seeds, cuttings, or transplanting potted plants will be most effective.

1. Select seed for quality, resistance, and germination properties. Determine the rates of seed application and the specific mix for the location and time of year.
2. Prepare the seedbed, planting site, or individual planting holes. Amend and improve the site as needed to promote growth. Add mulch to a site as necessary.
3. Handle plants with care and do not allow them to dry out during storing, transporting, and planting. Remember they are alive.
4. Prune all broken branches and reduce the size of woody shrubs by one third prior to planting. Prune trees but do not prune the leader (center main growing trunk).
5. Water or irrigate (if possible) after planting. Also, fertilize, spray, protect from disease and animals, and maintain occasionally to promote good growth. Note: it is generally best not to irrigate or fertilize plants in most applications unless such care is absolutely necessary for initial growth and unless it can be continued during the life of the young plant.

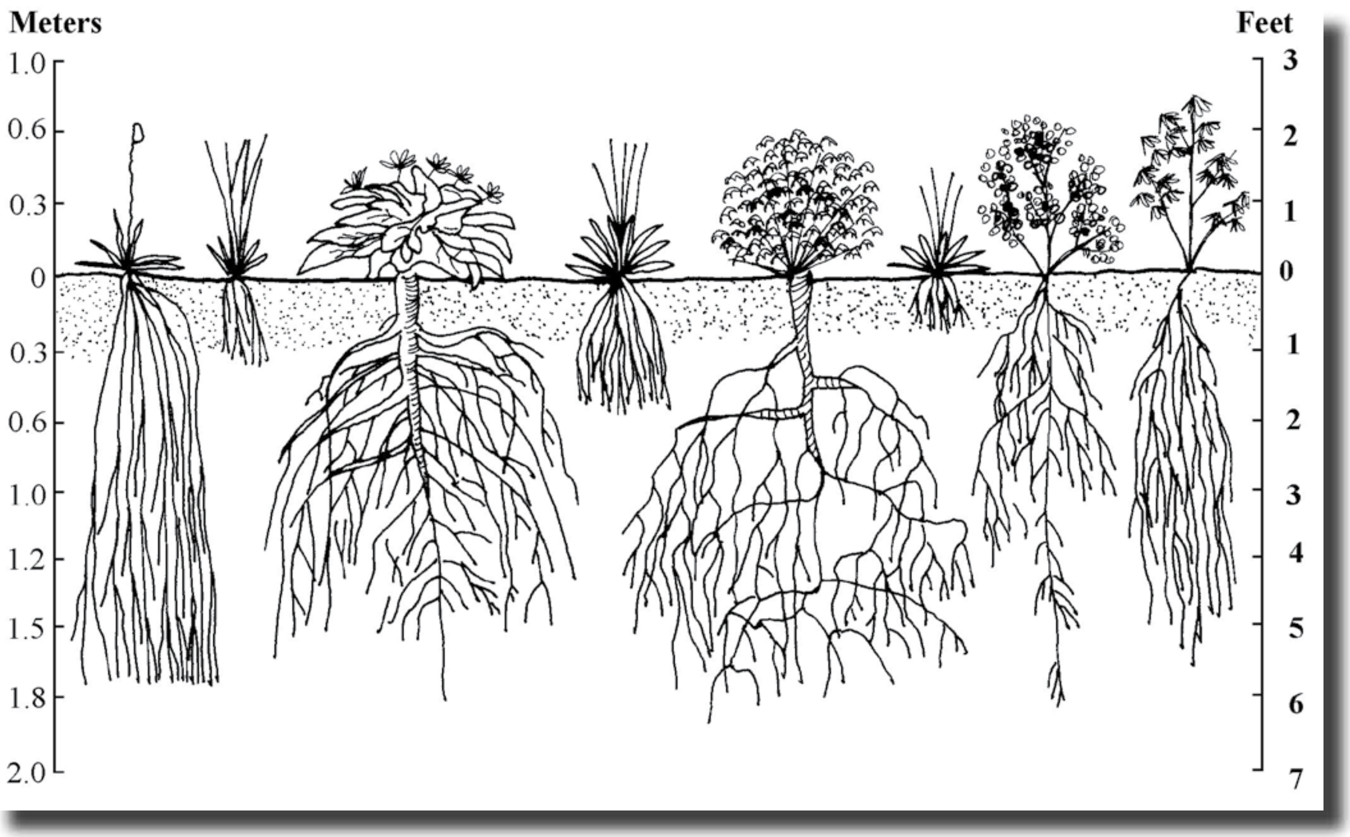


Figure 3-13—Different forms of root systems and ground cover vegetation.

Most revegetation projects will not have 100 percent success; parts of planted grass areas will have to be replanted. Staff will have to replace some tree or shrub plantings as individual plants die or are killed by animals, insects, or other damage. As with most projects, initial maintenance is necessary and ideally should be planned for a few years. However, a major advantage of vegetative stabilization is that with time, properly selected vegetation becomes self-sustaining, especially with the use of local native species.

There are a moderate number of tree and shrub species, such as willow, which can be cut and will sprout and regrow when put in the ground. This fact is an important consideration in the bioengineering measures discussed in the next section. The advantage of these species is the ease with which revegetation can be accomplished, and usually at a very reasonable cost. These plants can be buried in the ground, or driven into soil through voids between rocks.

The most commonly used vegetation species that reroots is willow (Salix family). Many varieties of this plant are found worldwide. However, many other species of plants are generally available in most areas. Discussions with the local citizens and some research can produce a list of locally available rooting vegetation, which can be used in an erosion control project. Some common species suitable for live-cut branch planting purposes include:

1. Red alder (Alnus rubra).
2. Coyote brush (Baccharis halimifolia).
3. Silky dogwood (Cornus amomum).
4. Red dogwood (Cornus sericea).
5. Fremont cottonwood (Populus fremontii).
6. Red raspberry (Rubus strigosus).
7. Pussy willow (Salix bonplandiana).
8. Prairie willow (Salix humilis).
9. Black willow (Salix nigra).
10. Red willow (Salix discolor).
11. Red elderberry (Sambucus racemosa).

An excellent classic reference on the many aspects of vegetative erosion control and slope stabilization methods and requirements with considerable engineering design information included, is presented in “Biotechnical Slope Protection and Erosion Control” (Gray and Leiser 1982).

"Roadside Revegetation: An Integrated Approach To Establishing Native Plants" (Steinfeld et al. 2007) provides a thorough discussion of benefits and issues dealing with native vegetation. The reader is guided through a comprehensive process of project initiation, planning, implementation, and monitoring for roadside revegetation. Link to the Web site <http://www.wfl.fhwa.dot.gov/td/>.

3.1.2.8. Erosion Control Using Soil Bioengineering

Soil bioengineering is an integrated technology that uses engineering practices in conjunction with ecological principles to assess, design, construct, and maintain living vegetation systems to repair and prevent damage caused by erosion and some slope failures and to protect and enhance healthy functioning systems (Sotir 2001).

Plant materials used in soil bioengineered structures should ideally come from local ecotypes and genetic stock similar to that found at the project site. Species that root easily, such as willow, are required for live fascines and live staking. Consult a plant material specialist for guidance on plant selection.

Some characteristics of soil bioengineering techniques are common to all methods. Except as noted in table 3-10, all methods immediately act to capture and trap raveling material and sediment. Because these methods use live vegetation (cuttings and plants), their effectiveness increases with time as they grow and, once established, are self-maintaining. Plant strength and the ability of roots to remove soil moisture, as well as the ability of above ground cover to intercept precipitation, increase as plants mature. The two primary limitations to the use of soil bioengineering are that it is labor intensive and the plantings do require time to develop full effectiveness.

Table 3-10—Soil bioengineering (see also Lewis 2000; Atkins et al. 2001; Gray and Sotir 1996)

Functions	Typical Uses	Limitiations
Live Stakes (Tamping of live, rootable vegetative cuttings into the ground.)		
❑ Stakes provide some immediate buttressing effect.	❑ On relatively steep, raveling cut and fillslopes. ❑ On wet seeping sites needing pioneering cover. ❑ To stake RECPs. ❑ Adds root strength in benches or riprap. ❑ To establish woody vegetation relatively inexpensively.	❑ Somewhat slow to establish vegetation. ❑ Has limited ability to immediately trap sediment.
Live Fascine (Stems and branches of rootable plant material tied together in long bundles and secured in shallow trenches.)		
❑ Slows runoff. ❑ Reduces slope into series of smaller slopes.	❑ Cut and fillslopes up to 1.5H:1V. ❑ On rocky, wet, or difficult to dig slopes with surface erosion. ❑ Supports establishment of vegetation on wet, seeping sites. ❑ Alternative to brush layers on cutslopes.	❑ May be undermined on steep or long slopes. ❑ May be difficult to dig on rocky slopes. ❑ May require large quantity of plant material. ❑ Not recommended for dry, coarse soil; can dry out if not properly installed.
Pole Drains (Rows of live fascines oriented downslope, and connecting to a central drain.)		
❑ Acts as conduit for water.	❑ Wet slopes with seepage and where seepage is causing downslope erosion. ❑ Diverts water from top of slope. ❑ May benefit large areas of unstable material.	❑ May not be suitable for rocky sites. ❑ May experience clogging and cause adjacent erosion in fine-grained soil.

Table 3-10—Soil bioengineering (see also Lewis 2000; Atkins et al. 2001; Gray and Sotir 1996) continued

Functions	Typical Uses	Limitiations
Willow Fences (Short retaining walls (i.e., a constructed wattle) built of living cuttings placed horizontally behind supporting vertical posts.)		
❑ Reduces effective slope angle. ❑ Provides cover for pioneering woody vegetation. ❑ Holds soil in place on moist sites while allowing it to drain.	❑ On stable slopes up to 1.3H:1V. ❑ For raveling and eroding material with moist conditions. ❑ For fine-textured soils that are wet during growing season.	❑ May not be suitable for dense or very coarse soil. ❑ May require nearby, and large quantity of plant material. ❑ Requires moisture for fence to grow.
Brush layers (Crisscross pattern of live cut, rooting branches placed between layers of soil.)		
❑ Establishes pioneering vegetation. ❑ Increases infiltration on dry sites and drains wet sites.	❑ For slopes up to 2H:1V and less than 15 feet (5 m) vertical height. ❑ Raveling or eroding slopes. ❑ Sites too dry for willow fencing. ❑ During fill construction.	
Modified Brush layers (Brush layers combined with constructed or manufactured wattles such as small logs, short boards, or willow fencing.)		
❑ Reduces effective slope angle of steep slopes by creating a series of smaller slopes. ❑ Increases infiltration on dry sites and drains wet sites. ❑ Establishes pioneering plants from cuttings.	❑ With logs or boards on sites too dry for willow fencing. ❑ With willow fencing in fine-textured soils or where there is suitable summer moisture. ❑ With willow fencing and maybe log or board on wet on seeping sites.	❑ Establishment of vegetation above log, board, or fence is critical for dry sites. ❑ May require large amounts of plant material. ❑ Should construct 2H:1V slope above fence, board, or log.

Table 3-10—Soil bioengineering (see also Lewis 2000; Atkins et al. 2001; Gray and Sotir 1996) continued

Functions	Typical Uses	Limitations
Branch packing (Alternating layers of live branch cuttings and compacted fill between wooden stakes.)		
❑ Reduces runoff.	❑ For small (up to 4 feet deep by 6 feet wide (1.3 m. by 2 m.)) slumps, holes, and head cuts in natural slopes, cuts, and embankments.	❑ Fill should be moist. ❑ Not recommended for rocky sites.
Live Slope Grating (Array of vertical and horizontal wood members fastened to a slope, filled with soil, and planted with cuttings.)		
❑ Provides new slope surface. ❑ Supports itself from the base. ❑ Protects underlying slope surface.	❑ For slopes between 1.5H:1V and 1H:1V that require anchoring (plants or mechanical) in order to revegetate. ❑ Where very little excavation is required.	❑ Does not armor or buttress the slope. ❑ May be quite expensive compared to other methods.

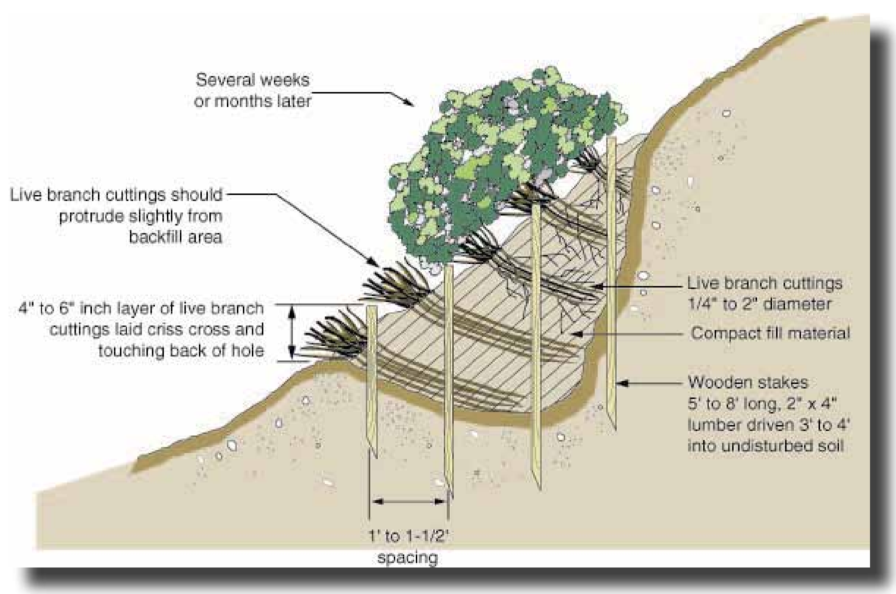


Figure 3-14—Typical branch packing (Lewis 2000).

Soil Bioengineering Design References

The use of soil bioengineering treatments to control erosion is a specialized technology. Useful installation tips can be found in several publications as well as by talking to experienced practitioners and/or contractors. Three available soil bioengineering publications are Gray and Sotir (1996), Lewis (2000), and Atkins et al. (2001).

Lewis (2000) provides field personnel with the basic merits of soil bioengineering concepts and gives examples of several techniques especially effective in stabilizing and revegetating upland roadside environments. Link to the document <http://www.fs.fed.us/eng/pubs/pdf/00771801.pdf>.

The U.S. Department of Agriculture, Natural Resources Conservation Service (1992) reference is Chapter 18 of Engineering Field Handbook- Part 650. Link to the document <ftp://ftp-nhq.sc.egov.usda.gov/NHQ/pub/outgoing/jbernard/CED-Directives/efh/EFH-Ch18.pdf>.

3.2. TREATMENT FOR SLOPE STABILIZATION ISSUES

Slope failures, or landslides, typically occur where a slope is oversteep, where fill material is not compacted, or where cuts in natural soils encounter ground water or zones of weak material. Good road location can often avoid landslide areas and reduce slope failures. When failures do occur, stabilize the slide area by removing the slide material, flattening the slope, adding drainage, or using vegetation and structures. Designs typically are site specific and may require input from geotechnical engineers and engineering geologists. Failures typically impact road operations and can be costly to repair. Failures near streams and channel crossings have an added risk of impact to water quality. A wide range of slope stabilization measures is available to the engineer to solve slope stability problems and cross an unstable area. In most excavation and embankment work, relatively flat slopes, good compaction, and the addition of needed drainage typically eliminate routine instability problems. Once the cause of failure has been determined, the most appropriate stabilization measure depends on site-specific conditions, such as the size of the slide, soil type, ground water condition, road use, alignment, and constraints.

Investigation and characterization of landslide deposits typically involves field mapping and often involves drilling, sampling, and testing, and ground water monitoring. Standard penetration tests (SPT) are often run during drilling to obtain samples and a measure of soil strength with depth. Piezometers are often installed to measure the ground water level and fluctuations with time. These procedures for landslide investigation and analysis are well documented in the references mentioned below.

For shallow slides, site and soil characterization with depth and correlations to SPT can be made using the Williamson drive probe, a simple field tool developed by the Forest Service using ½-inch (12 mm) pipe and a falling weight, similar to the dynamic cone penetrometer (DCP). Though less reliable than the DCP, some correlation information can be developed and the tool is quite inexpensive to manufacture. Information on the Williamson drive probe can be found in volume 1, appendix 3.6, of Prellwitz et al. (1994a).

"Landslides—Investigation and Mitigation" (Turner and Schuster 1996) offer a comprehensive treatment of landslide problems and solutions, including causes, risk analysis, investigations, stability analysis, case histories, and repair solutions.

The three-volume publication "Slope Stability Reference Guide for National Forests in the United States" (Prellwitz et al. 1994a) (1994b) (1994c) discusses many aspects of slope stability investigation and analysis and presents a wide range of slope stabilization solutions.
Links to the documents:
Prellwitz et al. (1994a) <http://www.fs.fed.us/rm/pubs_other/wo_em7170_13/wo_em7170_13_vol1.pdf>.
Prellwitz et al. (1994b) <http://www.fs.fed.us/rm/pubs_other/wo_em7170_13/wo_em7170_13_vol2.pdf>.
Prellwitz et al. (1994c) <http://www.fs.fed.us/rm/pubs_other/wo_em7170_13/wo_em7170_13_vol3.pdf>.

The FHWA training manual "Slope Maintenance and Slide Restoration Reference Manual" (Collin et al. 2008) also offers a good overview of slope management, stabilization options, and repair issues.

3.2.1. General Mass Movement Solutions (cut-and-fill failures, landslides, settlement, downslope creep)

Slope instability often occurs as a result of excavation and earthwork with some combination of excessively high slopes, excessively steep slopes, poorly compacted soils, planes of weakness in rock, or ground water. Slides may occur in constructed slopes and fills or in naturally occurring slopes, particularly if they have been modified or undercut. Whether naturally occurring or human induced, slides can add major costs to the construction or maintenance of a road, and may cause significant adverse environmental impacts from accumulation of sediments and damage to natural resources or downslope infrastructure. Also many slope stabilization measures, particularly those involving structures, can be quite expensive.

The two key things to do to minimize slide problems are:

1. Build stable slopes in the first place with proper design and construction practices.
2. Avoid naturally unstable or wet areas.

Road-related mass movement

A range of common slope stabilization options appropriate for stability problems on low-volume roads are listed below—from simplest and least expensive, to the most complex and expensive. Figure 3-15 shows some common roadway stabilization solutions:

- ❑ Simply remove the slide material.
- ❑ Ramp over or align the road around the slide.
- ❑ Repair or reestablish road drainage.
- ❑ Revegetate the slope and add spot stabilization.
- ❑ Add drainage to stabilize the slope.
- ❑ Flatten or reconstruct the slope.
- ❑ Raise the road level to buttress the cut or lower the road to remove weight off the fillslope.
- ❑ Relocate the road to a new stable location.
- ❑ Install slope drainage such as deep cutoff trenches or dewater with horizontal drains.
- ❑ Design and construct buttresses, retaining structures, or rock anchors.
- ❑ Use a lightweight fill.

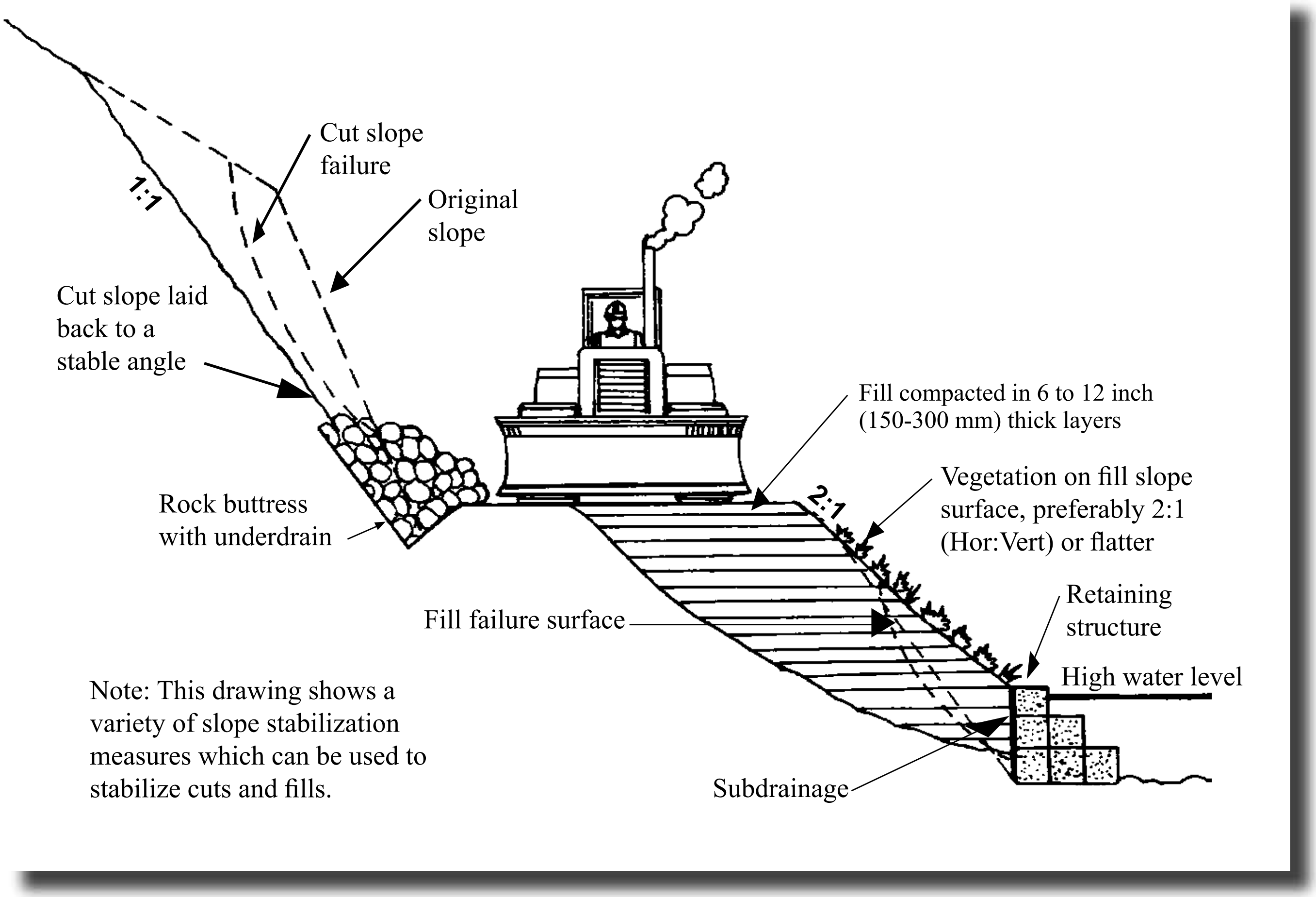


Figure 3-15—Slope stability solutions with a variety of stabilization measures.

Nonroad related mass movement

Every so often, roads cross large deep-seated mass wasting features that are not feasible to stabilize.Sometimes the mass movements are actually not affected by the road, even though their slow movement affects the road. There are few alternatives that are economically feasible on low-volume roads to deal with this aspect of road instability:

- ❑ Move the road or relocate it to a stable location.
- ❑ Reduce the road standard and width through the slide area.
- ❑ Eliminate or decommission the road if access travel management determines it is not needed.
- ❑ Reconstruct the road so it is more easily maintained (i.e., converting asphalt to a gravel surface).

- ❑ Recognize that any repair is temporary and select accordingly. If there is fill settlement, use a deep patch solution rather than a retaining wall (section 3.2.2.3).
- ❑ Manage water drainage so it does not concentrate and flow into the slide.
- ❑ Try to use only flexible materials in repairs. However, this can be challenging with culverts or cross drains in the repair area.

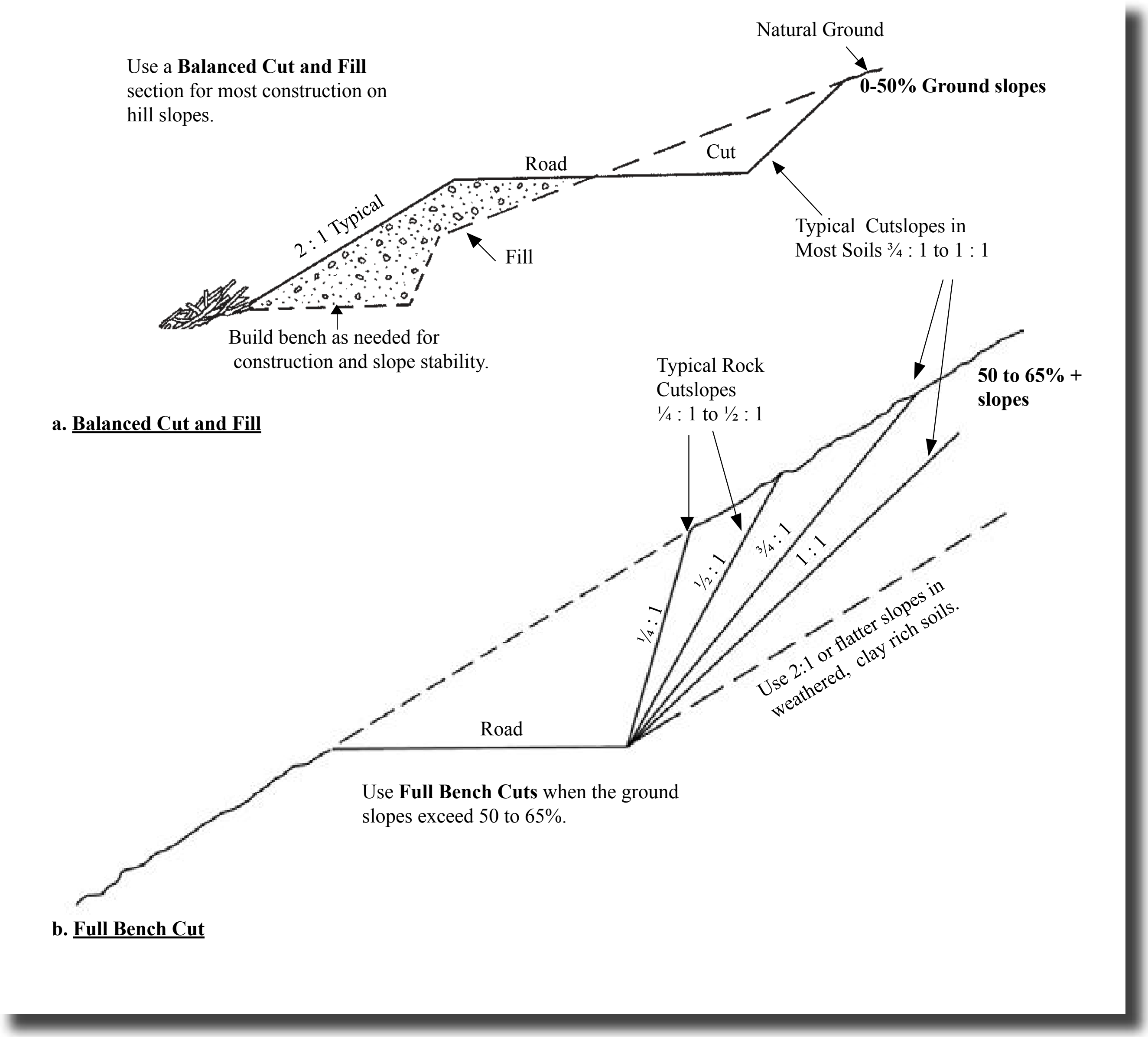
3.2.1.1. General Cutslopes

Cutslopes, as well as fillslopes, are routinely constructed in new construction or road reconstruction and repair projects. Failed slopes occasionally need to be repaired. They usually do not involve analysis, but rather are constructed at slope angles thought to be stable based on local experience and general guidelines. These general guidelines are meant to produce stable slopes in most soils most of the time. If a specific problematic, unstable, or wet area is encountered, the road can be realigned around this area, the slope can be flattened, drained, or a retaining structure or buttress considered. Designs typically are site specific and may require input from geotechnical engineers and engineering geologists.

For most cutslopes, typical slope angles are selected based upon the general soil or rock type found in that area and on field observations. For most rocky, silty to sandy soils in the Western United States, cutslopes of 1H:1V or ¾ H:1V are used. In rock cuts and rocky or cemented soils, near vertical cutslopes can be used, and a ¼ H:1V slope is commonly used, as shown in figure 3-16 and presented in table 3-11. In clay-rich soils (encountered in the South or tropical areas) flatter slopes, such as 2H or 3H:1V commonly are used.

In gentle to moderately steep terrain, the earthwork should be "balanced," where the material from the cut slope is used in a nearby fill embankment, as seen in figure 3-16a. On slopes steeper than 50 to 65 percent, depending on the soil type, a full bench cut will be required (figure 3-16b), with no fill.

Note: All slope references are shown as Horizontal:Vertical (H:V). However, current FP03 specifications use a designation of Vertical:Horizontal (V:H).



Figures 3 16(a) and (b)—Typical cutslopes used in low-volume roads.

Table 3-11 presents commonly used cutslope angles, as well as fillslope angles, for various soil and rock types. Note that stable cutslopes are variable and are very sensitive to local soil, weather, ground water conditions, and discontinuities. Thus, good field observations, local experience, and knowledge of stable cutslope angles are important.

Table 3-11—Common stable slope ratios for varying soil/rock conditions.

	Soil/Rock Condition	Slope Ratio (H:V)
CUTS	Most rock	¼:1 to ½:1
CUTS	Very well cemented soils	¼:1 to ½:1
CUTS	Most in-place soils	¾:1 to 1:1
CUTS	Very fractured rock	1:1 to 1 ½:1
CUTS	Loose coarse granular soils	1 ½:1
CUTS	Heavy clay soils	2:1 to 3:1
CUTS	Soft clay rich zones or wet seepage areas	2:1 to 3:1
FILLS	Fills of most soils	1 ½:1 to 2:1
FILLS	Fills of hard, angular rock	1 ⅓:1
FILLS	Low cuts and fills <7-10 ft (<2-3 m.) high	2:1 or flatter (for revegetation)

3.2.1.2. General Fillslopes

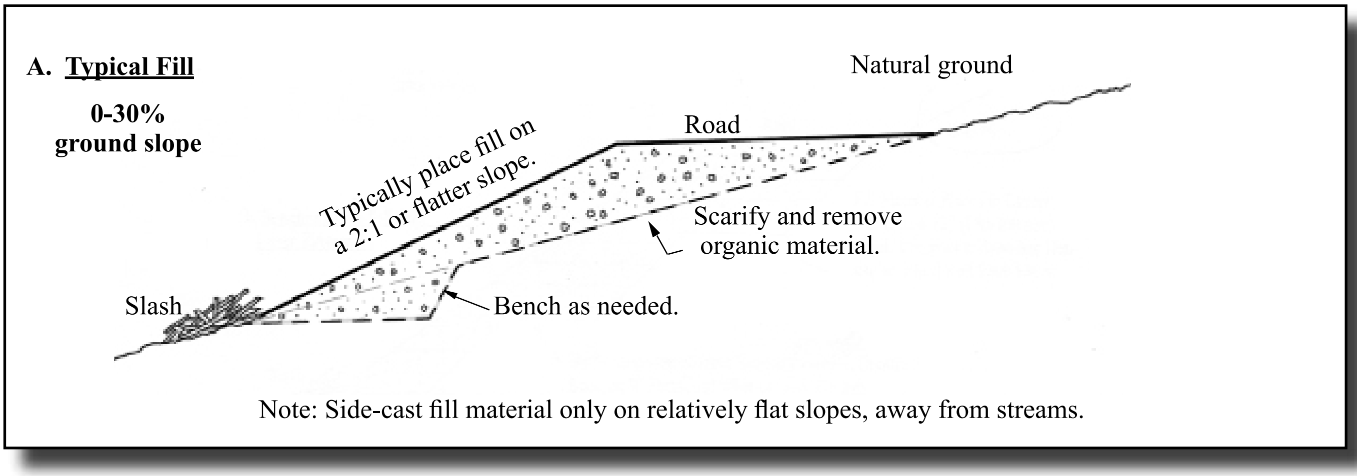
Fill construction and earthwork is a normal part of any road reconstruction project. Fill construction requirements are similar for either new construction or reconstruction and repairs. However a fill failure may imply the need for improved compaction or drainage. Fill construction guidelines also apply to materials disposal sites. The use of reasonable quality materials, good compaction control, good foundation conditions and drainage, and recommended standard fillslope angles generally produce a stable fillslope. The primary methods of fill construction are layer placement (structural fills) and sidecasting (sidecast fills). Layer placement generally achieves a more stable fill, but is more costly to construct. Sidecast fills are cheaper and easier to construct and use for repair, but are more likely to settle, slide, and erode on the surface, particularly on a steep ground surface, and so the practice is discouraged. Sidecasting is particularly undesirable for fills in sensitive areas, such as on steep slopes above a stream or drainage crossing.

Fills constructed with a 1½H:1V slope generally are stable. However, fillslope instability can occur for the following reasons:

- ❑ A fill constructed too steep for the internal strength of the fill material.
- ❑ A fill constructed on a natural slope steeper than the fill material angle of repose.
- ❑ An increase in the depth of the fill on an existent weak material.
- ❑ Inadequate clearing and scarification of the natural soil surface to provide good contact and a key between the natural soil and the fill material.
- ❑ Poor soil strength from inadequate compaction that does not meet optimum moisture content and maximum density during construction.
- ❑ An increase in the water table level and pore pressure in the fill due to inadequate subsurface drainage.
- ❑ Poor surface drainage that erodes the fillslope.
- ❑ Unstable foundation conditions.
- ❑ Fill constructed with inclusion of woody debris or stabilized at the toe on trees or logs that rot with time.

A slope of 1½H:1V to 2H:1V is most commonly recommended for fillslopes constructed with the majority of common soils. Rockfills can be stable on slopes as steep as 1 ⅓H:1V or even 1H:1V with angular rock and careful placement. To achieve good vegetative stabilization on a constructed fillslope, the slope should be 2H:1V or flatter, especially for low fills. Table 3-11 section 3.2.1.1 presents recommended fillslope angles for various materials.

Figure 3-17 shows the construction of typical fills under a variety of conditions and natural ground slopes. Routine fills or through fills placed upon relatively flat ground, with a slope less than 30 to 40 percent, are commonly built with a 1½H:1V or flatter slope since the ground is relatively flat and a fillslope will easily catch and not be excessively long. A 2H:1V or flatter fillslope also is used to help promote the growth of vegetation. On ground slopes between 30 to 50 percent, place the base of the fill upon a terraced surface to key the fill into the slope and prevent a failure along the fill-ground plane of contact (figure 3-17b).



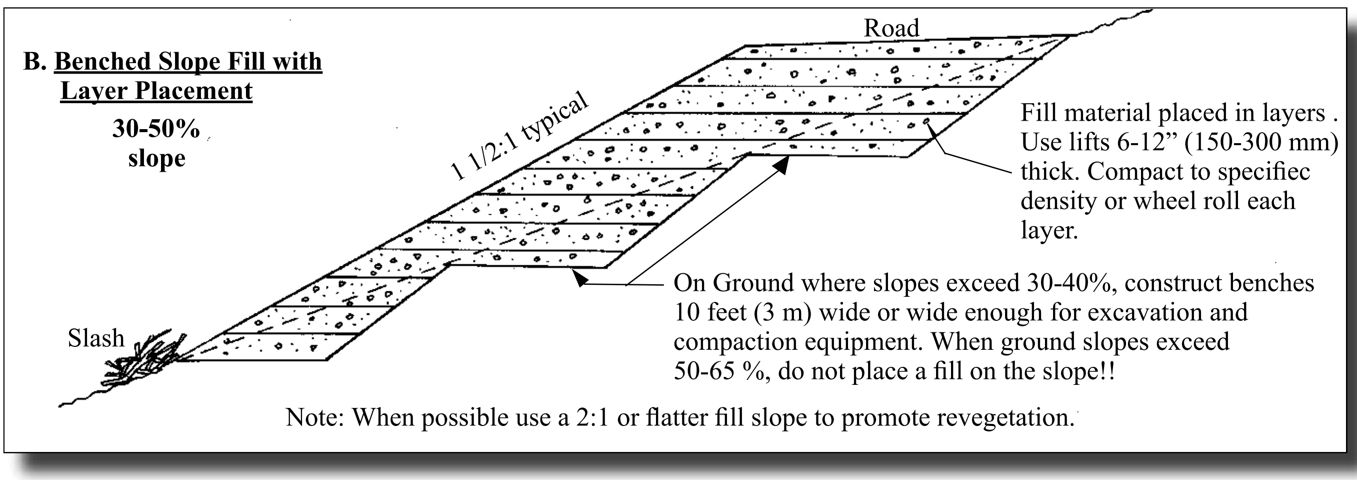


Figure 3-17(a) and (b)—Typical fillslope design options.

On ground steeper than 50 to 65 percent, do not place fills on the slope since they will be very long and thin, or they will not "catch" on the slope. On steep slopes, end-haul excavated material to a disposal site or to other fill areas on flatter terrain. Figures 3-17 and figure 3-18 show typical fill design options and construction options on slopes while figure 3-19 shows a common toe bench arrangement beneath a fill on steep slopes. A foundation is critical to the stability of the fill.

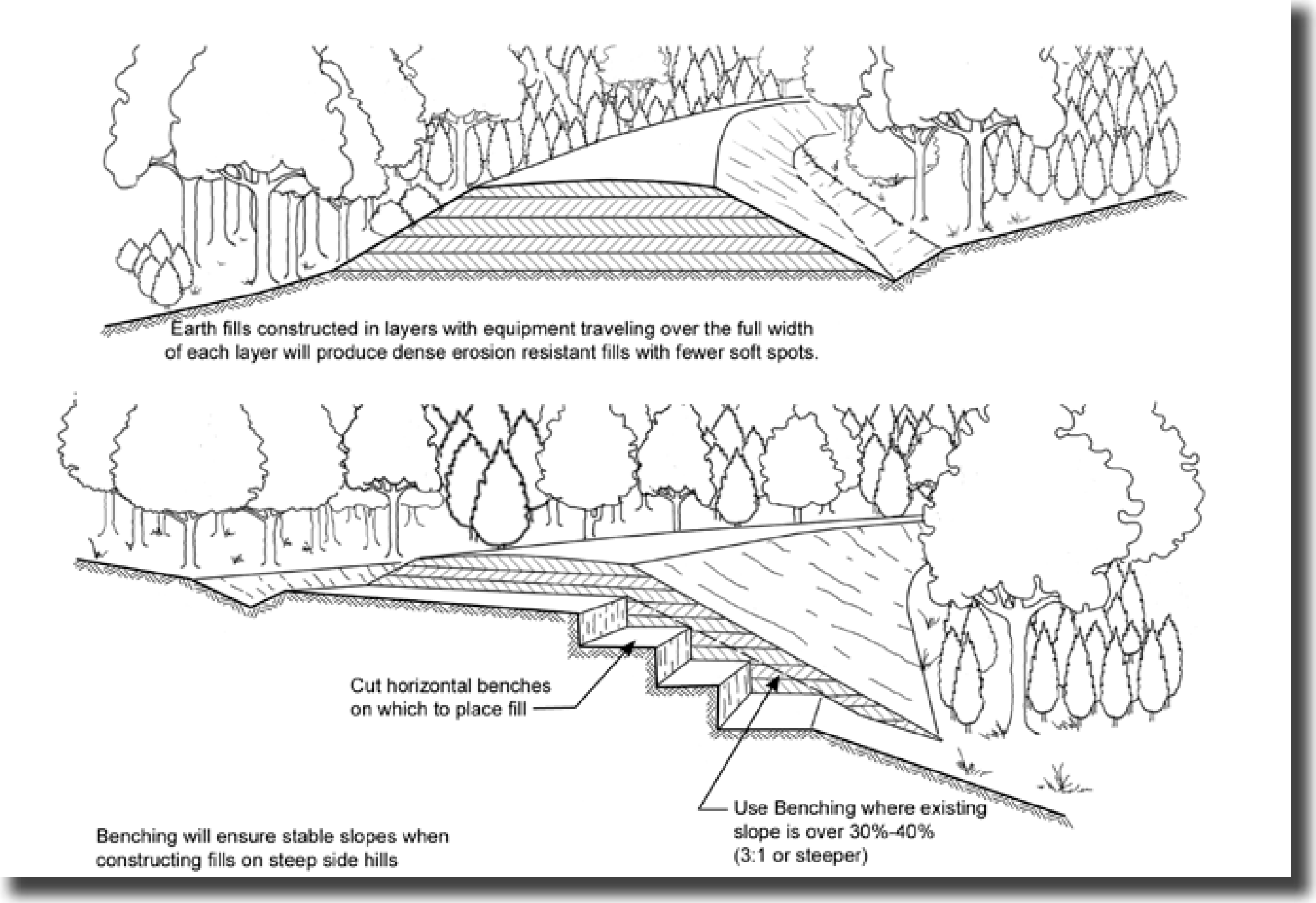


Figure 3-18—Fill construction options typically using layer placement (Used with permission Nova Scotia Roads 2004).

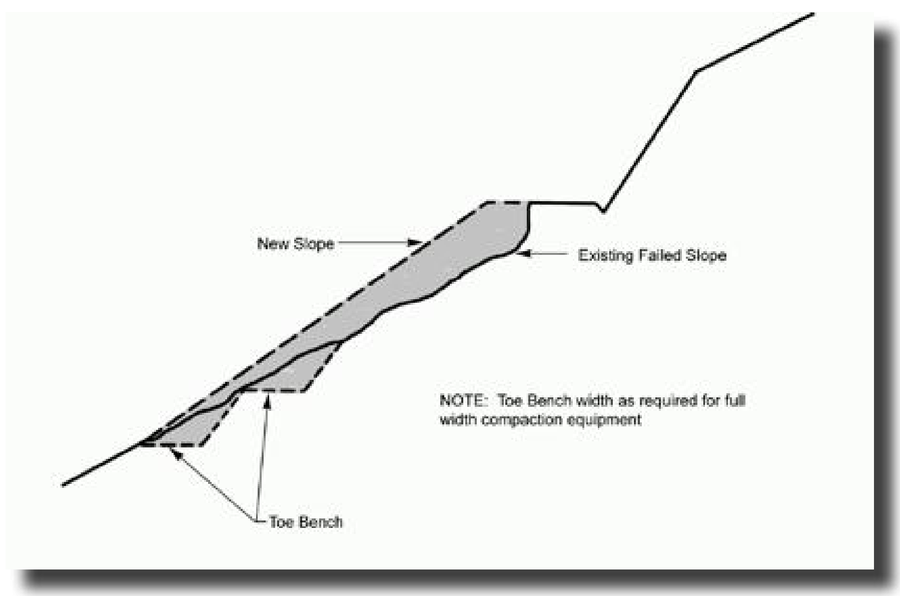


Figure 3-19—A typical fill toe foundation bench arrangement (Courtesy of Mark Truebe, Willamette NF).

Visual impacts, aesthetics, function, and stability are all influenced by the fills' construction style. Many large, straight fills have been built back into dissected, curving natural terrain, creating an artificial look and a fill that is not optimal from a stability standpoint. Natural landforms tend to have convex and concave surfaces, further sculptured by erosion, running water, and gravity processes. A convex shaped slope is inherently more stable than a planar slope, and has less soil loss from erosion. The flatter slope at the toe of a concave landform suffers less erosion, acts as a buttress against the steeper midslope area, and has a higher factor of safety against instability.

Grading fills to conform to the terrain may be slightly more expensive initially and is more a style that most engineers and equipment operators are not used to using. Also by building in swales in a slope, water will be concentrated, but run in a smaller area that can be armored and revegetated to simulate natural drainages. Thus the area of highest need for erosion protection is minimized. It is basically an effort to mimic stable natural hillslopes. An interesting discussion with applications of these concepts is presented in Schor and Gray (2007).

3.2.1.3. General Use of Drainage

Localized wet areas, clay-rich or deeply weathered soil pockets, and shear or fault zones are likely to have failures requiring relatively flat cutslopes. Seeps, springs, or wet areas, often recognized by water-loving vegetation, almost always require special consideration and drainage. If a cut opens a wet area, or a fill is placed on a wet area, extra measures must be taken to drain the slope, flatten the slope more than normal, or buttress the toe of the slope. A stable wet slope angle may be roughly half the angle of the same stable dry slope. In any excavation the water table should be below the exposed surface (where practical) to prevent instability. Drain slopes using ditches, cutoff trenches, collection galleries, horizontal drains, etc, to remove or redirect the water.

Use drainage measures, including drainage blankets, cutoff trenches, toe drains, or horizontal drains to remove the water and lower pore-water pressures within the slope. Any reduction in the water table or pore pressures in the slide improves the stability of the slide. Drainage measures are typically relatively inexpensive compared to the cost of walls, buttresses, slide removal, and so forth, and can improve the slide's factor of safety significantly. However, drainage measures are often difficult to predict in terms of effectiveness and reliability. Piezometers may need to be installed to measure the ground water level and effectiveness of drainage measures.

Install a drainage blanket between a spring or wet area and a fill embankment, as shown in figure 3-20, to keep ground water from saturating the fill. Install shallow, 3- to 6-foot- (1 to 2 m) trench drains or 10- to 15-foot- (3 to 5 m) deep vertical trench underdrains to cutoff water flowing into an unstable area or the road subgrade (see section 3.4.2).

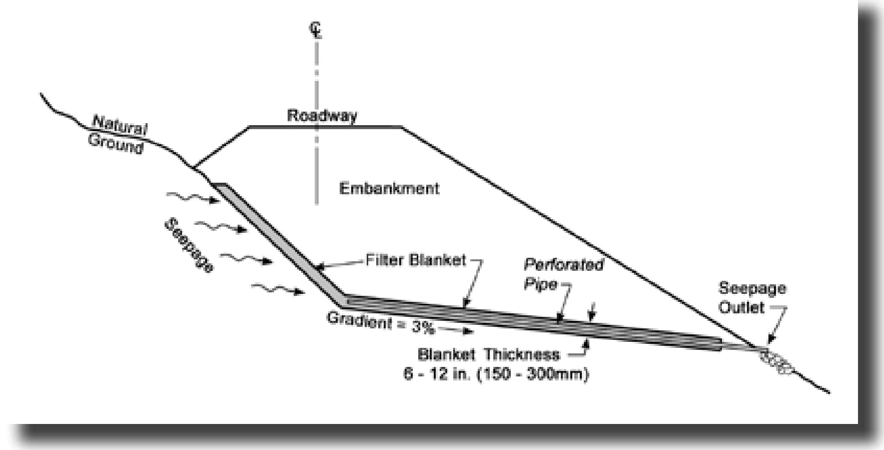
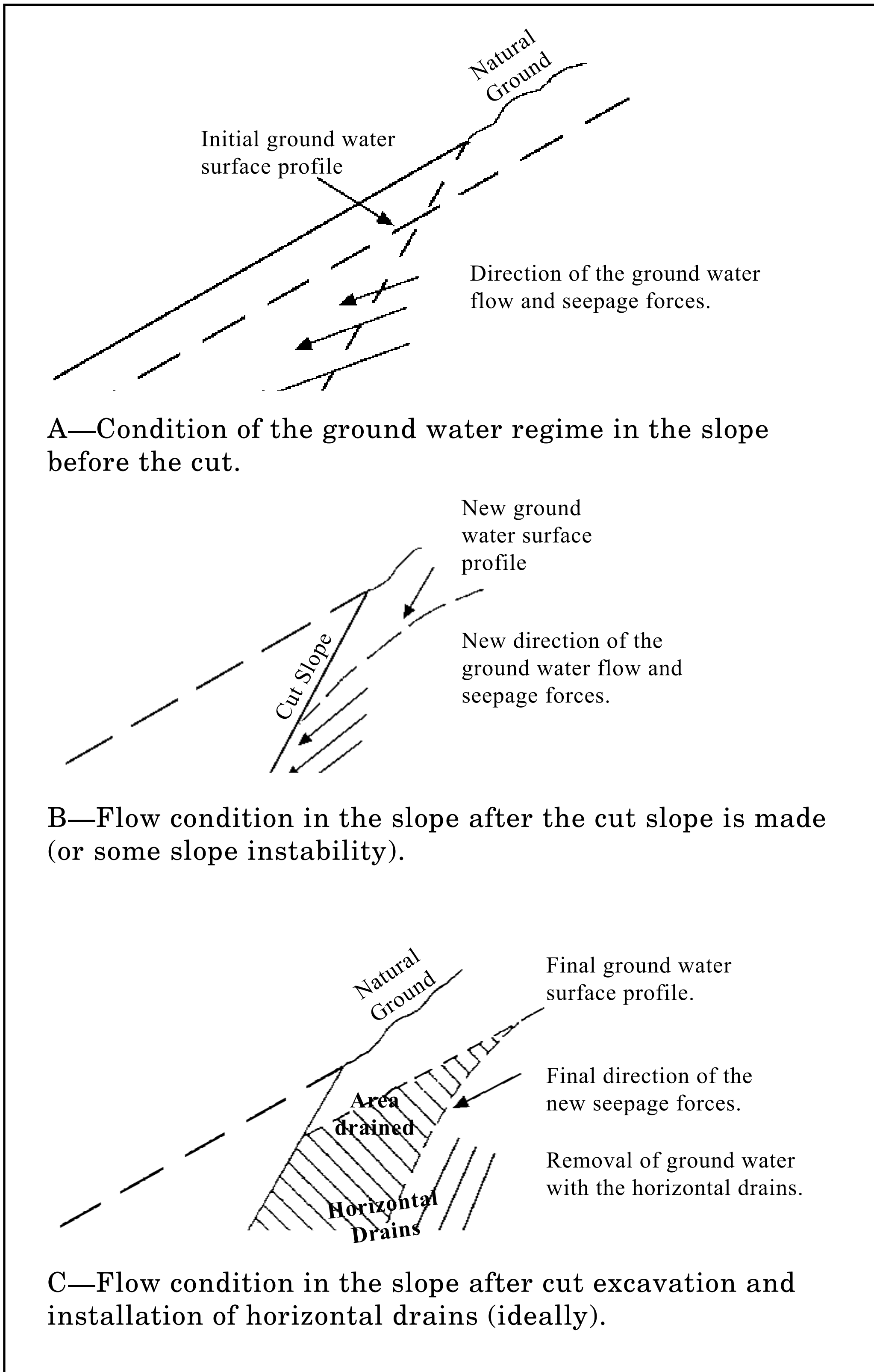


Figure 3-20—A typical drainage blanket configuration to prevent saturation of a fill embankment.

Install deep internal drains, such as the horizontal drains shown being drilled in figure 3-21, to intercept ground water before it reaches the face of the slope. The sketches in figure 3-22 show the ideal change in direction of the ground water flow and forces due to the cut, changes in ground water flow that can cause instability, and horizontal drains to improve stability before water can reach the face of the slope.

Figure 3-21—Horizontal drains being drilled to stabilize a landslide.



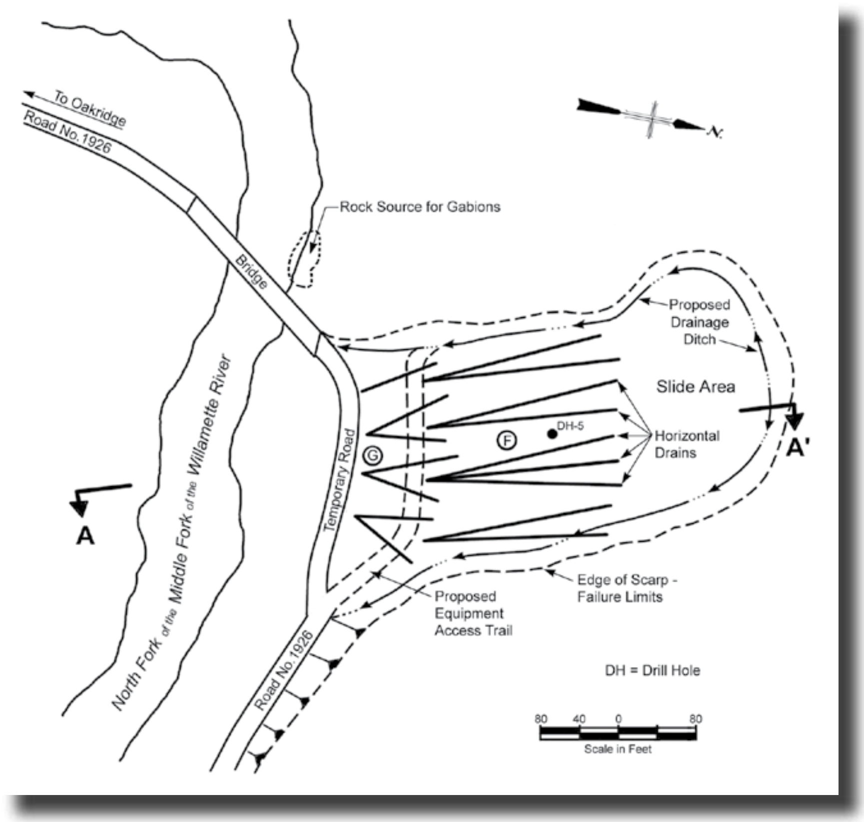
A—Condition of the ground water regime in the slope before the cut.

B—Flow condition in the slope after the cut slope is made (or some slope instability).

C—Flow condition in the slope after cut excavation and installation of horizontal drains (ideally).

Figure 3-22—Ideal effects of using horizontal drains to remove ground water, redirect seepage forces, and improve slope stability.

Horizontal drains are steel or plastic pipes, 2 to 3 inches (50 to 75 mm) in diameter, drilled with a 2 to 20 percent slope toward the road. The drains must be long enough to cross water-bearing zones and are typically drilled 100 to 300 feet (30 to 100 m) long into the hillside. A fan-type pattern is often used to intersect as much water as possible. A slope stabilization or drainage project involving horizontal drains must be coordinated with an engineering geologist or geotechnical engineer who understands the site geology and the objectives of the drainage project. Figure 3-23 shows a horizontal drilling pattern used on a slope stabilization project.



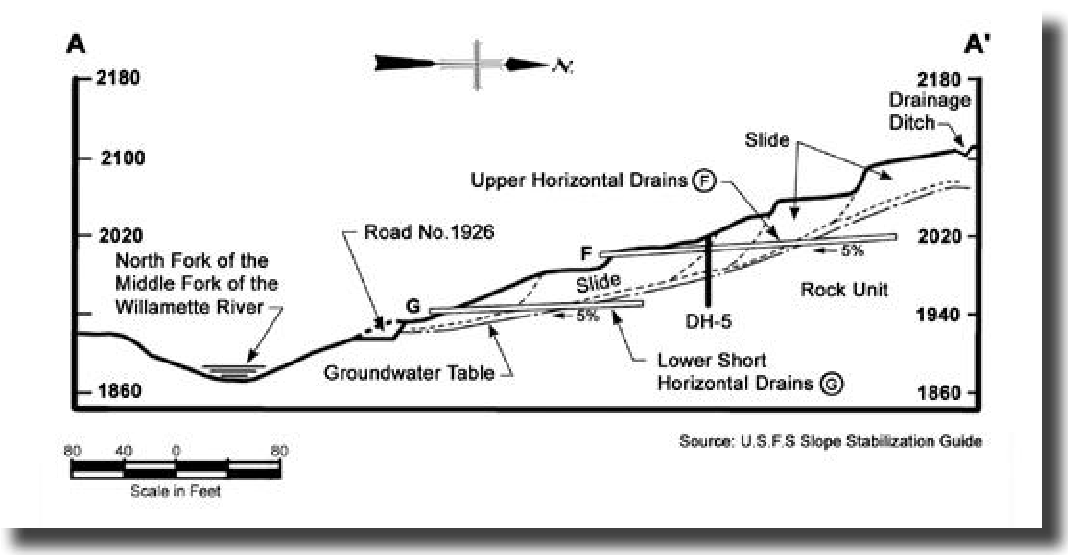


Figure 3-23 – Plan view and cross section of horizontal drains used on a slope stabilization project.

3.2.1.4. Vegetative Slope Stabilization Measures

Vegetative slope stabilization typically is achieved using soil bioengineering methods or biotechnical methods particularly for shallow failures. Vegetation use is strongly encouraged since it is typically inexpensive, though labor intensive, and it improves slope stability. Advantages of soil bioengineering are low initial cost; a visually pleasing result using natural, biological systems; and minimum long-term maintenance. Biotechnical slope stabilization measures typically are more expensive and engineered since vegetation is used in conjunction with other physical stabilization measures, such as rock buttresses or gabion walls, reinforced fills, and slopes, etc. Soil bioengineering measures also are discussed in section 3.1. Note that some soil bioengineering measures also are constructed with engineering elements, such as rock, geogrid, wood, etc. and with some engineering design input.

Vegetative stabilization works well on most projects. Vegetative and soil bioengineering measures are appropriate for surface erosion control and shallow slope failures, such as debris slides and small cut-slope failures. Do not use vegetative stabilization by itself for stabilizing large and deep-seated slides. Use deep-rooted shrub and tree species rather than shallow-rooted grasses for most slope stabilization applications. Also, vegetation and slash placed at the toe of any slope or fill helps control erosion and traps sediment coming off that slope.

Live stakes and brush layering are vegetative soil bioengineering techniques used for slope stabilization (figure 3-24). Ground cover with grasses, ideally mixed with deep rooted shrubs and trees, also is effective for erosion control and preventing surface instability.

While vegetative stabilization should be used on most projects, it's important to recognize its limitations. Do not use vegetative stabilization by itself for stabilizing large and deep-seated slides. Use it in addition to other physical measures. This is called biotechnical slope stabilization. Biotechnical refers to a conventional structure that has some added vegetative component but the vegetation serves a limited purpose and is not considered a main structural component.

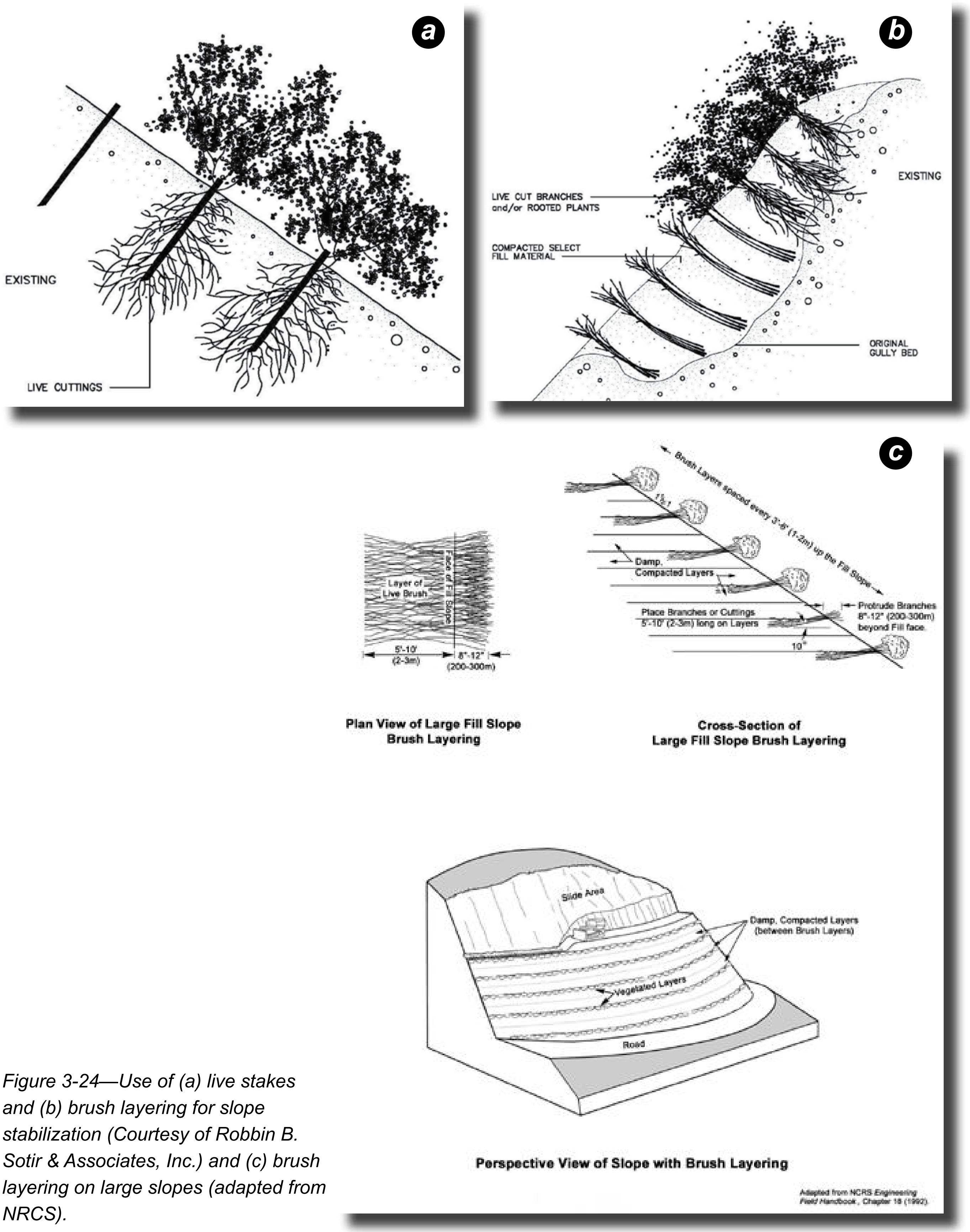


Figure 3-24—Use of (a) live stakes and (b) brush layering for slope stabilization (Courtesy of Robbin B. Sotir & Associates, Inc.) and (c) brush layering on large slopes (adapted from NRCS).

Some of the more common biotechnical slope stabilization measures include live cribwalls, vegetated rock walls and gabions, and vegetated reinforced soil slopes. These treatments depend on the strength and design of the traditional structure combined with the supplemental benefits of root strength and the long-term durability and aesthetics of vegetation. Figure 3-25 shows examples of a vegetated rock wall and vegetated reinforced soil slope. In vegetated reinforced soil structures, the roots of the woody vegetation have a very real and important face-stabilizing feature as they knit the system together. Root penetration through the geosynthetic is anticipated to provide a composite root/geosynthetic structure with a net gain in reinforcement strength (Sotir et al. 2002).

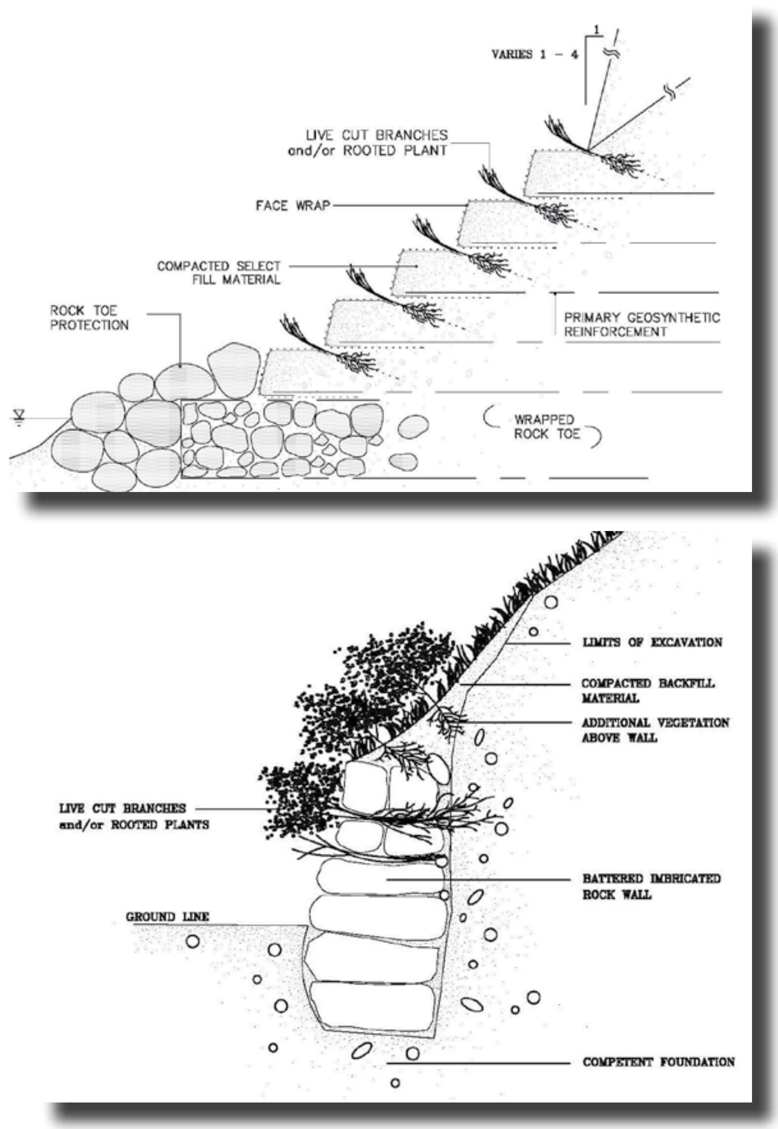


Figure 3-25—Examples of a vegetated rock wall and vegetated reinforced soil slope (Courtesy of Robbin B. Sotir & Associates, Inc.).

Assess any slide for its cause, depth of failure, physical limits, and relation to the road. In many situations the action may be simply to remove the slide material. In deeper or more significant slides, a structure such as a wall or buttress may be contemplated as a permanent fix. However, in most cases vegetation improves slide stabilization. For a simple slump with the material removed, the slide scar can be further stabilized and erosion controlled with a cover of vegetation. Around a structure, the slide margins can be strengthened with deep-rooted vegetation, as well as the structure itself with some biotechnical treatments, such as layers of brush between gabions or geosynthetic reinforcement layers. Table 3-12 presents a summary of soil bioengineering and biotechnical slope stabilization measures used on low-volume roads.

Table 3-12—Summary of soil bioengineering and biotechnical upland slope protection measures adapted for low-volume forest roads (Courtesy of Robbin B. Sotir & Associates, Inc.).

Summary of Soil Bioengineering and Biotechnical Upland Slope Protection Measures Adapted for Low-Volume Forest Roads			
Method	**Excavation Requirements**	**Useful for Specific Conditions**	**Comments and Restrictions**
***Live Stake**	No	Surface erosion: wet conditions, popouts, overbank runoff; after grading and drainage have been addressed.	Simple erosion problems. Best used in conjunction with other soil bioengineering measures and/or erosion control fabrics (ECF) and/or mulch. Offers little initial mechanical stabilization.
***Live Fascine and Pole Drains**	Yes (Small to medium trenches are excavated.)	Shallow slope popouts, rills, interrill (sheet) erosion, seepage, overbank runoff; use after grading has been addressed	Moderate to severe shallow erosion < 1-foot (300 mm) deep. Useful for collection and transport of surface and subsurface drainage (installed on incline, up and downslope, or on contour for dry sites). Maximum bank face length < 33 feet (10 m). Uses live cuttings. *May require engineering for internal seepage collection and transport conditions.*
***Bender Fence**	Yes/No (small)	Shallow slope rills and gullies.	Moderate shallow erosion. Requires wooden boards and rooted plants or live stake installation.

Table 3-12—Summary of soil bioengineering and biotechnical upland slope protection measures adapted for low-volume forest roads (Courtesy of Robbin B. Sotir & Associates, Inc.) continued.

Summary of Soil Bioengineering and Biotechnical Upland Slope Protection Measures Adapted for Low-Volume Forest Roads			
Method	**Excavation Requirements**	**Useful for Specific Conditions**	**Comments and Restrictions**
Branch Packing	Yes/No (May require excavation in the bottom.)	Small slope popouts; gullies eroded; overbank runoff or seepage; use after drainage has been addressed.	Repair of small sites; maximum dimension 5 feet deep by 4 feet wide by 10 feet long (1.5 m deep by 1.2 m wide by 3 m long). Requires posts for structural support. Uses live cuttings.
Live Gully Repair	No	Gullies eroded; overbank runoff or seepage; use after drainage has been addressed.	Repair of long gullies 1- to 2-feet wide by 1- to 3-feet deep by length (300-600 mm by 300 to 1,000 mm by length). Length: 20 to 50 feet (6 m to 15 m) long. Uses live cuttings.
***Brush layer (cutslope)**	Yes (Benches are excavated.)	Shallow surface failures	Small to moderate 1- to 3-feet- (300 mm - 1m) deep failures. Site at natural angle of repose. May be installed on incline or on contour. Requires some engineering to ensure existing slope stability.
***Brush layer (fillslope)**	Yes (Typically fairly large excavation and fill.)	Deeper failures	Medium to large failures 3- to 10-feet (1 m to 3 m) deep. Reconstructed at natural angle of repose and extends beyond original failure zone. Requires major engineering for fills > 5 feet (1.5 m) deep.
***Hedgelayer**	Yes (Benches are excavated.)	Shallow surface failures.	Medium failures 1.5 to 3 feet (0.5 to 1 m) deep. Uses rooted plants. This measure is useful when constructing in the growing season, cuttings are not readily available, and when specific species are required to address site conditions and/or habitat requirements. Requires some engineering to ensure existing slope stability.
Joint Planting	No	Toe erosion or shallow slope failure.	Gentle to moderate slopes typically 2 to 3 H:1V. Requires engineering for riprap.

Table 3-12—Summary of soil bioengineering and biotechnical upland slope protection measures adapted for low-volume forest roads (Courtesy of Robbin B. Sotir & Associates, Inc.) continued.

Summary of Soil Bioengineering and Biotechnical Upland Slope Protection Measures Adapted for Low-Volume Forest Roads			
Method	**Excavation Requirements**	**Useful for Specific Conditions**	**Comments and Restrictions**
Live Gabions, Rock Walls, and Live Cribwalls	Yes (Foundation and typically excavation into the slope.)	Steepened toe for medium height slope sloughs and popouts; toe support.	Steep slopes up to 1H:1V where space is limited and requires gravity type wall. Restricted to heights up to 6.5 feet (2 m). Fairly detailed but well known and used measure. Includes foundation. Uses live cuttings and/or rooted plants. Requires engineering.
Live Slope Grating	Yes/No (Foundation excavation and some surface scaling preparation.)	Very steep slopes where the unstable material has been removed or there is surface erosion and where space is limited.	Very steep slopes up to 0.5H:IV. Can be constructed in sections up to 25 feet (8 m) wide and 15 feet (5 m) high. Protects slope face, is anchored to the slope face, and supported at the base. Drainage features are often included in the bottom and over the top. Highly detailed measure, typically more expensive than other measures. Uses live cuttings and/or rooted plants. Requires major engineering.
****Vegetated Reinforced Soil Slope**	Yes (Typically large excavation and fill operations.)	Large deep slope/bank failures.	Steep slopes (0.25 to 0.5 H:1V) where space is limited and soil reinforcement (geogrid) required. Foundation is required. Detailed measure. Major cut/fill earthwork operations. Uses live cuttings and/or rooted plants. Requires major engineering.
Vegetated Imbricated Stone Wall	Yes (Foundation and typically excavation into the slope.)	Steepened toe for short to medium-high slopes.	Steep, low slopes where space is limited and requires gravity type wall. Restricted to heights up to 6.5 feet (2 m), includes foundation. (Soil is required behind stone to vegetate using live cuttings or rooted plants.) Requires engineering.

** Slope is equal to or less steep than the natural angle of repose.*

*** Requires geogrid reinforcement, typically with a wrapped face.*

Note that soil bioengineering:

- Uses live cut branches except for hedgelayer that uses rooted plants.
- Offers immediate mechanical stability except for live stakes (allows for no sediment movement off the site, has addressed failure conditions, and drainage is controlled).
- Becomes stronger with age:
    - Develops roots that provide soil-particle reinforcement, which causes the area to function as a unitary mass.
    - Develops top growth that provides surface protection.
    - Provides a host of above- and below-ground environmental functions.
- Removes moisture from the soil through evapotranspiration.
- Reverses the direction of seepage flows from horizontal to vertical for brush layer cut and fill and vertical reinforced soil slope (using live cuttings). As the water meets the live branches it is directed downward following the orientation of the branches.

Gray and Sotir (1996) offer a comprehensive treatment of the many uses of vegetation for slope stabilization, both independently as soil bioengineering measures and as biotechnical treatments with structural measures.

3.2.1.5. Shallow Surficial Instability Solutions

The solutions for shallow surface instability range from simply removing the material and implementing drainage measures to using shallow reinforcement elements and anchors or soil nails. These solutions are discussed in following sections. The most common and effective solutions include the following:

- Remove the failed material, dry it, and recompact it into the slope. Where this is insufficient, replace the material with a select granular material and recompact.
- Flatten the slope somewhat and reshape to increase stability.
- Dig drainage trenches across the slope to improve slope drainage.
- Excavate, reshape, and plant the slope with vegetation, preferably using deep-rooted species and occasionally in conjunction with erosion control or turf reinforcement mats. Biotechnical treatments, such as live stakes and brush layering, have been very effective.

- ❑ Excavate and refill the failed area of the slope with improved soil, such as soil cement, or fill the void with a rock riprap.
- ❑ Excavate the failed zone, dig a toe key, and construct a geosynthetic (usually geogrid) reinforced fill in the area, using alternate layers of geosynthetic and compacted soil.
- ❑ Backfill and reshape the failed area with a series of pipe piles, wood lagging, or fiberglass/plastic rods that can be driven into the slope to a depth greater than the failure zone, to reinforce the slope. Place these reinforcing elements uniformly across the slope, in rows, or in groups at the toe and midslope in the failed area, depending on the size of the failure.
- ❑ Drill or drive soil nails into the failure area using a soil nail launcher. This technique may be adequate, or the slope surface may be rebuilt and treated with erosion matting or shotcrete anchored to the nails with a wire mesh.
- ❑ Drive or push mechanical earth anchors into the slope, pull back to lock the anchor, and anchor in place an erosion control blanket or turf reinforcement mat.
- ❑ Construct a small retaining structure, such as gabion baskets or a rock buttress at the toe of the failure area.
- ❑ Stabilize a failed fillslope with micropiles.

Many of these treatments are discussed in Titi and Helwany (2007).

3.2.2. Specific Road Stabilization Solutions for Slopes

Specific slope stabilization solutions used along roads include retaining walls and structures, reinforced soil slopes, deep patch techniques, soil nails, lightweight fills, roadway grade or alignment changes, and rockfall protection. These solutions are discussed in the following sections.

3.2.2.1. Retaining Structures

Retaining structures are used in many road applications as well as for slope stabilization measures. Their primary use is to resolve a space constraint in steep ground, where a wall is needed to support the roadway in a steep location and avoid a large cut or fill. Also, they are used to rebuild the roadway in fill-failure areas, to avoid cutting into a hillside in a slide area, or to support a roadway across a steep, narrow saddle. “Retaining Wall Design Guide” (Mohney 1994) offers a comprehensive coverage of basic retaining walls, their use, selection, design details for a variety of wall types, and sample calculations. It is available on the Association of

Environmental and Engineering Geologists, Geoscience Library Web site under Section 5, Transportation Geology, Low-Volume Roads Collection, Slope Stability Issues (To access this site, one must initially register with the GeoSci Library at <www.geoscilibrary.org>.

Retaining walls are relatively expensive structures, so look at other options, such as road relocation, cutting into the hillside to place the road prism on a full bench, using a reinforced or rock fill, etc. However, when needed, walls offer a positive solution to support the roadway. Their use can avoid creating additional slope stability problems; avoid long fillslopes, which may be erosive or unstable; and keep the toe of fills out of drainages (all of which can have adverse environmental impacts). Design and construct walls placed into a cutslope to allow ditch cleaning without undermining the wall or damaging its facing.

Several basic types of retaining structures exist, with a variety of wall options within each type, as shown in figure 3-26. The fundamental types are the gravity retaining structures where the mass of the structure resists sliding and overturning; earth reinforced systems where the backfill material is actually reinforced with material such as welded wire, geogrid, or geotextile to form a solid unit that becomes the wall; and special types such as cantilever H-piles or tieback walls, which are used in special applications such as high walls on very steep slopes or bedrock areas to avoid excavation. Alternatively, less expensive soil bioengineering or biotechnical measures, such as live crib structures, vegetated rock walls, or vegetated gabions, which rely on the engineered structure and the anchoring effects of roots from vegetation, may be appropriate for small slopes. It is a good idea to consult a geotechnical or geological engineer when selecting and designing retaining structures.

The most common gravity structures are made of reinforced concrete, cellular bins, gabions, masonry, dry rock walls, and large rocks. The size of the structure depends on the height of the wall needed to fit the site and provide the desired roadway width and elevation, loading conditions on the wall, and allowable foundation conditions. Common heights for gravity structures are a few feet (1 m) to 25 feet (8 m) high. Above this height, gravity structures become relatively difficult and expensive to build. On simple gravity structures, the base width of the structure is typically about 0.6 to 0.7 times the height to achieve a stable design for simple loading conditions. For traffic loading, the base-to-height ratio ranges from 0.6 to 0.8. For a hillslope immediately above the wall, the base-to-

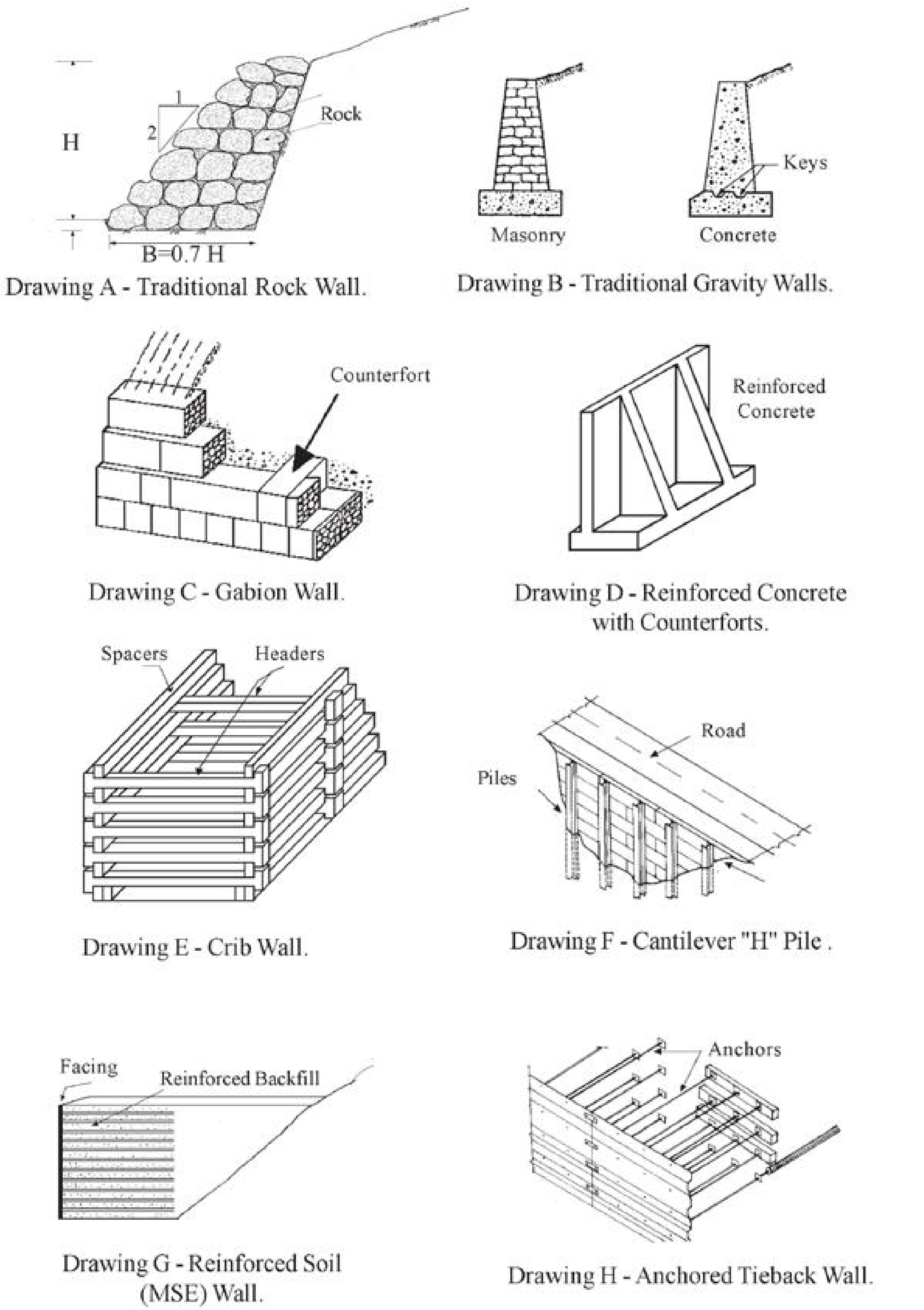


Figure 3-26—Commonly used retaining structures (adapted from Gray and Leiser 1982).

height ratio ranges from 0.7 to 1.0 (figure 3-27). A wider base may be needed for unusual conditions, such as a soft foundation or high lateral or seismic loads. Any structure should be set onto firm, in-place materials, as discussed below.

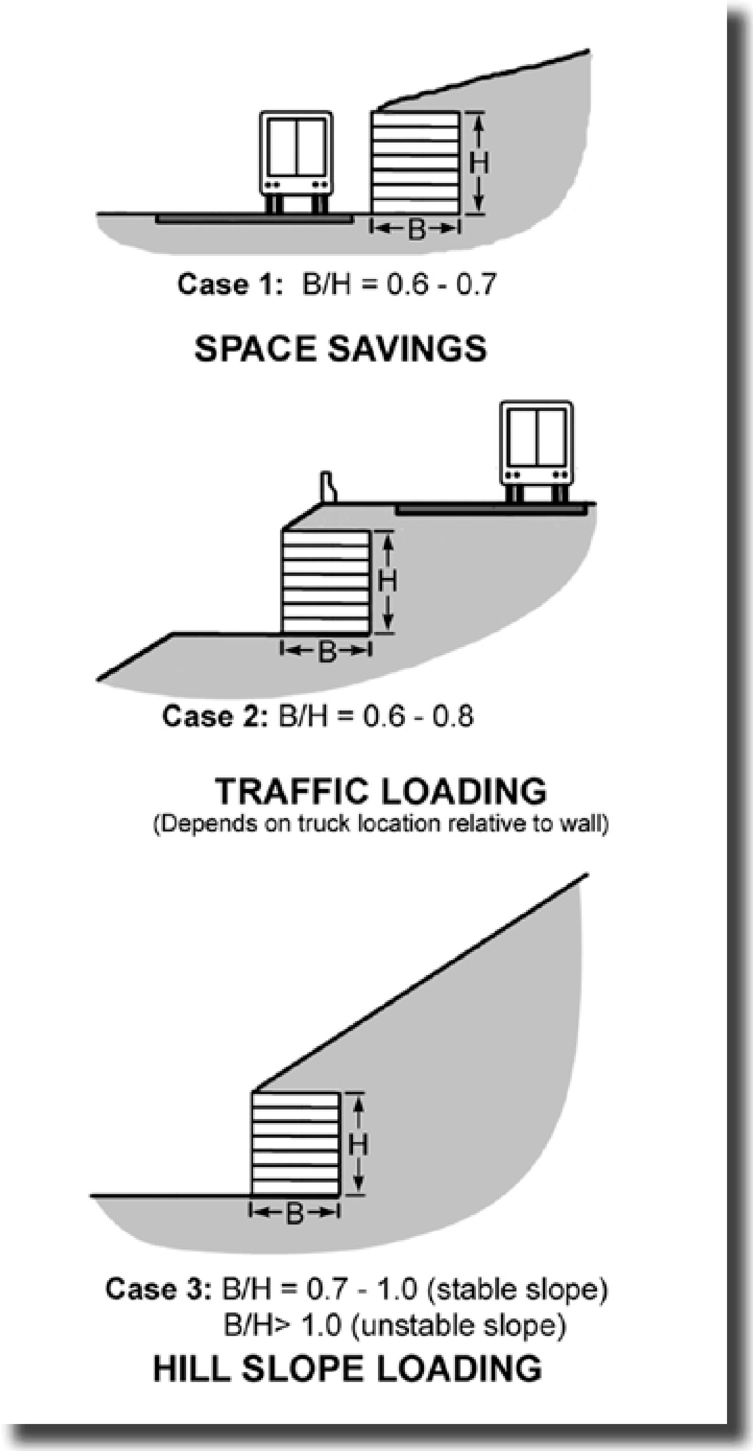


Figure 3-27—Typical wall width-to-height ratios for different retaining wall loading conditions (Source: State of California Department of Transportation).

A mechanically stabilized earth (MSE) wall is slightly wider than a gravity structure, with a typical width of 0.7 to 0.8 times the height for simple loadings. In poor foundation soils, a base width of 0.8 or wider may be used. The major advantage of an MSE wall is cost. For most moderate to high retaining structures, earth reinforced structures usually are less expensive than gravity structures, particularly for construction in remote or rural areas. Local material often can be used in the reinforced zone and as backfill. This type of wall is advantageous in soft soils and in unstable areas since the foundation is relatively wide, thus reducing the foundation bearing pressure, and the facing can be very lightweight. These walls, particularly a geotextile wall with closely spaced reinforcement, can tolerate a large amount of deformation as has been demonstrated in several major earthquakes. Earth reinforced structures have been built over 100 feet (30 m) high.

Various computer programs are available for analysis and design of retaining structures for gravity walls and MSE (reinforced soil) structures. Some computer aided design programs include simple gravity retaining wall analysis programs. Some private wall manufacturers have their own programs available or present design tables for simple wall design as a function of loading conditions and wall height. The slope stability program XSTABL has a module for wall analysis. The Federal Highway Administration (FHWA) has it’s mechanically stabilized earth walls program available for analysis of MSE walls and is available for limited Federal agency use. More sophisticated versions of this program also are available on the open market. All walls should be designed and inspected by qualified geotechnical, geological, or structural engineers.

Good compaction control is desirable behind any retaining structure. The standard density specified for backfill behind walls is 95 percent of AASHTO T-99, unless otherwise specified by the manufacturer. Poor compaction can result in additional and variable stresses on the wall and result in undesirable settlement in MSE structures. Compaction is particularly desirable with marginal quality soils, which are often moisture sensitive to maximize their strength.

The structure’s foundation is very important in avoiding failures, since most retaining wall failures have been caused by poor foundation conditions. Ideally, the structure should be set into bedrock or at least set into firm, inplace soil with a reasonable bearing capacity that will not settle or allow a global foundation failure. Dig a foundation bench deep and wide enough to accommodate the width of the structure plus several feet (1 m) of working bench in front of the wall, all set into firm material. Most common, commercially available wall designs, or designs developed using available wall design software programs, are internally stable and conservative. However failures still occur, usually because of an inadequate foundation. Therefore use a conservative design and put your energy into ensuring that the wall is set deep enough on the slope to be on good foundation material.

Good drainage is extremely important, since most wall designs assume that the site and the backfill material are drained. **All walls should be built with a drain!** If a water table builds up behind the structure, the loads on the wall likely exceed the design assumptions. Drains commonly used behind retaining structures (either gravity or mechanically stabilized earth structures) are gravel or geocomposite chimney drains placed just behind the structure, or preferably at the back of the backfill behind the structure, to intercept and remove any ground water. Alternatively the wall and backfill can be constructed using a free draining material, such as rock. Unless ground water is actually encountered, drains typically are not necessary behind gabion walls since the wall itself is free draining. However, for filtration purposes place a geotextile behind the gabion baskets.

Simac (2006) has summarized the key design and construction factors necessary for good reinforced soil retaining wall performance, particularly for segmental walls built with a concrete block facing. However, these factors apply to most types of retaining structures. Conversely, ignoring these key design and construction factors has caused the failure of many walls. These factors are:

- ❑ Use a good, site-specific design for the given site, height, and load conditions.
- ❑ Have good topographic control and site survey to fit the wall to the site.
- ❑ Provide for a stable, safe excavation during construction.
- ❑ Provide internal drainage and protect the drainage outlets to keep them open.
- ❑ Monitor the construction activities, including approval of the foundation, approval of the backfill material, compaction-control testing on the backfill, and keeping good construction records.
- ❑ Achieve good compaction just behind the wall face.

- ❑ Use the correct type, strength, and length and spacing of geosynthetic reinforcement. Generally best performance has been achieved using closely spaced reinforcement (i.e., 6 to 8 inches (150 to 200 mm)), pulled tight across the reinforced fill area.
- ❑ Provide surface drainage and erosion protection around the wall.

AASHTO (2007) has a thorough treatment of retaining wall and earthen structure design in its "Specifications for Bridges." It is available at the AASHTO bookstore <https://bookstore.transportation.org/category_item.aspx?id=BR>.

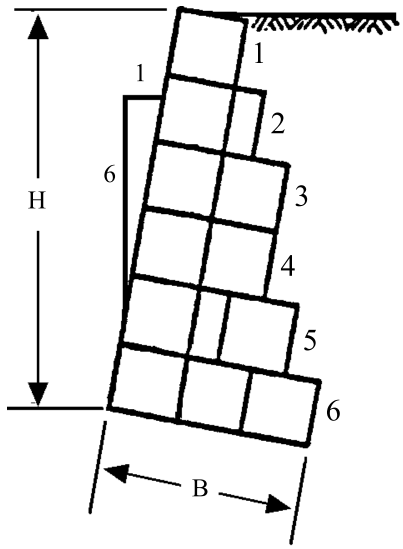
3.2.2.1.1. Gravity Structures

3.2.2.1.1.1. Gabions

Gabions used as retaining walls are a functional, economical solution and a good alternative to other retaining structures due to their flexibility and permeability. Gabions also are used to stabilize toe cutslopes that protect the slopes that may be susceptible to erosion. They can be installed with layers of brush placed on each layer of basket, creating a biotechnical solution with vegetation.

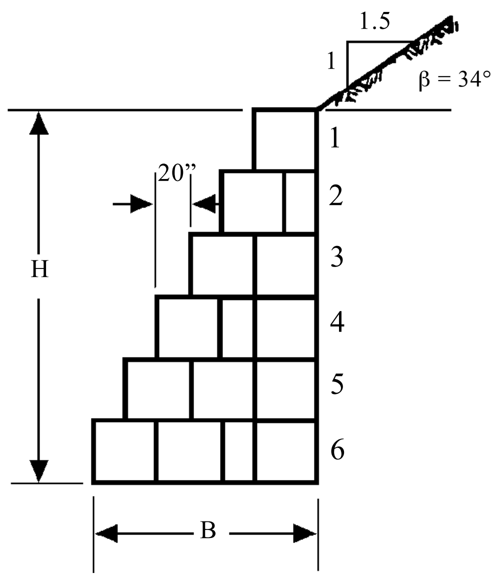
Gabion baskets have some advantages over loose rock buttresses because of their modularity and ability to be stacked in various shapes. If large rock is not available locally, fill the gabion baskets with 4- to 8-inch (100 to 200 mm) rock. Gabion baskets also have advantages over more rigid structures because they can conform to some ground movement, dissipate energy from flowing water, and drain freely. Their strength and effectiveness may increase with time in some cases, as silt and vegetation fill the interstitial voids and reinforce the structure. Gabions are sometimes used as barriers to keep stones, which may fall from a cutslope or cliff, from endangering traffic on the roadway.

Figure 3-28 (a) and (b) show a simple gravity wall design for two different configurations of gabions, and two different loading conditions. Figure 3-28 (a) shows the basket configuration needed for a flat backfill above the wall, as a function of the number of baskets high. Figure 3-28 (b) shows a slope above the structure that the gabion structure must support. To be a true gravity retaining structure, the gabions are place in a pyramid configuration to provide adequate mass and resisting forces against the driving forces of the fill or slope. A simple layer of baskets on the surface offers good erosion control, but it is not a retaining structure capable of preventing deep-seated instability.



No. of layers	H	B	No. of gabions (per width)
1	3' 3"	3' 3"	1
2	6' 6"	4' 11"	1 1/2
3	9' 9"	6' 6"	2
4	13' 1"	6' 6"	2
5	16' 4"	8' 2"	2 1/2
6	19' 7"	9' 9"	3

Figure A - Flat Backfill (smooth face).



No. of layers	H	B	No. of gabions (per width)
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2	6' 6"	4' 11"	1 1/2
3	9' 9"	6' 6"	2
4	13' 1"	8' 2"	2 1/2
5	16' 4"	9' 9"	3
6	19' 7"	11' 5"	3 1/2

Figure B - 1 1/2:1 Sloping Backfill (Face Stepped).

Note: Loading conditions are for silty sand to sandy gravel backfill. For finer or clay rich soils, earth pressure on the wall will increase and the wall base width (B) will have to increase for each height.
- Backfill weight = 110 pcf. (1.8 Tons/cu. m.)
- Safe against overturning for soils with a minimum Bearing Capacity of 2 Tons/Sq. Ft. (192 kPa)
- For flat or shaping backfills, either a flat or stepped face may be used.

Figure 3-28—Standard design for gabion retaining structures to 20 feet high (6 m) with flat or sloping backfill (adapted from Gray and Leiser (1982).

Gabions also are used in stream channels to buttress the toe of a fillslope and prevent scour of the fill, or for streambank protection, particularly on the outside bend of a stream near a structure. They work effectively as an alternative to loose rock riprap or other bank stabilization measures. However with time, the wire baskets corrode or wear through from abrasion. After 20 to 30 years, many gabion structures in a stream environment begin to fail. Their life can be maximized by use of galvanized or plastic coated wire. Gabions also are susceptible to piping of soil under or behind the basket, so install them on a filter blanket, such as geotextile.

Soil reinforced gabion designs also have been developed where typical gabion baskets form the face, while gabion wire mats are used to reinforce the backfill. Reinforcing spacing is typically 3 feet (1 m), the height of a basket, and length of reinforcement is a function of the wall height and loading conditions, similar to other MSE designs. Advantages of this design are the comfort people have using traditional gabion baskets, combined with reinforced soil technology. Fewer baskets go into any moderately high wall compared to a conventional gravity structure, and use of a reinforced soil backfill reduces cost. Figure 3-29 depicts the construction process of a Terramesh reinforced soil wall with a gabion face.

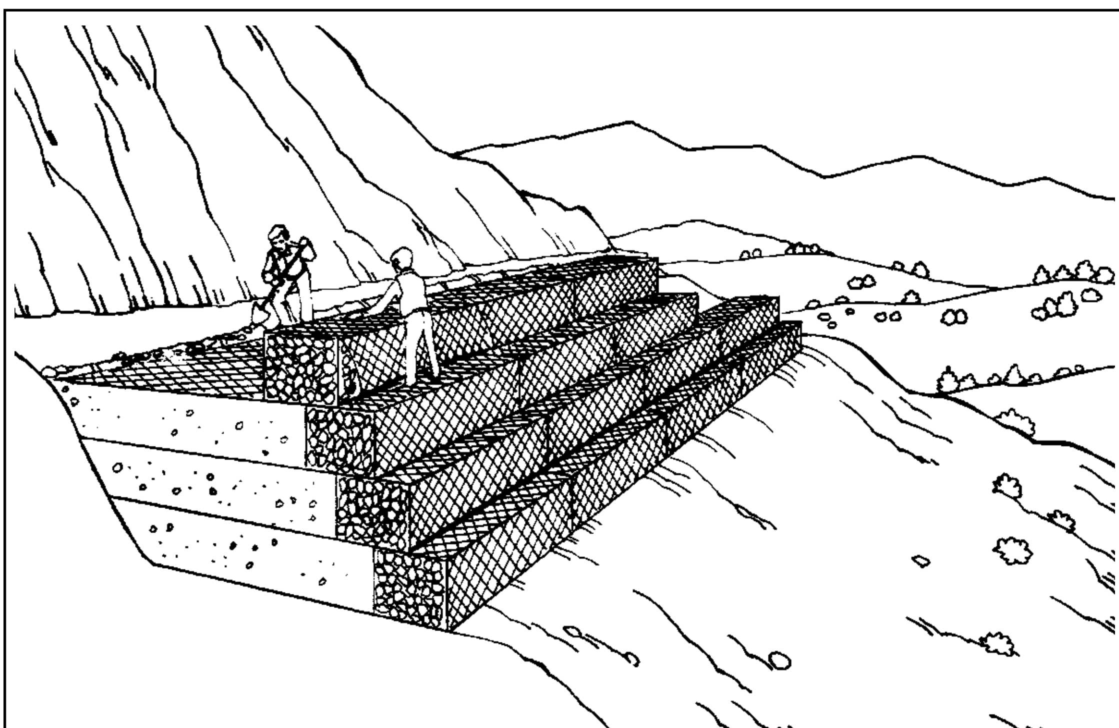


Figure 3-29—A soil reinforced gabion design (Courtesy of Maccaferri Gabions Inc.).

The Problem

Figure 3-30—Oversteep slopes, wet areas, or existing slide areas can cause instability problems for a road and increase repair and maintenance costs, as well as sediment production.

The Solution

Figure 3-31—Gabions are a commonly used type of low gravity retaining structure because they use locally available rock and are relatively inexpensive.

3.2.2.1.1.2. Concrete Blocks

Manufacturers have developed designs for large concrete blocks used as gravity retaining structures. Often they interlock or are keyed together to form a somewhat solid unit. Each block may weigh several hundred pounds to a couple of tons. They may be available from concrete manufacturers as a way to use excess or reject concrete. Designs are available with sculptured or textured blocks, and blocks that can be used as flower pots to grow vegetation on the face.

One advantage of concrete blocks is that they can be moved into place and constructed quickly, avoiding construction and traffic delays and minimizing the time that a slope excavation is open. The primary disadvantage is that the blocks place a large load on the foundation, so good foundation conditions are needed. Also, construction equipment is needed to lift and place large blocks.

3.2.2.1.1.3. Rockery Wall

A rockery or rockery wall is built to provide slope stability, as well as erosion control, and to provide a decorative or natural look for slopes. While stability is provided to the slope, the amount is difficult to calculate. If a slope stability problem exists, contact a geotechnical engineer for further recommendations; otherwise use rockeries only where minor support is needed. The resistance to movement depends to a large extent on the quality of the workmanship, size, and shape of the rocks used. The term rockery used here refers to rock that is placed and keyed together, not dumped. Rockeries up to 20 feet (7 m) high are seen, but few are built to this height today. It is recommended that rockery heights be limited to less than 15 feet (5 m). Typical rock wall configurations and widths needed for a specific height are shown in figure 3-32.

Design

Many rockeries are not designed; they are just built. Rock wall construction is somewhat of an art. However, there is some design information available in the references. A rockery is not an engineered system in the sense that a retaining wall is. Rock wall stability has been improved occasionally by sandwiching pieces of geotextile between the rocks and burying the end of the geotextile in the backfill, effectively creating a reinforced soil structure.

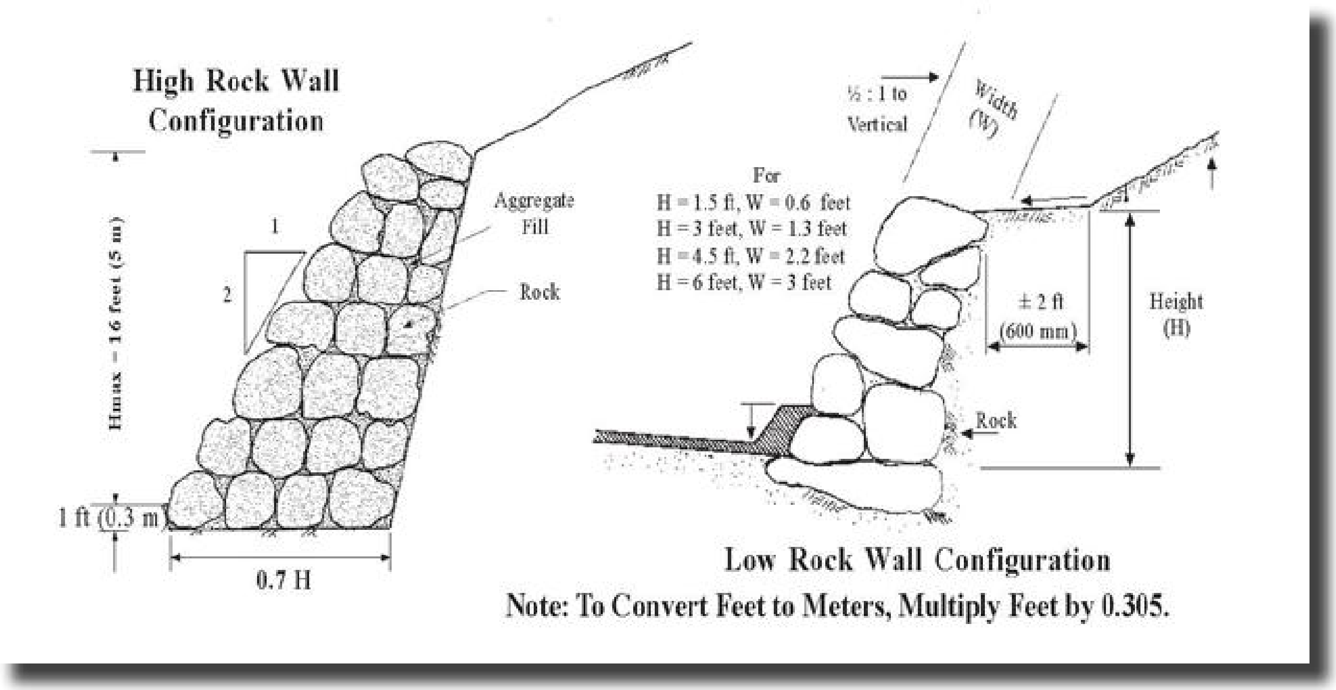


Figure 3-32—Typical rock wall construction.

An important factor in rockery construction is the quality of the rock material used. All rock should be sound angular with the longest dimension not exceeding three times the width. All rock should meet the minimum specifications shown in table 3-13.

Table 3-13 - Minimum rock specifications.

Absorption ASTM C127 AASTHO T-85	No more than 2.0 percent for igneous and metamorphic rock types and 3.0 percent for sedimentary rock types.
Accelerated expansion (15 days) CRD-C-148 *1, *2	No more than 15 percent breakdown
Soundness (MsSO4 at 5 cycles) ASTM C88 CRD-C-137	No more than 5 percent loss
Unconfined compressive strength ASTM D 2938	Intact strength of 6,000 pounds per square inch (psi) or greater
Bulk specific gravity ASTM C127 AASTHO T-85	Greater than 2.48 (155 pounds per cubic foot (pcf)).

**1 The test sample will be prepared and tested in accordance with the U.S. Army Corps of Engineers testing procedure CRD-C-148.*
**2 Accelerated expansion tests should also include analyses of the fractures and veins found in the rock.*

Rocks used in rockery construction are frequently sized as man rocks. For example, a two-man rock is a rock that can be placed by two men using steel pry bars. Sizes of rocks commonly used are shown in table 3-14.

Table 3-14—Sizes of rocks commonly used.

Rock size	Rock weight (pounds)	Average dimension (inches)
One-man	50-200	12-18
Two-man	200-700	18-28
Three-man	700-2,000	28-36
Four-man	2,000-4,000	36-48
Five-man	4,000-6,000	48-54
Six-man	6,000-8,000	54-60

Note: 1 Kg = 2.2 pounds; 1 meter = 39.37 inches

For additional technical information about rockery walls, consult Mohney (1994). This design guide streamlines and standardizes the art and science of slope management.

3.2.2.1.1.4. Rock Buttresses

Typically a rock buttress is used only to maintain existing equilibrium. This approach involves removal of some slide material (e.g., in a roadway) and replacing it with a smaller volume of drained rock material (e.g., a drained buttress) large enough to maintain the existing slide equilibrium. It involves some simple analysis of the slide toe conditions but does not attempt to analyze the entire slide or to stabilize it. This solution should be less expensive than a permanent solution and should maintain stability until conditions or storm events worse than those that caused the slide occur again; however, this solution is still relatively expensive.

A buttress also can be designed to resist the full pressure of a slide and be a permanent structural fix. One may achieve improved stability and an increased factor of safety against movement by placing a geotextile filter layer at the back of the buttress, or providing a filter blanket behind the buttress to help drain the slope. Thus, the water within the soil behind the buttress is lowered and stability improved. Figure 3-33 shows a large rock buttress stabilizing the toe of a slide in the cutslope above the road.

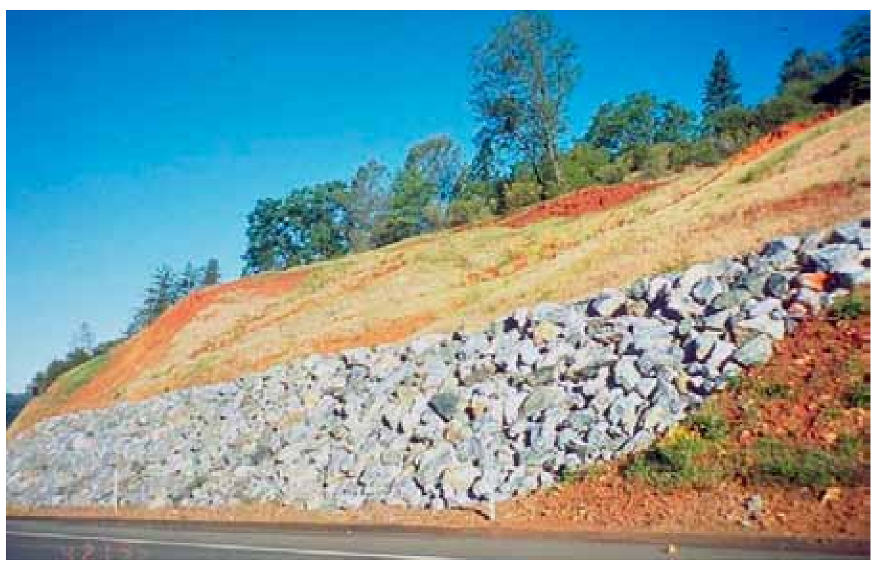


Figure 3-33—A drained rock buttress used to stabilize a cutslope failure.

3.2.2.1.1.5. Live Cribwall

Cribwalls constructed of concrete, metal, timbers, or wood posts traditionally have been used as gravity retaining structures. The crib serves as a form to hold backfill material and the mass provides stability. Live cribwalls, as a biotechnical treatment, typically consist of hollow, box-like interlocking structures constructed of untreated logs or timbers. Fill the crib with suitable backfill material as in a traditional cribwall, and place live branch cuttings or rooted plants between each layer of cribs; with time they will root inside and behind the cribwall, as seen in figure 3-34. Once the vegetation becomes established, it gradually provides support and may, depending upon the specific application, take over the structural function of the wood members.

This application is appropriate on slopes where a retaining structure is needed, such as to stabilize the toe of a slope, or to use in some space-constrained areas. Limit live cribwall use to structures lower than 6.5 feet (2 m). They are not designed to resist large lateral loads.

Figure 3-34—A live cribwall during construction and completed with sprouted vegetation (courtesy of Robbin B. Sotir & Associates, Inc.).

3.2.2.1.2. Mechanically Stabilized Earth Walls

Today earth reinforced systems, reinforced soils, geosynthetic confined soils, geosynthetic reinforced soils or mechanically stabilized earth (MSE) walls offer an economical and effective alternative to traditional gravity type structures for most wall heights and applications. Actually, reinforcement fibers to strengthen soil have been a concept used since biblical times. For walls over 25 feet (8 m) high, MSE walls offer significant cost advantages over gravity structures. In the case of rural or forest low-volume roads, where the access may be very difficult and the budget limited, the prefabricated or lightweight materials, combined with local or onsite soils, such as used in MSE technology, generally are recommended.

Various reinforced soil or MSE retaining structures use strength properties of wire or geosynthetics and soil reinforcement concepts. Soil reinforced structures include welded wire walls, geotextile reinforced walls, modular block walls, tire-faced walls, concrete face panel walls, timber walls, lightweight wood or sawdust walls reinforced with geosynthetics, etc. MSE walls use a variety of facing materials, including tires, wood beams, straw bales, concrete blocks, gabions, concrete panels, geotextile or turf reinforcing mats, and other facings. Soil reinforcement commonly is achieved using geotextile and geogrid, though welded wire, chain-link fencing, metal bars, and metal strips have been used. Figure 3-35 shows a welded wire MSE wall, commonly used in the Forest Service because of its flexibility, minimal foundation pressure, and ease of construction.

Figure 3-35—A welded wire MSE wall, commonly used by the Forest Service.

A popular design used commercially is the segmental retaining wall using concrete blocks for facing and typically geogrid reinforcement, as seen in figure 3-36. This design can be very durable and aesthetic, with patterns and colors built into the blocks. One easily can shape the wall around corners, with steps, etc. The National Concrete Masonry Association (NCMA) has developed programs for their design and published construction information. Its disadvantage is a relatively heavy wall face load that requires a footing to support the facing. The concrete blocks usually used for facing elements serve to retain the very face material in the wall and act as a form during construction to retain each subsequent lift of material and reinforcement. NCMA Web site: <http://www.ncma.org/Pages/default.aspx>.

Figure 3-36—Concrete block-faced MSE wall under construction.

Because of the wide variety of facing elements that can be used, MSE walls offer many design options and potential cost savings over many conventional gravity structures or other systems, such as anchors or tieback walls. The least expensive type of MSE wall appears to be a geotextile wall where the geosynthetic is used for reinforcement as well as wrapping the material around the face, as seen in figure 3-37.

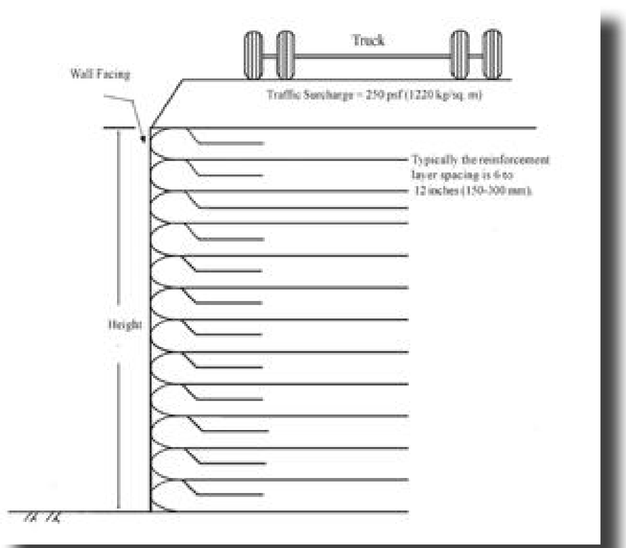


Figure 3-37—Design drawings of a geotextile wall (adapted from Wu 1994).

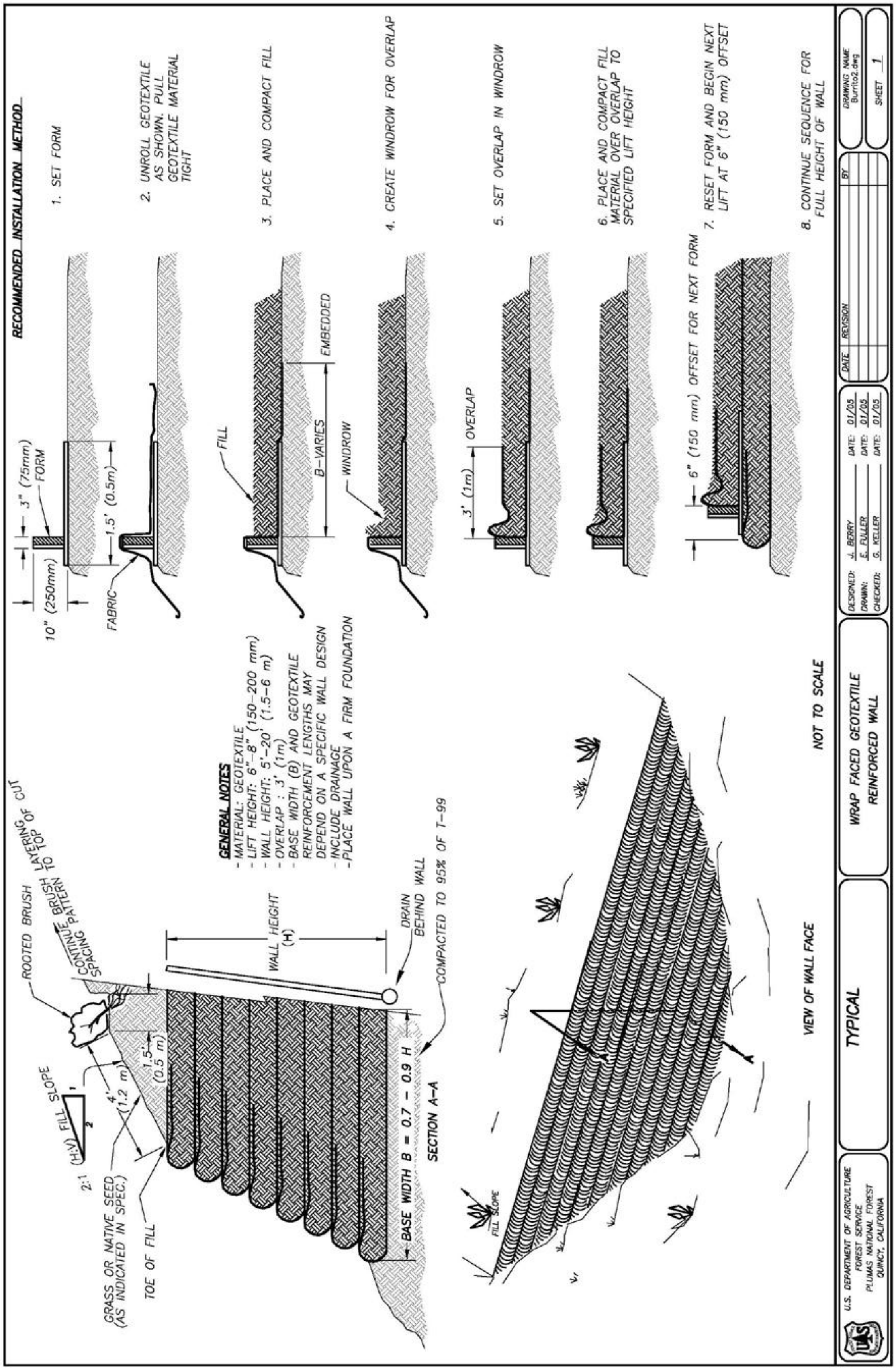


Figure 3-38—Design drawings of a wrap-faced geotextile reinforced wall.

An emulsion spray, or a more durable facing such as gunite, may need to be added to the geotextile to prevent degradation when exposed to the sun (figure 3-39). A geotextile stabilized with carbon black helps minimize degradation. Other inexpensive designs involve using hay bales or tires as facing elements for the MSE wall, with geosynthetic reinforcement layers buried in the backfill soil.

Figure 3-39—A geotextile wall constructed to support the roadway prism.

The connection detail of the facing element to the reinforcement layer is subject to current research and varying opinion. Many designs provide for a positive connection, with strength equal to the maximum tensile forces in the reinforcement layer at that elevation. On the other hand, closely spaced reinforcement, such as in 6- to 8-inch (150- to 200-mm) lifts, produces very small horizontal loads on the face, and many walls and abutments have been constructed where concrete blocks are just placed directly upon a reinforcement fabric, with no other connection beyond the friction between the materials. The backfill material between reinforcement layers should be a granular soil with a moderately high friction angle, and it should be well compacted. Walls also have also been constructed successfully with marginal soils, but they need more quality control and wall deformation may be high.

The design, construction, and use of MSE walls is well documented in Elias et al (2001).

A comprehensive updated version titled "Design and Construction of Mechanically Stabilized Earth Walls and Reinforced Soil slopes", Volume 1 and 2 (Berg et al 2009a, b) is available from FHWA. Note, however, that the FHWA design procedure can be very conservative, particularly regarding the strength reduction factors for geosynthetics and face connection strength requirements. It is available at <http://www.fhwa.dot.gov/engineering/geotech/pubs/nhi10024/nhi10024.pdf>.

3.2.2.2. Reinforced Soil Slope

Reinforced embankments (reinforced fills), MSE slopes, or reinforced soil slopes, consist of an embankment fill built up in compacted lifts with layers of a reinforcing material, such as a geogrid, geotextile, or welded wire, placed throughout the embankment. Geogrid is most often used for reinforcement because of its superior strength. The reinforcing material adds tensile resistance to local (face) and deep-seated shear failure in the embankment. In granular soils, reinforced fills placed with a 1H:1V or steeper face slope can offer an economical alternative to retaining structures for those sites where the ground is too steep to catch a conventional 1½:1 fillslope yet is flat enough to catch an oversteep reinforced fill, as seen in figure 3-40 and figure 3-41.

Reinforced fills are somewhat less expensive than a retaining structure for the same site, since no facing material is involved and construction can be relatively rapid. In poor, plastic soils, reinforcement can steepen the stable slope angle of an embankment. A slope range of 67 to over 150 percent can be achieved, depending on the reinforcement, soils, and facing measures used. On forest projects, reinforced fill heights typically have ranged from 15 to 50 feet (5 to 15 m). However, reinforced fills have been built over 115 feet (38 m) high.

Additional advantages of reinforced fills can be their ability to increase the stability of any slope, particularly after a failure; to improve on the construction behavior of poor quality soils, such as silts and clays; and to make slopes fit when constrained by space, right-of-ways, and so forth. Reinforced embankments built into a road cut also have been used as a drained buttress in limited space applications. Improved compaction at the edge of the slope by equipment operating on the secondary reinforcement decreases the tendency for surface sloughing and face erosion. Use of reinforced fills can save on materials if fill material is scarce or expensive, and polymer reinforcement material can be used in corrosive soils or harsh acidic, saline, or alkaline environments because of it's general resistance to chemical degradation.

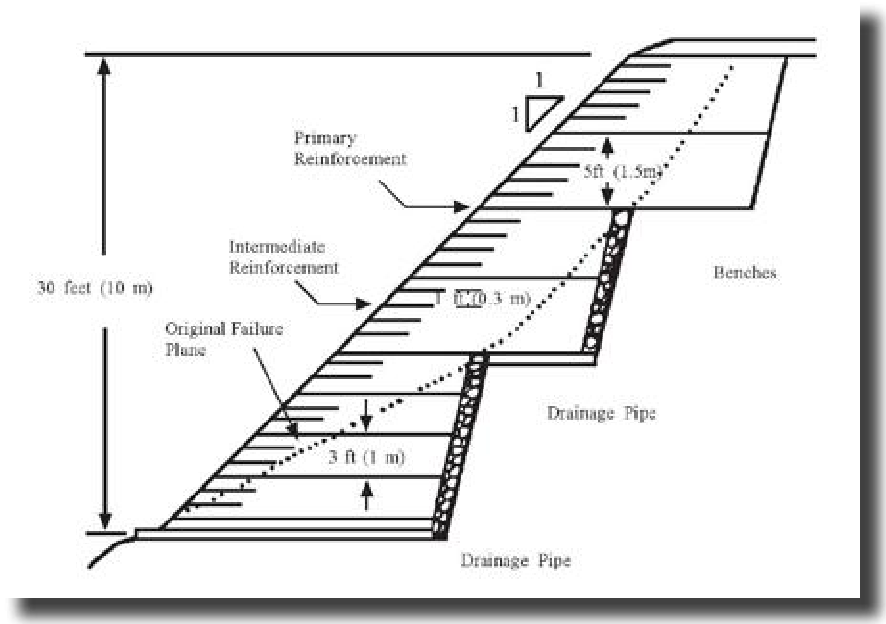


Figure 3-40—Reinforced fill built over a slide area on a steep slope.

Figure 3-41—Construction of reinforced fills using layers of geogrid or geotextile.

The spacing of the primary reinforcement is chosen to add the tensile strength needed to support the oversteepened fillslope and to prevent a deep-seated slope failure. Spacing typically varies between 2 and 5 feet (0.6-1.5 m), depending on soil parameters, fill height, and strength of the geogrid. Intermediate reinforcement, placed between the primary reinforcement, typically consists of narrow (5-foot (1.5 m) wide) strips of low-strength geogrid placed along the fill face on a 1-foot (0.3 m) vertical spacing. These strips prevent local failure on the oversteep face between the primary reinforcement layers and prevent failures due to construction equipment loading.

Installation of the geogrid is quite easy, but commonly requires hand labor. A disadvantage of reinforcement can be that the geogrid must be oriented correctly. Incorrect orientation may lead to a material strength lower than required by design, as well as wasting money. Some geogrid is biaxial, with the same or similar design tensile strengths in either direction. Others are uniaxial, where one direction is substantially stronger than the other, so correct orientation of this material is critical. Some geogrid is in a hexagonal form. Install all materials according to manufacturer's recommendations.

Backfill gradation requirements recommended for reinforced fills and slopes are shown in table 3-15. These gradation requirements are broad and can include excellent to marginal quality material. The plasticity index should not exceed 20. Soil pH range should be 3-9 to avoid excessive corrosion problems. Although reinforced embankments typically are constructed with select frictional backfill, successful projects also have been constructed using onsite or local materials; marginal, silty backfill materials; as well as clay-rich plastic materials. Most local soils can be used if the project incorporates good drainage, careful materials evaluation, and good field construction control. Coarse rockfill material, occasionally available, often has enough oversize material to make layer placement difficult, and rocks can damage the reinforcement material.

Table 3-15 - Backfill gradation requirements recommended by the AASHTO Task Force T-27 for reinforced slopes.

Sieve Size	Percent Passing
4 inch	100-75
No. 4	100-20
No. 40	0-60
No. 200	0-50

The reinforcement concept also can be applied in biotechnical slope stabilization where layers of live cut branches, such as willows, or rooted plants are installed into the fill surface with each layer of reinforcement. This method is commonly known as vegetated reinforced soil slope. (See section 3.1.2.8.) This addition of vegetation provides a significantly more durable and aesthetic facing treatment, not only protecting the outward surface but improving the internal drainage and stability of the system (Sotir et al. 2002).

Stability of reinforced slopes and fills is typically analyzed using versions of conventional limit equilibrium analysis, modified to account for the added tensile strength of the reinforcing material. Detailed design procedures for reinforced fills have been summarized in the FHWA reference Elias et al. (2001) and its recent update (Berg et al. 2009). Readers are recommended to read technical information on reinforced soil slopes techniques. Link to the document <http://isddc.dot.gov/OLPFiles/FHWA/010567.pdf>.

A comprehensive reinforced fill design program called reinforced soil slopes (ReSSA) has been developed by the FHWA, and other programs such as the XSTABL stability analysis program (Sharma 2007) can be used. Other programs are available commercially, such as PCSTABL6, STABGM, and UTEXAS II, or from geosynthetic manufacturers. Simplified hand solutions also are available in Elias et al. (2001).

3.2.2.3. Deep Patch

As forest roads age, the effects of decomposing woody debris and fill consolidation and settlement have become increasingly apparent. A single road can have numerous areas of cracking and subsidence. Typical methods for repairing fillslope-settlement problems, such as reconstruction, realignment, or retaining structures, can be expensive. The deep patch is a cost-effective technique for repairing and stabilizing the areas of roadways damaged by subsidence or cracking (figure 3-42).

Certain maintenance approaches often are considered inexpensive methods of dealing with settlement because road maintenance crews can do the work as part of their normal routine. Such methods usually consist of grading over the areas of settlement and cracks (aggregate-surfaced roadway) or filling cracks and adding asphalt (paved roadway) to level the road surface. While these approaches temporarily restore the road’s driving surface, the cause of the cracking and continual settlement in the road remains untreated. Grading does not stop the settlement either, but begins a long-term commitment to continual roadway repair. Deep patch as a maintenance technique reduces or stops the continual settlement. Engineers also have used deep patches on some less common applications. Deep patches have reinforced and slowed sections of roads crossing areas of large-scale slope movement. Road settlement and road maintenance costs have been reduced (Wilson-Musser and Denning 2005).

The deep patch design is a shallow road-fillslope repair where the upper 3 to 6 feet (1-2 m) of the subsiding section of roadway is excavated, the fill material is replaced with compacted select backfill, and several layers of geogrid or other reinforcing material are installed as shown in figure 3-43. Geogrid has been the most commonly used type of reinforcement. However, multiple layers of closely spaced geotextile (every 6 to 8 inches (150 to 200 mm)) might offer additional cost savings to this technique for road shoulder fill stabilization. Figure 3-44 shows a typical cross section of a deep patch design.

Figure 3-42—Oversteep settling fillslope before deep patch repair.

Figure 3-43—Geosynthetic reinforcing material (a geogrid) being placed in a deep patch shoulder repair.

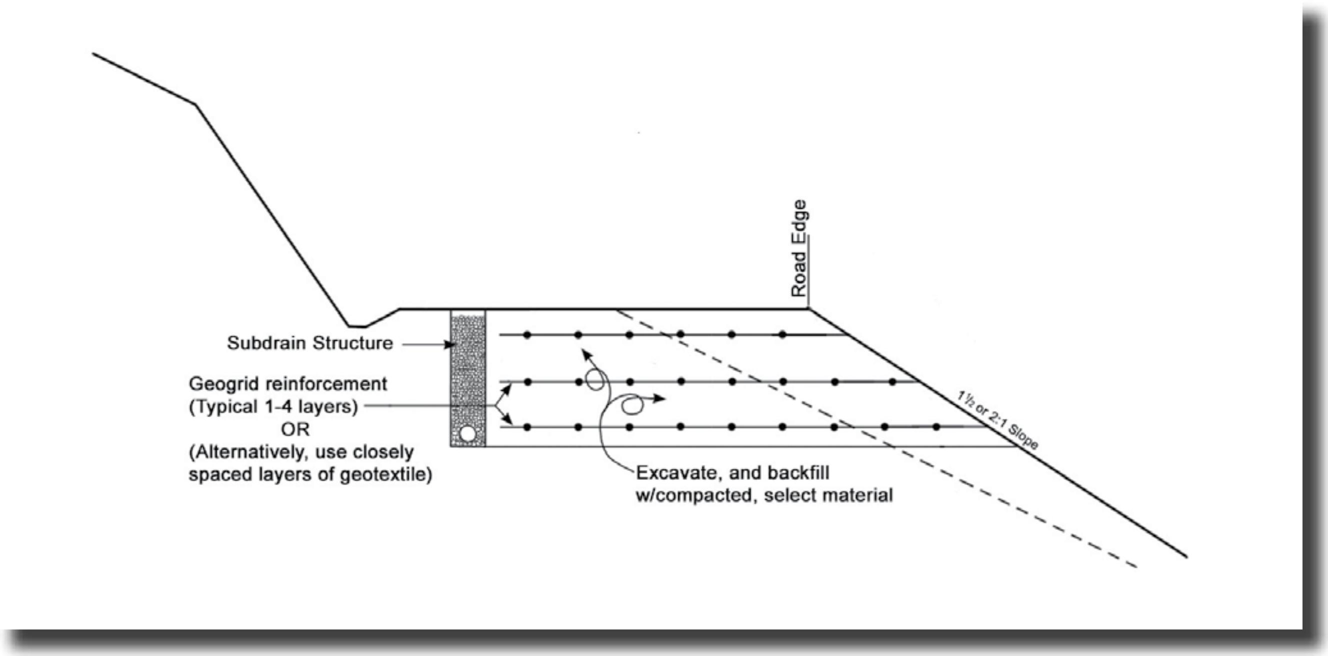


Figure 3-44—Cross section of typical deep patch road embankment repair.

The cost of repairing a road embankment failure with the deep patch method depends on backfill material (type and source), type and number of reinforcement layers, and drainage (if needed). However, when compared to other methods (such as road realignment or reconstruction, or retaining structures), the deep patch generally is the least expensive option.

Successful application of the deep patch design depends on characterizing the project site accurately, including the cause and location of the feature. Careful site mapping allows construction of the reinforcement in the right place, so an accurate field-developed cross section is desirable. Accurate field measurements are necessary to locate and define the zone of movement. The single most common cause of deep patch failure is insufficient embedment of the geosynthetic reinforcement behind the zone of movement. In other words, the reinforcement may be too short!

For additional technical information about the deep patch, consult the "Deep Patch Road Embankment Repair Application Guide" (Wilson-Musser and Denning 2005). The application guide describes the background, performance, design, and construction details of the deep patch technique. The authors describe the structure of the deep patch, present a simplified design method, and describe construction guidelines and steps for use by engineers and technicians. Link to the document <http://www.fs.fed.us/eng/pubs/pdf/05771204.pdf>.

3.2.2.4. Soil Nails

Soil nailing is a reinforcement method that involves insertion of long steel rods into an unstable or potentially unstable existing soil mass. These rods or nails reinforce the soil mass by transferring the nail tensile and shear resistance to the sliding soil. The nails maintain the resisting force because they are anchored beyond the slip surface. In general, there are two types of application: (1) soil nail walls, typically not used on low-volume roads and (2) soil nail slope stabilization of an existing soil, in which the soil nails are driven, inserted in drilled holes, or launched into the ground.

Soil nailing can be used to strengthen and densify a cut or fillslope, helping to pin a failing deposit to deeper, stable materials. Spacing and number of nails is determined by analysis based on the soil properties and slide characteristics. Figure 3-45 shows a slope stabilized with soil nails and a shotcrete face. This application keeps the backslope of a larger welded wire retaining wall stable during construction.

Figure 3-45—A slope stabilized with soil nails and a shotcrete face (stabilizing the excavation behind a welded wire wall under construction).

These ground types are considered favorable for soil nailing: naturally cohesive materials (silts and low plasticity clays not prone to creep); naturally cemented or dense sands and gravels with some real cohesion (due to fines) or apparent cohesion (due to natural moisture); and weathered rock. From a construction viewpoint, soil nailing is very adaptable and is therefore appropriate for mixed-face conditions, such as competent soil over bedrock.

3.2.2.4.1. Conventional Soil Nail Wall Solutions

Soil nail walls are typically specified in areas where a slope cannot be excavated because the slope is too unstable to survive full wall height excavation or because there is infrastructure above or behind the proposed wall that cannot be disturbed. These walls are constructed from the top down, excavating small vertical sections and stabilizing them with the soil nail wall before continuing excavation.

Benefits of soil nailing include the following: (1) ability to easily follow the building outline (i.e., ability to zigzag as required), (2) suitability of small construction equipment compared to alternative methods of construction, (3) suitability for special applications and remedial work, (4) ability to mobilize to a site quickly, (5) elimination of need for soldier piles required with tieback walls, (6) flexibility to allow for modifications during construction (e.g., nail locations can be moved to miss obstructions), and (7) compatibility with the usual constraints of operating in urban environments (e.g., need for minimum noise, small overhead clearance, etc.). Structural elements (soil nails and facing) and installation methods can easily be adapted, even during construction, to provide the most appropriate solution for specific site and ground conditions.

The limitations of soil nailing include the following: (1) inability to excavate where ground water is a problem, (2) difficulties associated with soil raveling in cohesionless sands and gravels without use of special, expensive measures, (3) problems associated with heavy concentrations of utilities, vaults or other underground obstructions behind the wall, and (4) potential performance problems if used in expansive or highly frost susceptible soils. In addition, because wall performance is sensitive to the method of construction, optimal results typically are best achieved by experienced specialty contractors.

The more common construction problems encountered on nail wall projects typically have involved encountering loose fill, granular soil with no apparent cohesion (e.g., caving sands), residual soils with remnant rock structure dipping adversely into the excavation, water, and manmade obstructions such as utility trenches. Other problems have involved contractor failure to construct the wall in accordance with the plans and specifications, such as excessive overexcavation of lifts, elimination of nails, use of poor grouting procedures, or misapplication of the method in ground conditions not suited to nailing. In a few cases, where significant excavation face sloughing has occurred without prompt remedial action, face collapses have occurred.

The FHWA publication (Byrne et al. 1998) provides guidance on selecting, designing, and specifying soil nailing for suitable applications of soil nail walls. It is a practitioner-oriented manual. Link to the manual <http://isddc.dot.gov/OLPFiles/FHWA/010571.pdf>.

Also see Porterfield et al. (1994). The manual provides field inspectors with the knowledge necessary to effectively monitor and document the construction of soil nail retaining walls. The manual provides information useful to both the experienced and inexperienced soil nail inspector. Link to the manual <http://isddc.dot.gov/OLPFiles/FHWA/009632.pdf>.

3.2.2.4.2. Soil Nail Slope Stabilization/Launched Soil Nails Applications

Launched soil nails are a rapid, economical alternative to recurring maintenance or other reconstruction solutions, particularly for road shoulder failures. Often several small fill failures can be fixed in one day without any excavation. The launcher can be moved easily between trees and shrubs with little or no vegetation removal and little need for environmental or visual mitigation. The machinery typically operates from the roadway.

The soil nail launcher was developed in Great Britain in the late 1980s and brought the United States in 1992 as a demonstration project partially supported by the FHWA and the Forest Service. The launcher, which is mounted on a tracked excavator, uses suddenly released high-pressure air to project steel nails up to 1.5 inches (37 mm) in diameter and up to 20 feet (7 m) in length into the soil to depths ranging from 5 to 20 feet (1.5 to 7m). Fiberglass bars are now available that can be launched into corrosive soils. Hollow bars with drilled holes also can be launched that serve as tensile inclusions and horizontal or vertical drains. Threaded bars can be used as well for tiedowns and micropiles.

The launcher, because it is mounted on a tracked excavator, can reach very remote locations to install nails and drains. One of its most useful applications is to stabilize roadway shoulder fill failures and shallow slides rapidly and without needing excavation for a wall that can result in long traffic delays. Figure 3-46 shows a sketch of a roadway shoulder failure stabilized with launched soil nails. Soil nails also can be used to stabilize a toe zone for the foundation of a retaining wall.

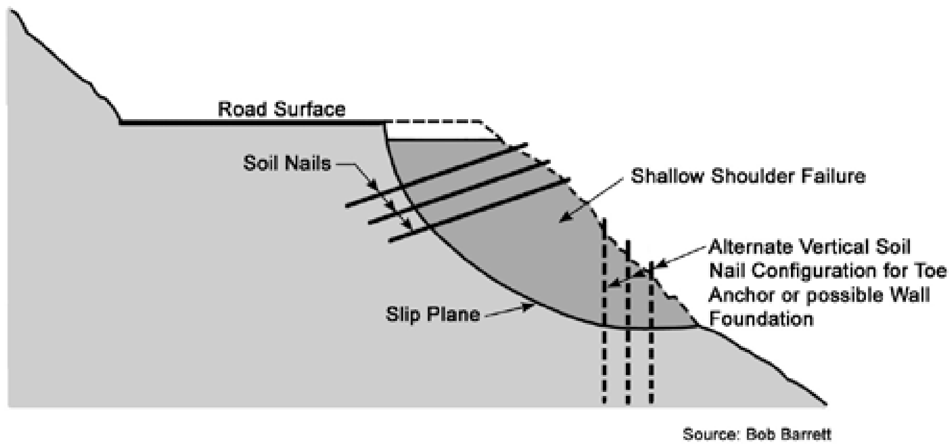


Figure 3-46—A roadway shoulder failure stabilized with launched soil nails.

The feasibility and economical design of repairs for unstable slopes using the launched soil nailing method depends upon an accurate assessment of existing physical conditions at the project site. The launched soil nails technique requires adequate investigation, establishment of the failure boundary, and appropriate analysis to determine if this technique is applicable to fix the slope failures. The design process includes an assessment of the cause of failure, estimated depth of the failure plane, and the collection of field data. One can gather the required design information from a visual assessment of the site and preparation of a field-developed cross section.

To ensure full penetration by the soil nails, the soil should not contain a high percentage of cobbles or boulders. Launching nails in ordinary sands, gravels, silts, and clays, or mixture of these, have presented little problem. Penetration is reduced in dense gravels and stiff clay.

The cost of launched soil nail stabilization for a site is almost equal to an MSE wall, but the difference and savings are in the speed of installation, lack of disturbance to the road and slope, and lack of need for road closure, thus minimizing traffic delays. Figure 3-47 shows the installation of launched soil nails from a road.

Figure 3-47—Installation of launched soil nails from the road (Courtesy of Bob Barrett).

For additional technical information about the launched soil nails, consult U.S. Department of Agriculture, Forest Service (1994 a, b). Link to the volume 1 document <http://www.fs.fed.us/eng/pubs/pdf/em7170_12a.pdf>.
Link to the volume 2 document <http://www.fs.fed.us/eng/pubs/pdf/em7170_12b.pdf>.

Currently launched soil nails is a proprietary method of Soil Nail Launcher, Inc. Link to Web site at <http://soilnaillauncher.com/dnn/>.

3.2.2.5. Lightweight Fills

Lightweight fills are used when it is important to reduce driving forces on an unstable slope. Lightweight materials are particularly useful in large slides or unstable mountainous terrain where it may be difficult to exactly define the limits of the slide, where alternative routes are impractical, or where the depth to suitable foundation material for a conventional structure is great. Many materials are suitable, including wood fiber, shredded tires, and geofoam. As with any retaining types structure, install the drain behind or under the fill.

3.2.2.5.1. Wood Fiber

Washington State roads have used wood fiber fills on various sites with slope stability concerns since 1972 with good results. Their density is about 21 pounds per cubic foot (pcf) (336 kg per cubic meter) (kg/m^3) and they reduce the weight of the fill by about 70 percent. In 1992, monitoring showed little to no degradation of the wood fiber in the 20-year-old fills and the road surfaces were in as good as or better condition than the adjacent road surfaces. Wood in the fill will not decompose if air and water cannot get to it.

The wood fiber used for road fills consists of various wood waste products from the milling of logs, such as hog fuel, planar chips, bark chips, or sawdust. Figure 3-48 shows the construction of a lightweight retaining wall using wood chips. For use in a fill, the material should be irregular in shape and size to ensure good interlock and improve stability of the fill. Because these are waste materials that are usually discarded, their cost may be minimal. However, today there may be competition for wood chips as fuel in cogeneration plants. Also, transportation costs can be a large factor if the source of wood fiber is not near the project site.

Figure 3-48—Lightweight wood chips in a MSE retaining wall.

There are two areas of concern in the use of wood fiber: spontaneous combustion and leachate. Studies have shown that spontaneous combustion is not a problem if the material is well compacted so that air oxidation does not occur. Leachate is any liquid, including any suspended components in the liquid, that has percolated through or drained from hazardous waste as defined by the EPA and is produced by deterioration of the woods in the wood fiber fills. The production of leachate is increased if there is water in the wood material, so it is important to minimize contact with surface and ground water. Leachate causes an increase in the biological oxygen demand and a depression in the dissolved oxygen of the receiving water, which can be harmful to aquatic life. Monitoring Washington Department of Transportation's wood fiber fills in high rainfall areas of western Washington at sites where water was found downslope of the fills found none to very minor increases in biological oxygen demand in the water.

The Washington Department of Transportation publication (Kilian et al. 1992) is posted on its Web site. Link to the document <http://www.wsdot.wa.gov/research/reports/fullreports/239.1.pdf>.

3.2.2.5.2. Shredded Tires

Shredded waste tires have many beneficial engineering properties as a lightweight fill material. To begin with, compacted shredded tire material is more porous than washed gravel (Geisler et al. 1989). California Department of Transportation conducted a constant head permeability test on two types of shredded tires, and the permeability coefficients were on the order of 10,000 feet per day (3,000 m/day) (Dresher et al. 1989). When used in the road base or subbase, shredded tires improve drainage below the pavement and therefore should extend the life of the roadway. Additionally, tire shreds are very elastic. This property enables the tire material to better distribute the roadway loads over unstable soils.

However, the same elastic properties can lead to higher than normal deflections. Shredded tires also possess vibration damping properties, a benefit in situations where vibratory compaction is hazardous to the surroundings. Furthermore, shredded tires are easily compacted and consolidated. Their angular shape and excellent friction characteristics allow the individual tire shreds to lock together very well. Lastly, shredded tires have bulk densities comparable to wood chips, approximately 20 pcf (320 kg/m^3) (Geisler et al. 1989). Compacted densities are about 40 pcf (640 kg/m^3).

Although there are no widely accepted design standards for shredded tires, construction contracts have produced some similar specifications for tire shreds as a lightweight fill material. First of all, the size of the tire shreds is always specified. Different shredding processes can produce shredded tires with highly varying characteristics. The source of the tires (i.e., automobile, truck, tractor, etc.) also may complicate the situation. A maximum size shred or chip along with a specification for percent passing a certain size screen is usually given. For example, 80 percent of the material (by weight) shall pass a 6-inch (150 mm) screen. Additionally, it is usually stated that the tire chips shall be free of oil, grease, or any other contaminants that may leach into the soil or ground water. If any metal fragments are present in the tire shreds, they must be firmly attached and 98 percent embedded to the material. No metal fragments are to be allowed in the fill material unless they are embedded within the tire shreds. Specifications also frequently state that all shredded tire pieces shall have at least one sidewall severed from the face of the tire. Finally, the weight (by truck measure) of the shredded tire material is normally specified.

The long term environmental impacts of using shredded tires as fill material are still unknown. In 1989, the Minnesota Pollution Control Agency (MPCA) initiated a laboratory study which attempted to model several scenarios that could develop in the field. The tests submerged the tire shreds in solutions with pH levels varying from 3.5 to 8.0. Potentially harmful substances were found in the laboratory studies when tires were exposed to highly acidic solutions (pH 3.5). This led the MPCA to issue guidance concerning the use of shredded tires below the water table or in contact with ground water. Wisconsin also conducted laboratory leachate studies on shredded tires, but did not find the leachates to be as harmful as Minnesota’s tests indicated. However, these States do not currently recommend that shredded tire material be placed below the water table.

For additional information on tire chips, or tire shreds, consult the FHWA-Turner Fairbank Highway Research Guidelines for “Recycled Materials in the Highway Environment.”
Link to the document <http://www.tfhrc.gov/hnr20/recycle/waste/st4.htm>.

For additional technical information about shredded tires, consult Engstrom et al. (1994). Link to the document <http://www.mrr.dot.state.mn.us/research/mnroad_project/mnroadreports/mnroadonlinereports/94-10.pdf>.

3.2.2.5.3. Geofoam

Geofoam refers to the super lightweight expanded polystyrene (EPS) blocks used in embankment construction. The first widespread application of geofoam technology in highway construction was for insulation and pavement frost damage mitigation, but geofoam is now used in many transportation-related applications. The use of geofoam in embankment construction avoids the problem of excessive settlements and affords benefits, including reduction of overburden pressure, reduction in the magnitude of ultimate settlement, and savings in construction time. Differential settlements between the approach fill and bridge abutments also can be reduced. Lateral pressure from approach fills onto abutments and wingwalls can be lessened significantly with geofoam fill.

Geofoam is extremely light, weighing only about 2 pounds per cubic foot (32 kg/m^3). Thus, the material is ideal for crossing unstable areas where the weight of a structure needs to be minimized. A structure can be assembled like building blocks, as seen in figure 3-49. However, since the material is lightweight and floats, any structure needs to be drained to prevent water buildup behind the structure. Typically, several feet (m) of fill material, gabions, or other material should be placed on top of the structure to anchor it down, to prevent crushing of the geofoam, and to provide a wearing surface for a road. Last, the polystyrene breaks down with exposure to the sun. Thus, any structure needs to be covered or someway protected from sunlight. Figure 3-50 shows a completed lightweight geofoam wall.

Figure 3-49—Geofoam wall under construction.

Figure 3-50—A completed geofoam wall project.

For more technical information on geofoam fill, consult “Guidelines and Recommended Standard for Geofoam Applications in Highway Embankments” (Stark et al. 2004). The report provides a design guideline and recommended standard for geofoam applications in the design and construction of highway embankments. The report will be of immediate interest to engineers in the public and private sectors involved in the design, construction, and material specification of lightweight embankments constructed on soft foundation soils. Link to the document <http://onlinepubs.trb.org/Onlinepubs/nchrp/nchrp_rpt_529.pdf>.

3.2.2.6. Road Realignment, Narrowing, or Raising/Lowering Grade

Road realignment around a slide area, narrowing the road through a slide, or raising or lowering grade through a slide area are all solutions for dealing with slope instability, improving slope stability, or living with and managing slope failures, particularly on forest low-volume roads.

Slide avoidance or prevention is most cost effective, and for many small slides, removal of the slide material and some stabilization with vegetation is common. However, changes in alignment, vertically and horizontally, can be effective solutions for low-volume roads. A more crooked road, a hump or dip in the road, a short narrow section, or a minor road realignment or road relocation can be acceptable and very cost effective on a low-speed, low-standard road. A road may be shifted into a stable cutslope if the outside edge of the fill is failing. Also, a narrower section of road may be acceptable on the stable cut portion of the roadway, again shifting away from the edge of an unstable fill. A road alignment may at least temporarily shift outward and away from an unstable cutslope.

Raising or lowering the road grade can improve stability, depending on the site as shown in figure 3-51. Raising the roadway elevation minimizes the cutslope height, and the roadway material helps buttress the toe of a failing cut. Lowering the roadway platform can remove material from the top of a failing fill, which removes weight off the slide and reduces the driving forces causing the instability.

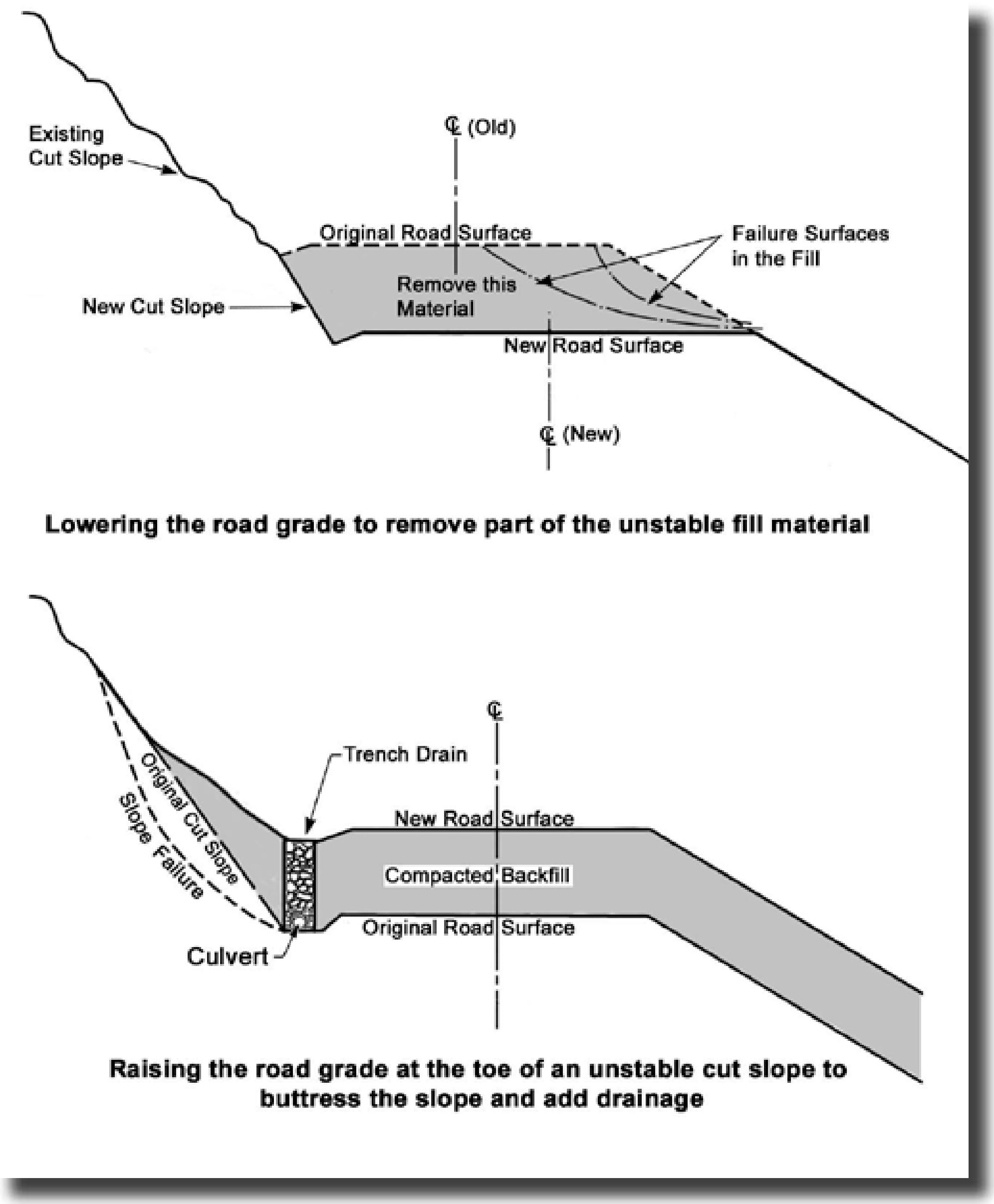


Figure 3-51—Raising or lowering the road grade to improve stability.

A combination of stabilization methods may be useful, and often one or more stabilization measures will be used in a problematic area, such as flattening the slope, shifting the road alignment, improving drainage, and adding a small local retaining structure.

3.2.3. Rockfall Protection

Rockfall refers to quantities of rock falling freely from a cliff face. A rockfall is a fragment of rock (a block) detached by sliding, toppling, or falling, which falls along a vertical or subvertical cliff and proceeds downslope by bouncing and flying along ballistic trajectories or by rolling on talus or debris slopes (Varnes 1978). Alternatively, a rockfall is the natural downward motion of a detached block or series of blocks with a small volume involving free falling, bouncing, rolling, and sliding.

Rockfall problems are typical on steep slopes in fractured rock deposits. To counteract the instability, the engineer can choose from a wide range of rockfall-protection solutions adopted to suit a particular situation. Some solutions are passive, which do not affect the process of rock detachment. Rolls of fabric with lacing, or metal fencing or netting, are provided as a blanket to cover the surface of the slopes to protect any infrastructure built on the foot of the slopes against rockfall, or to trap rock against the slope before it rolls or bounces onto the road (see figure 3-52). Gabions constructed as a retaining wall are an alternative to keep stones, which may fall from a cutslope or cliff, from endangering traffic on a road. Other solutions are catch fences and rockfall-protection embankments or berms.

Figure 3-52—Rockfall prevention netting that traps rocks before they hit the highway.

Active systems are those that act to prevent rock detachment. On rock slopes, where loss of rock fragments from the face is the prime concern, wire mesh solutions usually are the most appropriate. The wire mesh typically is pinned tightly in place with rock bolts or anchors. Also rock bolts may be used to pin down specific rock blocks.

Other solutions require a combination of scaling, rock bolting, buttressing, constructing terraces, and wire mesh or netting system. Scaling is used to remove loose rock, terraces catch rockfall, and road shoulder barriers prevent the rock from reaching the roadway, as shown in figure 3-53. Use rock bolts or rock anchors to hold large rocks in place to further stabilize the rock slope above the road and to hold rock-slope protection netting to trap random rockfall in fractured rock deposits. Rockfall netting is held tight with rock bolts to prevent rock movement or held loosely to control/catch rockfall. Use cable fencing along the slope to prevent future rocks from falling onto the road. Rock anchors usually involve a specific design and are used on low-volume roads only in problematic areas.

Other mitigations include installing traffic signs along the road to warn of falling rock in mountainous areas where the road has a history of rockfall problems. Removal of loose rock, unstable soil, trees, and other debris from the slope is the best preventative measure.

Large terraces or benches are often built into large cut and fillslopes, roughly every 20 to 40 vertical feet (7 to12 m), to catch falling rocks or debris, to shorten the surface drainage path, and to overall flatten the effective slope angle (figure 3-53). Also the rock cut may be flattened, especially to match the dip angle of rock joints in a cutslope.

The Colorado Department of Transportation Web site has information on its rockfall simulation program for design of protection measures. The Colorado Rockfall Simulation Program was developed to model rockfall behavior and to provide a statistical analysis of probable rockfall events at any given site. One can use this analysis as a tool to study the behavior of rockfall, determine the need for rockfall mitigation, and aid in the design of rockfall mitigation measures. View the Web site at <http://www.dot.state.co.us/geotech/crsp.cfm>.

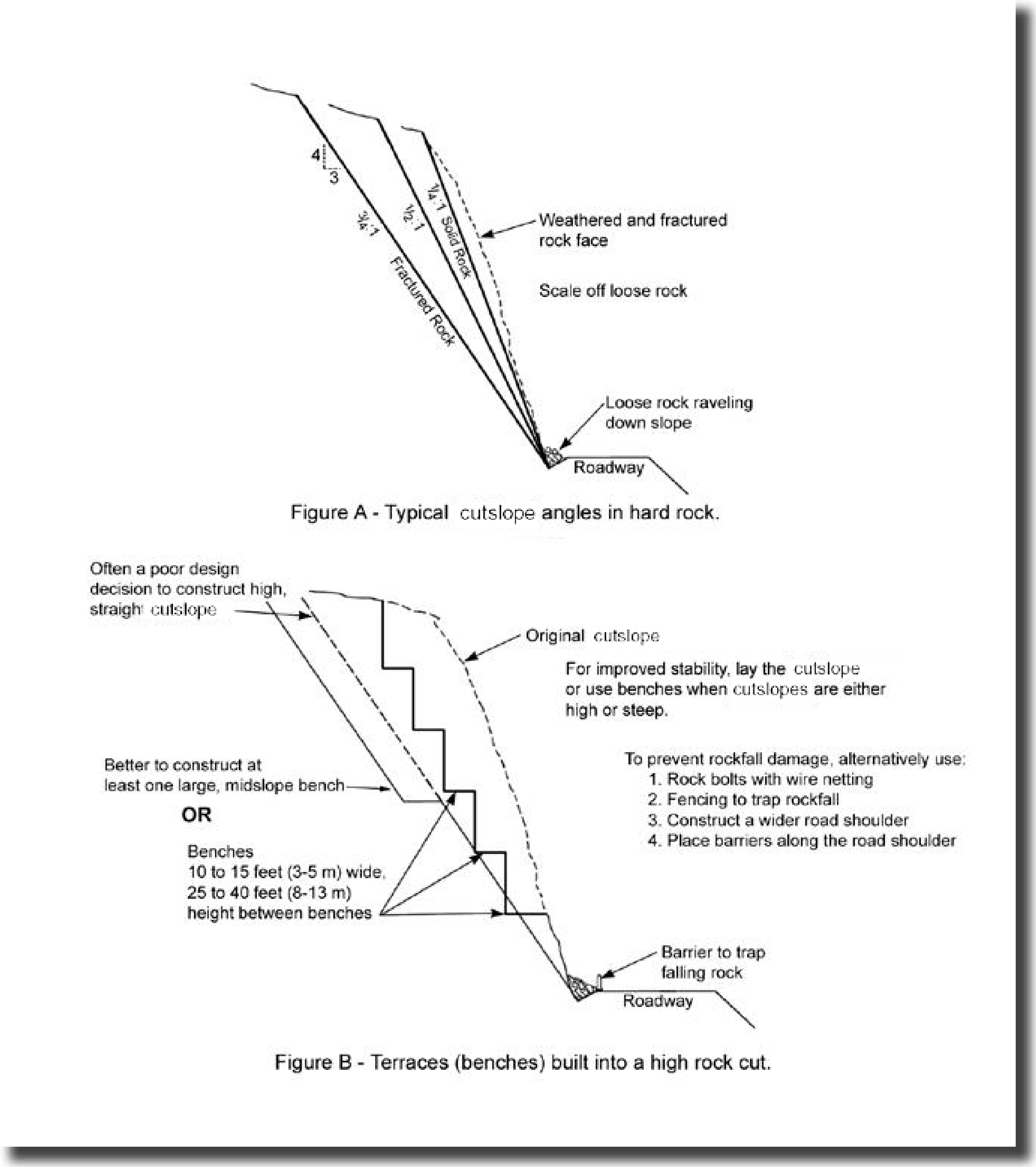


Figure 3-53—Rock cutslope stabilization options.

Additionally the Washington State DOT, in cooperation with the FHWA, has developed considerable information on rockfall analysis and mitigation measures. Their publication (Muhunthan et al. 2005) offers definitive design information and guidelines for a variety of rockfall protection and prevention measures involving cable netting, wire mesh, and anchors. The document provides design guidance on site suitability, load characterization, fabric selection, anchorage requirements, and system details.

Link to the document <http://www.wsdot.wa.gov/Biz/mats/Geotech/WA-RD612.1WireMesh.pdf>.

3.3. TREATMENTS FOR ROAD SURFACE AND SUBGRADE STABILIZATION

Maintaining a hard, smooth, dry roadway surface is important for the function of the road for user comfort, and for the safety of the driving public. The road surface should not be rough with potholes, ruts, or washboarding, nor should it have an accumulation of loose fine material or coarse raveled material on the surface. A fine, dry roadway surfacing material dusts, which creates a driving and environmental hazard. Maintaining a durable and strong roadway surface is a function of good materials and good drainage. This section deals with roadway materials, how to produce and improve them, how to maintain them, and presents alternatives to aggregate use. Also, solutions for dust and frost heave are discussed. Last, a number of common asphalt pavement distresses are discussed, along with a range of maintenance and rehabilitation options.

Whether one has a native-surface or an aggregate-surface road (often called a gravel road), periodic maintenance is needed to maintain the shape and smoothness of the road surface, and to remove ruts, potholes, and corrugations (washboarding). In many circumstances, one can reduce road wear and maintenance frequency by reducing vehicle tire pressure. Dust palliatives can reduce dust problems and help maintain a firm driving surface. However, in any case, as a function of time and traffic, roads need to be maintained.

An aggregate surface is the most common way a native-surfaced road is improved to add structural strength to the road and to minimize dust and surface erosion. For erosion and dust control, an aggregate thickness of 4 to 6 inches (100 to 150 mm) is commonly applied to the road. To develop a roadway structural section adequate to resist rutting, aggregate thickness is typically 6 to 12 inches (150 to 300 mm), and may be thicker depending on soil type and traffic loading. Aggregate thickness designs have been developed as a function of traffic and soil strength, commonly expressed as the soil California Bearing Ratio (CBR). For proper performance of any aggregate surfacing material, specific gradation ranges should be specified and used with hard durable aggregate, a well-graded material, and enough fines and plasticity to help bind the aggregate wearing surface together. For base aggregate confined under a pavement or a seal coat, less fines and no plasticity is desirable to maximize structural strength.

A quality well-graded aggregate is best achieved using a crushing operation. However, at times, suitable unbound aggregate or pit-run materials can be achieved if a well-fractured pit-run material is available directly out of the quarry with minimal or no processing. Also, the soil-aggregate material may be improved by screening off oversize rock, blending in plastic fines, or modifying the gradation through screening. A soft coarse rock may be broken down under a grid roller, or oversize hard rock may be reduced in size using a mobile rock crusher.

With geotextile and geogrid placed into the structural section, aggregate thickness may be reduced, marginal materials improved, or aggregate prevented from becoming contaminated. A geosynthetic layer placed between the subgrade soil and the aggregate surfacing can provide some reinforcement as well as separation (of the fine soil and aggregate).

Alternatives to aggregate surface stabilization include materials, such as chunkwood to pave the surface; improving the in-place soil strength with a variety of soil stabilization techniques and materials, such as cement or lime; or paving/hardening the soil surface with asphalt concrete or a variety of BSTs, such as a chip seal.

Any roadway surface that can be kept well drained performs better than a saturated soil surface. Too much water in the base material weakens the road. Water allowed to remain on top of the road weakens the surface and, when combined with traffic, causes potholes and ruts. Where concentrated or improperly channeled, the water causes erosion and loss of surfacing materials, particularly the fines. Thus, good drainage prevents water damage on a road as well as reduces maintenance and repair costs. Drainage issues are discussed in section 3.4.

3.3.1. Roadway Aggregate, its Maintenance and Alternatives

Road maintenance is the most common way to remove surface deformations, such as potholing, rutting, and washboarding. A good aggregate surface minimizes these problems, so use aggregate surfacing to improve soft soil areas. In this section we discuss many factors regarding the proper or most cost-effective selection and use of aggregate materials. Typically, the better the quality of the aggregate placed on the road, the less maintenance the road requires. Thus, one pays more initially or one pays more later with increased maintenance. Alternatively, aggregates placed over very soft soils can be helped with the use of geosynthetics, ruts can be minimized by reduced tire pressure on vehicles, or in some applications wood products can be used as an alternative to aggregates. Finally, the in-place soil can be improved with stabilizers to reduce or eliminate the need for aggregate, particularly in areas where aggregates are very expensive or not available.

3.3.1.1. Road Maintenance for Ruts, Washboards, Potholes, and Soft Soil Solutions

Forest roads must be maintained during active use, after periodic operations have been completed, and after major storm events. Good maintenance is key to keeping a road surface in good condition. Any road needs routine maintenance to keep the road serviceable, its surface smooth, and its drainage system working. A well-maintained road reduces road user costs, prevents road damage, and minimizes sediment production.

Crews should perform these maintenance items routinely:

- ❑ Grading and shaping the roadway surface to maintain a distinct insloped, outsloped, or crown shape to move water rapidly off the road surface and keep the road bed dry.
- ❑ Compacting the graded roadway surface to keep a hard driving surface and prevent the loss of fines. Keep the road surface moist for proper compaction.
- ❑ Replacing surfacing material when needed.
- ❑ Removing potholes and ruts in the road surface that pond and trap water.
- ❑ Cleaning ditches when necessary to avoid ponding water that saturates the road subgrade.
- ❑ Trimming roadside vegetation (brushing) adequately, but not excessively, for sight distance and traffic safety.
- ❑ Patching potholes and sealing cracks in asphalt surfacing.

Good gravel road maintenance or rehabilitation depends on two basic principles: (1) proper use of a motorgrader (or other grading device) (figure 3-54) and (2) use of good surface gravel. The use of the grader to shape the road properly is obvious to almost everyone, but the quality and volume of gravel needed is not as well understood. Most gravel maintenance/rehabilitation problems are blamed on the grader operator when the actual problem is often material related. This is particularly true when dealing with the problem of corrugation or washboarding. The problem is often perceived as being caused by the grader but is primarily caused by the material itself, or aggravated by water ponding on the road surface, as seen in figure 3-55. Materials considerations are discussed throughout this section.

Figure 3-54—Use grader maintenance to keep the road surface properly shaped and drained.

Figure 3-55—A road that lacks a good crown for surface drainage. There is centerline corrugation (washboarding), a problem that grows worse when there is inadequate crown or infrequent maintenance (Skorseth et al. 2000).

Causes of Washboarding

Washboarding (or corrugations) on a road surface is caused by three principal factors. They are:

1. Lack of moisture. Prolonged dry weather characteristic of dry regions can cause washboarding, even with relatively low traffic. However, on gravel roads washboarding occurs under most road conditions including the wet Pacific Northwest with time and moderate traffic.
2. Driving habits. People's driving habits can aggravate washboarding. Hard acceleration or hard braking are the greatest problems. As a result, washboarding normally appears first at intersections, around sharp curves, and on steep grades. When vehicle tires lose a firm grip on the road and spin or skid, a slight amount of gravel is displaced. As this is repeated over and over, the gravel aligns itself into the washboard pattern. Light vehicles with small wheels and light suspensions cause more washboarding than heavy trucks.
3. Poor-quality gravel. Washboarding almost certainly develops if the surface gravel has poor gradation, little or no binding characteristic, and a low percentage of fractured faces on the aggregate.

Of the three major causes of washboarding, the Forest Service only can change the material it uses. It is not realistic to expect to change motorists' driving habits, nor can we change the weather. In prolonged dry weather, almost any section of road with high traffic volume develops corrugations. However, well-graded and dense gravel reduces the problem. With high traffic volumes, anticipate more frequent maintenance.

Surface Maintenance Practices

The main objectives of maintaining aggregate or unbound road surfaces are to:

- ❑ Provide a good riding surface.
- ❑ Minimize safety hazards to vehicular traffic.
- ❑ Provide a free draining surface.
- ❑ Prevent or reduce resource damage in wet weather.

To achieve these objectives, agencies must adapt maintenance to the physical condition of the pavement, traffic volume, and predominant vehicle type and climate. Each road, no matter how carefully designed and constructed, deteriorates as a result of traffic movements, climatic conditions, and the properties of pavement materials. Regular maintenance is therefore essential to provide the desired level of service for each road in the network.

The severity and frequency of defects, such as washboarding, potholes, rutting and loss of surface drainage cross-fall, coupled with service levels commensurate with available resources, should set the maintenance requirements for the road network. Maintenance can vary from on demand corrective maintenance, when a defect arises, to preventative maintenance, which attempts to predict defects in advance of their occurring and taking action to eliminate or reduce the occurrence or frequency of the defect.

It is not always possible to place new and better quality gravel on the road surface to reduce washboarding problems. Simply blading over washboards and filling the depressions between the ridges is nearly useless. The best blading method is to loosen and remove the very compacted material at the bottom of the corrugation to a depth of 1 inch (25 mm) or more below the bottom of the washboards. This brings up some fines to mix with the surface material. Then, mix the materials and relay them into the proper crown or shape. Finally, compact the surface!

Remember that another cause of washboarding is dry conditions. Never work on washboarding problems without good moisture in the material. When possible work the problem areas after a good rain, or work with a water truck.

A useful tool when repairing washboard sections of road is to use replacement carbide tipped bit cutting edges on the grader. Carbide bits or replacement cutting edges tend to have a shallow scarifying effect and make it easier to cut material loose and mix it. These replacement cutting edges can be used effectively on a front-mounted blade. The operator can drop the blade to cut out washboards and use the moldboard to shape the area. A conventional scarifier also works. Be careful not to cut too deep and bring up dirt and large rock from the subgrade; this contaminates the gravel.

When placing new material on a washboard area, always cut and rework the area before adding the new material. If this is not done, the washboard pattern in the original surface invariably reflects right up to the new surface, and the problems begin all over again.

The road should be properly crowned and shaped. Sometimes the original material has to be cast to the side and used as shouldering material because adding a depth of new material makes the finished roadway surface too high relative to the surrounding ground. This can create a safety problem.

Another method to improve the surface gravel gradation is to pull material from the shoulders and mix it with the loose surface gravel. Generally, the material is not the best binder, but it does have some benefit in restoring some fines to the gravel. Note, however, that too many fines contaminate the gravel and it loses strength. This approach works best in the spring when moisture is present and before too much vegetation has grown on the shoulders.

Gravel can be treated with either calcium or magnesium chloride. These products are not binders but aid in keeping gravel in place. They work by simply drawing moisture from the air. The key to success with these products is to treat gravel that has a good gradation and good binder. The chlorides aid by keeping the surface slightly damp, and the gravel remains tightly bound (Monlux and Mitchell 2006).

Crews can use reclaimed asphalt as part of the surface gravel. This high-quality product is not available everywhere but sometimes it is stored by local agencies. The best results are with a 50/50 blend of recycled asphalt and virgin gravel. In this mix the asphalt becomes the binder, and the material usually has a good binding characteristic and will resist washboarding. Place the product at a compacted depth of at least 3 inches (75 mm). If not affordable for a whole section of road, it works well in trouble spots.

Maintenance normally consists of reshaping roadway cross sections, replacing lost material, adding material where weaknesses show up, cleaning and extending roadside drainage, and removing surface defects. Table 3-16 lists the typical surface defects and potential remedial maintenance treatments. The Australian Roads Research Board provides useful tips to road maintenance practices in their “Unsealed Road Manual: Guidelines to Good Practices” (Giummarra 2009). Link to the Web site <http://www.arrb.com.au/documents/lrnews/LocalRoadsNews69.pdf>.

Considerable additional information on maintenance of gravel roads is found in the “Gravel Road Maintenance and Design Manual” (Skorseth and Selim 2000). The manual is an excellent reference on many aspects or gravel road maintenance and design. Link to the manual <http://www.t2.unh.edu/nltapa/Pubs/south_dakota_gravel_manual.pdf>.

Minnesota Local Technical Assistance Program (Minnesota LTAP 2006) has produced a complementary video on gravel road maintenance. Link to the video <http://www.mnltap.umn.edu/Publications/Videos/GravelRoadMaintenance/>.

The Oregon Department of Forestry (2000) State Forests Program has developed useful information on forest road maintenance practices. Link to the manual <http://www.oregon.gov/ODF/STATE_FORESTS/Roads_Manual.shtml>.

The San Dimas Technology and Development Center (SDTDC), in cooperation with the FHWA, has produced a set of road maintenance videos titled "Forest Roads and the Environment" (San Dimas Technology and Development Staff 2006). This five-set presentation covers many aspects of road maintenance on the roadway and beyond the traveled way, including the road surface, ditches, and cross drains. It addresses the needs for surface stabilization and surface drainage, with maintenance conducted in an environmentally sound way.

The SDTDC has developed a concise guide "Guidelines for Road Maintenance Levels" (Apodaca et al. in preparation) that summarizes road maintenance levels. The explanations and photos can help agency road managers, transportation engineers, and particularly equipment operators and field personnel achieve consistent application of road management and maintenance standards.

Finally, another useful publication on road maintenance has been developed by the Pennsylvania State Center for Dirt and Gravel Roads Studies. This publication, "Environmentally Sensitive Maintenance for Dirt and Gravel Roads" (Gesford and Anderson 2006), focuses on the many issues, including surface, road shoulder, and slope maintenance, related drainage needs, surfacing materials, etc, all conducted in a manner to minimize damage to the environment. This publication is available at <http://www.epa.gov/owow/nps/sensitive/sensitive.html>.

For additional information about causes and cures for washboarding, see Street Wise (2002).

Link to the document <http: www.t2.unr.edu/StreetWise/streetwiseSum02-V11-01.pdf>.

Table 3-16—Maintenance defects and remedial treatments.

Defect	Cause	Potential Treatments
Washboarding	Material displacement due to tire action; granular material with particle sizes greater than 0.2 inch (5 mm) with low plasticity and limited fine are susceptible.	Respread material and cut to the depth of the washboarding; motorgrader should be operated at low speeds; addition and blending of selected clay binder.
Potholes	Flatter grades and cross slope are susceptible, which allows water to infiltrate surface and/or strip material from the surface.	Restore surface shape and cross slope in flat spots; severe potholes may require scarifying and reshaping.
Rutting	Longitudinal deformation in the wheel tracks caused in dry season with noncohesive materials with low fines content; wet season rutting is associated with excess water weakening one or more of the surface materials	Provide correct cross slope; blend material to improve quality; stabilize material.
Loose Material	Lack of binder to hold the aggregate in place.	Blend existing material with well-graded material.
Loss of Surface Material	Combination of vehicle use and lack of strength and cohesion in the surface materials.	Blend existing material with well-graded material or add new material with suitable grading
Surface Erosion	Excessive grade or lack of compaction.	Use high quality, well-graded aggregate (either blend with existing or add new); modify drainage to ensure that water finds the shortest possible route off the pavement.

Very Soft, Weak Subgrade Areas

Although it is extremely important to remove surface and subsurface water from the roadways, there are situations where water simply cannot be removed. A good example is a section of road that passes through naturally occurring swampland or wetlands that cannot be drained. These areas often have very weak subgrades that cannot support heavy loads. Sometimes it is even hard to maintain the road for light traffic. The road ruts and potholes quickly form due to poor soil support. Avoid these areas whenever possible.

Soft subgrade areas require more than routine maintenance and reshaping if the problem is to be fixed permanently. The most common solution is to excavate and remove the weak, wet soil, often to a depth of 3 feet (1 m) or more, and refill with a select material or gravel. This select material varies depending on what is available in the region. Select material should be clean and free draining. It is also advisable to get advice from a materials engineer to ensure that materials are adequate before starting this rehabilitation challenge.

A second method involves the use of a geosynthetic layer. These products, often called fabrics (geotextiles) and grids (geogrids) (figure 3-56), are placed over the subgrade soil before the select material or aggregate is brought in. This reduces the thickness of required aggregate. A woven or nonwoven geotextile placed on the subgrade becomes a separator between the weak soil and the new material (usually gravel) placed above it. Nonwoven geotextile is typically less expensive than the woven and can be cost effective compared to the cost of an additional aggregate thickness.

Figure 3-56—Geosynthetics and gravel placed over a local soft area in a road. Note that the geotextile is showing on the road surface so more cover aggregate is now needed.

The geotextile prevents very fine, wet soils from pumping or migrating up into the aggregate. The pumping action occurs when traffic passes over the surface and the road deflects under the load. Pressure from the load causes water in the subgrade to rise to the surface and carry fine soil particles with it. This contaminates and weakens the new material and makes it weak, undrainable, and unstable. A layer of geotextile prevents this by filtering out the fine soils while allowing water to pass through it and drain out of the clean, granular material above.

Geogrid also can be used in combination with or without a geotextile layer. Geogrid is a very strong geosynthetic which, in simplest terms, confines the material placed on it and does not allow lateral movement or shoving of the material. Geogrid has been rolled out over swamps and roads built over it with remarkably good results, as seen in figure 3-57. The ability to carry and distribute the soil and traffic load is referred to as reinforcement, or a snowshoe effect. Geogrid also can be placed within layers of select material. There are many types and variations of this product. It is wise to get good engineering advice when dealing with difficult soil stabilization problems. Geosynthetics are usually considered effective for subgrade reinforcement when the native soils are quite weak, with a CBR of less than 3.

For true reinforcement over a very soft soil, a strong material is needed, such as a geogrid. A geotextile layer also may be used to act as a filter in conjunction with the geogrid. Alternatively, multiple layers of a closely spaced woven geotextile can be used between layers of a compacted aggregate to form a stiff raft over the soft subgrade material.

Figure 3-57—Geogrid has been rolled out over a swamp to provide reinforcement for the roadway fill (note that this is a poor road location).

Holtz et al. (2008) provide considerable information on the use and design of geotextiles and geogrids for building reinforced embankments across soft soils.

The U.S. Departments of the Army and Air Force (1995) publication has useful soil stabilization design information for crossing soft soils.

3.3.1.2. Reduced Tire Pressure (Central Tire Inflation)

In 1983, the Forest Service began an extensive program to test the feasibility, development, and implementation of reduced tire pressures on forestry trucks and central tire inflation (CTI) technology. CTI is a system that allows the driver to conveniently monitor and adjust tire pressures while the truck is in motion. Tire pressures are adjusted according to tire manufacturer's recommendations to achieve optimal all round tire performance (e.g., traction, puncture resistance, sidewall life, tread wear, and fuel efficiency). Recommended inflation typically ranges between 25 and 120 psi (170 and 825 kPa) depending on the load, speed, and road conditions encountered throughout the work cycle. Trucks without tire pressure control devices may achieve a partial measure of the benefits by operating with a constant reduced pressure of 60-70 psi (415 to 520 kPa). The Forest Service estimates more than $20 million would be saved annually in road construction and maintenance with the use of reduced tire pressures on national forest roads. Additionally significant environmental savings were estimated.

Benefits of Reduced Tire Pressure

Benefits of reduced tire pressure have been demonstrated in structured tests on test courses (controlled conditions) and field operational tests (actual field conditions) (figure 3-58). Tests and subsequent industrial usage have confirmed the following benefits from using reduced tire pressure:

- ❑ Reduce road surface structural thickness by 25 percent or more.
- ❑ Reduce road maintenance costs by minimizing road wear and tear (less gravel loss and breakdown, less washboard and dust, slower rutting, trucks can heal existing ruts and washboard).
- ❑ Reduce truck maintenance, labor, and parts costs (less component loading and wear).
- ❑ Improve traction, mobility, and braking performance.

- ❑ Reduce tire wear and damage.
- ❑ Improve driver comfort and ergonomic condition.
- ❑ Extend hauling season, with hauling under weak, wet road conditions that normally cause shut down.
- ❑ Reduce sediment generated from the road surface.

Figure 3-58—Photos showing the advantages of reduced tire pressure to reduce rutting depth (photos from Maureen Kestler).

Though CTI currently is not used much in the United States for a variety of reasons, the benefits of reduced tire pressure and CTI are reasonably well known and appreciated, particularly in other countries. Today, CTI is used by the U.S. military and in logging and commercial trucking operations in Australia, Canada, Mexico, and Brazil. It is an underutilized technology.

The Forest Service produced several publications and videos on CTI. For additional information on CTI safety consult Fleming (1995). The publication provides technological advances to drivers with the ability to control vehicle tire pressure while in motion. CTI allows operators to match tire pressures to surface and loading conditions without delaying progress. Link to the document <http://www.fs.fed.us/eng/pubs/html/95511304/95511304.html>.

SDTDC staff developed a video (U.S. Department of Agriculture, Forest Service 1990b), which documents many tests that were used to prove the benefits of CTI. It shows the early prototype systems, the external air lines, and commercial technology employing internal air lines routing and microprocessor-driven dashboard display. Another publication developed by the SDTDC staff (U.S. Department of Agriculture, Forest Service 1990a) provides benefits on vehicle operating costs, savings on road surfacing and maintenance, and impacts on the environment. Link to the document <http://www.fs.fed.us/eng/pubs/pdfimage/fs_415.pdf>.

Ongoing research into CTI has been done by the Forest Engineering Research Institute of Canada including its publication “The Effects of Reduced Tire Inflation on Road Damage: A Literature Review” (Bradley 2003).

3.3.1.3. Rocking (Aggregate Surfacing)

Whether placing new aggregate, replacing aggregate that has worn off a road (surface replacement), or repairing a damaged section of road, one needs to select an aggregate with quality appropriate for the job. This requires consideration of the available materials, reliance on specifications, judgment as to what properties are critical, and some knowledge of materials and maintenance costs. The following sections discuss many of these properties and considerations.

Properties and Requirements for Aggregates

Aggregate is granular material of graded and/or crushed sand, gravel, or stone. It is used for surfacing secondary roads and collector-road systems, as well as a base course under pavements.

Also it is used as a material for stabilization of low-standard roads in local, soft soil areas. Aggregate materials are classified as either a quality crushed material or lower quality material, such as pit run, borrow, primary jaw, or coarse cone-crushed aggregate.

Material properties that influence aggregate performance (smoothness, strength, resistance to raveling, wet and dry stability, and skid resistance) are the particle size distribution and the chemical/physical properties of the coarse material. For surface course aggregate, the suggested gradation requirements are:

- ❑ For ease of grading and compaction and for the safety and comfort of traffic, 100 percent of the material should pass the 1-inch (25 mm) sieve. For erosion control on steep grades, a 2-inch minus (50 mm) aggregate is desirable.
- ❑ For resistance to raveling, the percentage of material retained on the No. 8 (2.36 mm) sieve should be between 20 and 60 percent.
- ❑ For stability and to reduce permeability, the fines-to-sand ratio should be between 0.20 and 0.60.
- ❑ For stability and to reduce raveling in dry climates, the plasticity index should be between 2 and 9.

Crushed Aggregate

Crushed aggregates are used for surfacing as well as base material, such as under pavements, where structural support is the primary function. Crushed aggregate used for base courses can be either well graded or open graded. Well-graded aggregate has the highest density and strength, and lowest permeability. Maximum strength for base course is typically achieved with 4 to 8 percent fines (minus No. 200 sieve (0.75 µm)). Some commonly specified base course aggregate gradations appropriate for forest roads are shown in table 3-17. Aggregate without plastic fines is preferred for structural support and strength. There are criteria for the quality requirements of the material, such as percent wear, durability, and plasticity.

As a surfacing material, crushed aggregate should have structural support, but it also needs to be very well graded and have some plastic binder to reduce ravel and washboarding. Maximum density is achieved with between 6 and 12 percent fines. Ideally, aggregate used for road surfacing materials or a wearing surface should have 10 to 15 percent fines and a plasticity index (PI) of 2 to 9. In a wet climate the PI requirement is less critical, and too many clay fines can contribute to local water quality degradation. In a wet region, the ideal PI range may be 0 to 5. In a dry, semiarid climate a PI range of 5 to 9 appears more desirable. Aggregate wear and durability requirements are shown in table 3-18. Figure 3-59 shows gravel road surfaces that are reasonably firm and performing well.

Table 3-17—Gradation requirements for base and surfacing aggregate (FP-03 Special Project Specifications, Section 703.05).

Sieve Size	FS B (Subbase)	FS C (Base)	FS D (Base)	FS F (Surface)	FS G (Surface)
2 ½ inch (63 mm)	-	-	-	-	-
2 inch (50 mm)	100	100	-	-	-
1 ½ inch (37.5 mm)	97-100			100	-
1 inch (25 mm)	-	80-100	100	97-100	100
¾ inch (19 mm)	-	64-94	86-100	76-89	97-100
½ inch (12.5 mm)	-	-		-	-
⅜ inch (9.5 mm)	-	40-69	51-82	56-68	70-80
No. 4 (4.75 mm)	40-60	31-54	36-64	43-53	51-63
No. 16 (1.18 mm)	-	-	-	23-32	28-39
No. 40 (425 µm)	-		12-26	15-23	19-27
No. 200 (75 µm)	4-12.0	4.0-7.0	4.0-7.0	10-16 (1)	10-16 (1)

Note: (1) Range for No. 200 Sieve is 6.0 to 12.0 ***if*** *the PI is greater than 0.*

Table 3-18—Aggregate wear and durability requirements.

Test Requirement	Base and Subbase	Surfacing
Los Angeles Abrasion, AASHTO T 96	40 % maximum	40 % maximum
Sodium Sulfate Soundness Loss, AASHTO T 104	12 % maximum	12 % maximum
Durability Index (coarse and fine), AASHTO T 210	35 minimum	35 minimum
Fractured Faces, ASTM D 5821	50 % minimum	75 % minimum
Liquid Limit, AASHTO T 89	25 maximum	35 maximum
Plastic Limit, AASHTO T 90	Nonplastic	2 to 9 (1) < 2 (2)

Note:

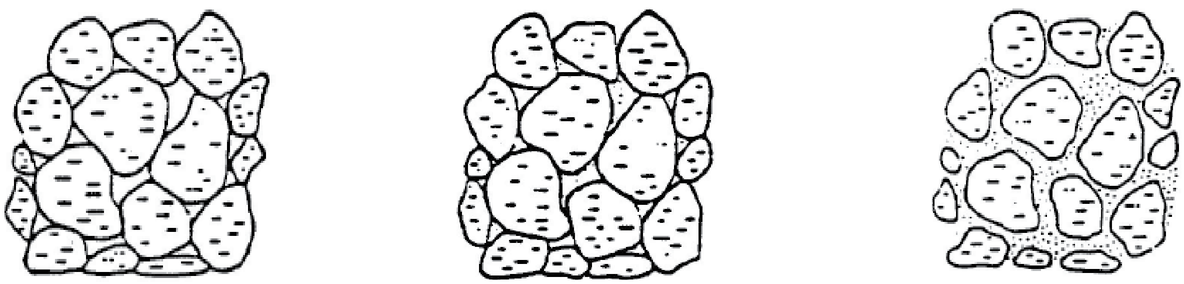
(1) If the percent passing the 75 µm sieve is less than 12 percent.

(2) If the percent passing the 75 µm sieve is greater than 12 percent.

Figure 3-59—Gravel road surfaces that are reasonably firm and performing well.

For collector and arterial roads, the materials used for surfacing would be smaller than 2 inches (50 mm), and often a 1-inch (25 mm) minus aggregate is specified. For low-standard roads, such as on most forest roads, the maximum aggregate size is smaller than 3 to 4 inches (75 to100 mm). Larger size aggregate, unless very well graded and angular, is very difficult to drive upon and maintain. Aggregate smaller than ½ inch (12 mm) loses structural support and becomes more erosive on the road surface. The crush stone with fractured faces versus rounded stone is stronger, less slippery, and interlocks better.

Some fines are needed to produce a dense aggregate mix, but fines beyond about 15 percent reduce the structural strength of the material. With material having more than approximately 25 percent fines, point-to-point contact of the rock particles is lost and the fines begin to control the strength of the aggregate. Figure 3-60 shows the relationship of aggregate with no fines, with an ideal amount of fines, and excessive fines. Each blend of materials has distinct physical characteristics. Either too little or too many fines are undesirable for road aggregates, particularly on the road surface.



Aggregate with no fines (0 fines)	Aggregate with sufficient fines for maximum density (8-15 percent fines)	Aggregate with high amount of fines (>25 percent fines)
❑ Grain-to-grain contact.	❑ Grain-to-grain contact with increased resistance against deformation.	❑ Grain-to-grain contact destroyed, aggregate “floating” in soil.
❑ Variable density.	❑ Increased to maximum density.	❑ Decreased density.
❑ Pervious.	❑ Low permeability.	❑ Low permeability.
❑ Nonfrost susceptible.	❑ Frost susceptible.	❑ Frost susceptible.
❑ High stability if confined, low if unconfined.	❑ Relatively high stability in confined or unconfined conditions.	❑ Low stability and low strength.
❑ Not affected by adverse water conditions.	❑ Not greatly affected by adverse water conditions.	❑ Greatly affected by adverse water conditions.
❑ Difficult to compact.	❑ Moderately difficult to compact.	❑ Not difficult to compact.
❑ Ravels easily.	❑ Good road performance.	❑ Dusts easily.

Figure 3-60—Physical state of soil-aggregate mixtures. Note that fines are soil passing the No. 200 sieve. (Reprinted with permission of John Wiley and Sons, Inc.) Adapted from Yoder and Witczak (1975), a Wiley-Interscience Publication.

An open-graded aggregate base material without any fines is desirable for good drainage but the material must be confined, such as under a pavement for drainage. It ravels significantly if used as a surface aggregate. Figure 3-61 graphically presents the requirements of road aggregate plotted as a range of gradation curves. Very coarse material ravels, but moderately coarse, well-graded material is ideal for base aggregate that is confined. Surface course aggregate needs to be somewhat finer to retain moisture and minimize raveling and have some plasticity. An aggregate rich in fines loses its strength, is moisture sensitive, and produces dust. Thus, base course aggregate and surface course aggregate each have their ideal gradation ranges. To have a well-graded aggregate, the desired gradation should be in the middle of the ranges shown and parallel to the curves.

Base course aggregate is often used as road surfacing material because it is the only aggregate available. This is not ideal, but realistic if only base course aggregate is available commercially. Custom crushing to produce a surface course aggregate can be very expensive, especially for a small quantity of material. However, with road use, the base course aggregate ravels and requires relatively high maintenance.

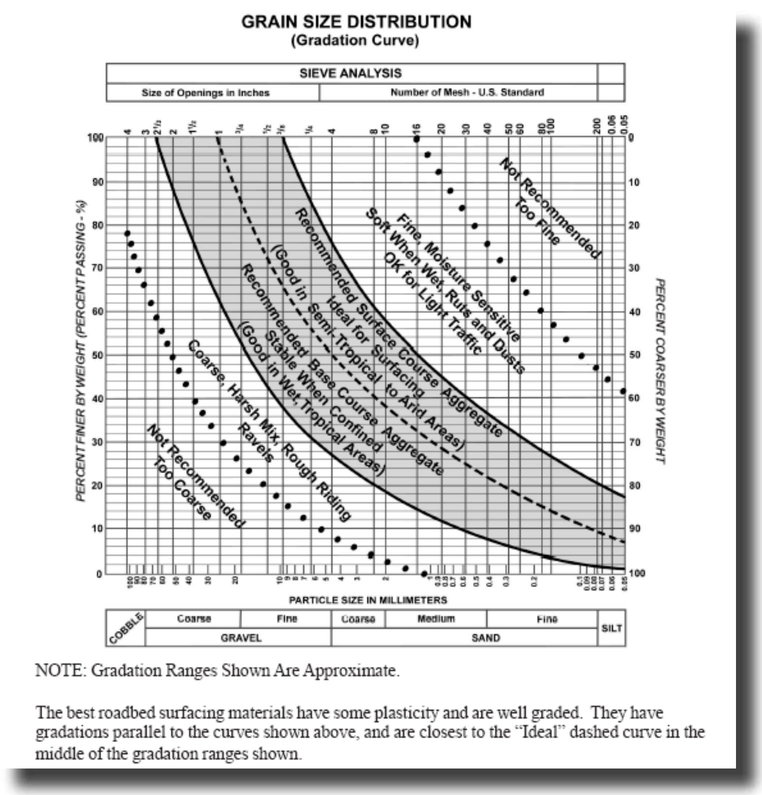


Figure 3-61—Ideal grain size distributions for surface course and base course aggregate (Keller and Sherar 2003).

Quality requirements are important to the service life of the aggregate, including its wear characteristics, durability, and plasticity. Aggregate wear, or abrasion resistance (Los Angeles Abrasion (Rattler) Test, AASHTO T-96), is particularly important to aggregate surfacing. Durability (Durability Index, AASHTO T-210) represents the aggregate's resistance to weathering and softening or disintegration with time. A fairly durable aggregate is desirable, so a specified durability index of 35 (minimum) is common. Plasticity is important, particularly in dry regions, to help bind the aggregate together, thus a PI (AASHTO T-90) of 2 to 9 is often specified.

An aggregate gradation that achieves the maximum density usually is the strongest and most desirable gradation. To achieve maximum density, the aggregate mix must be well graded and have a reasonable percentage of fines (figure 3-62). To help determine the maximum density gradation, the curve in figure 3-62 can be helpful. The straight base line is a theoretical maximum density grading line plotted for each gradation sieve size raised to the 0.45 power. The closer any given gradation can plot to this straight line, the denser the mix will be (U.S. Bureau of Public Roads 1962).

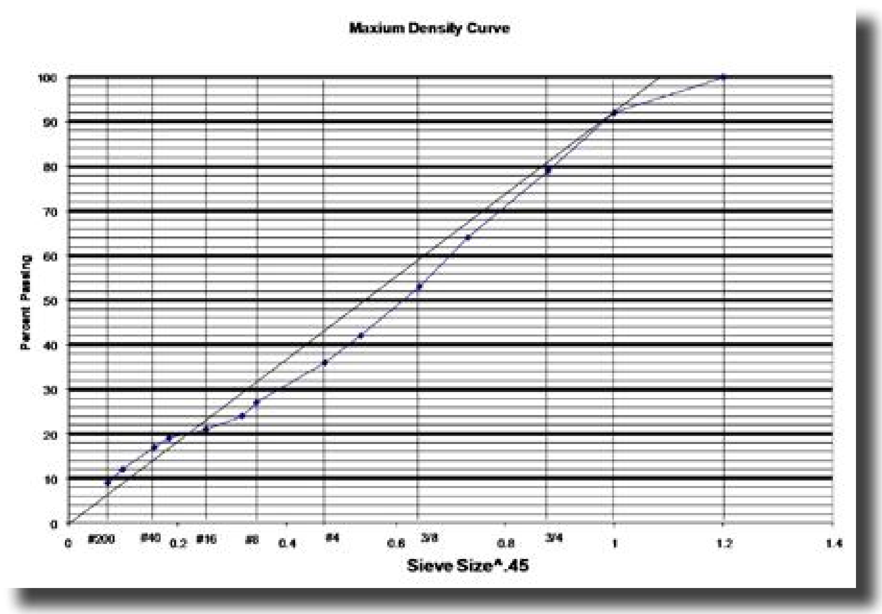


Figure 3-62—Maximum density curve.

Legere and Mercier (2004) discuss some specific surface course aggregate requirements for roads.

The U.S. Army Corp of Engineers publication by Freeman et al. (2006) discusses material requirements for aggregate surfacing materials (unbound aggregate) and compares the specifications of a number of different agencies, including the Forest Service. The publication is available at <http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA460698>.

For additional technical information and an overview on aggregates and gradation requirements, consult chapter 12, Roadway Materials, of the "Low-Volume Roads Engineering—Best Management Practices Field Guide" (Keller and Sherar 2003). The purpose of the manual is to present recommended best management practices for all aspects of low-volume roads engineering. Link to the Web site <http://www.fs.fed.us/global/topic/welcome.htm#8>.

Pit Run, Grid Roll, or Marginal Aggregates

Pit-run aggregate, grid roll, mobile rock crusher, or tractor-rolled aggregates are ways to produce aggregate at a relatively low cost. However, minimal processing usually results in a lower quality material, depending greatly on the characteristics of the original material used. A well-fractured, dirty rock source can produce a good roadway surfacing material or aggregate to fill in soft spots, particularly for a low-use road. A coarse soft rock may be broken down further under a grid roller or tractor, producing a finer, more desirable surfacing material. Figure 3-63 shows a soft volcanic rock being broken down under an Elliott Grid Roller.

Figure 3-63—A soft volcanic rock broken down under an Elliott Grid Roller.

Often it is appropriate and cost effective to use poor or marginal quality aggregate for low-volume roads. The tradeoff is usually a reduced construction cost but poorer performance and higher maintenance costs. Poor materials also may produce more sediment or dust, presenting greater environmental impacts. Thus the savings in initial production of the aggregate must be weighed against poorer performance and increased operation and maintenance costs. Poor materials should usually not be placed under a pavement considering the high cost of the pavement.

Cobbles or big stones without fines are suitable for a subbase material but make a poor surfacing material. If they are used on the roadway surface, traction and trafficability is difficult, particularly on steep grades; a rough driving surface results; maintenance of the road is difficult. A 3- to 4-inch (25 to 75 mm) maximum size aggregate is the largest size rock practical to drive on, and even this size may produce a very rough driving surface. Normally the maximum specified crushed aggregate size is 2 inches (50 mm). It can be very cost effective to screen a pit-run or river-run material to remove the coarse-size rocks. The resulting finer material, free of large rocks, is much smoother to drive on and easier to maintain.

Alternatively, roadway materials that contain a high percentage of coarse rock or boulders may be processed with a mobile rock crusher to breakdown the oversize rock to a manageable size, as seen in figure 3-64. In several test sections, the material produced from the mobile rock crusher was half the cost of a commercially available aggregate. However, quality was poor or variable, so maintenance costs were higher. Additional information on mobile rock crushing is found in Bassel and Clements (1998) and Bassel (1998). The publications are available at <http://www.fs.fed.us/eng/pubs/pdf/98771206.pdf> and <http://www.fs.fed.us/eng/pubs/pdf/98771205.pdf>.

Limited published information exists on the use of marginal materials on roads. Papers on the subject can be found in the Proceedings of the Transportation Research Board International Low-volume Roads Conferences. Two useful references that discuss the use of nonstandard and marginal materials for use in low-volume roads are McNally (1998) and Metcalf (1991). They are available for purchase at <https://commerce.metapress.com/content/nk556t8j4125q024/resource-secured/?target=fulltext.pdf&sid=jcm5nmmc2hekho55sp1ibdyp&sh=www.springerlink.com>.

Figure 3-64—A mobile rock crusher processing a windrow of roadway material with boulders (Note hardhat for scale).

Blending Materials

Two or more different materials with specific gradations can be mixed together or blended in certain specific percentages to produce a more desirable composite gradation. A coarse aggregate free of fines might be blended with a rocky soil with some plasticity to produce an aggregate with moderate fines; or river gravel could be blended with a sandy clay material to produce a more desirable roadway surfacing material with improved strength, abrasion resistance, and compactability. Blending ratios should be fairly simple since field mixing equipment is not very sophisticated. Also, do a trial mix to ensure that the mixture has the right characteristics or performs as expected.

Blending of two materials to improve the gradation to meet a specification can be determined by a graphical method. Figure 3-65 shows a blending chart used to mix two specific materials.

The percentages passing the various sieve sizes can be determined for the combined mixture. An example calculation of two materials (A and B) and the proposed specification limits are as follows:

Sieve size	Percent passing by weight		
	A	B	Specification
¾ inch (19 mm)	95	75	70 - 100
⅜ inch (9.5 mm)	83	45	50 - 80
No. 4 (4.75 mm)	75	26	35 - 65
No. 10 (2.0 mm)	64	15	20 - 50
No. 40 (425 μm)	52	5	15 - 30
No. 200 (75 μm)	30	2	5 - 15

Plot the percentage passing each sieve for materials A and B on the left and right vertical scales of figure 3-65, and draw a line between them for each sieve size. Plot the specification limits on each line for each sieve size, using the vertical scale, as shown with small circles. Notice than the ¾-inch line does not have any circles since the entire line lies within the 70-100 percent passing limits. Use the circles to determine the maximum and minimum limits of the combination percentages of the two materials. The critical sieve sizes appear to be the No. 40 on the right side and the No. 200 on the left, as indicated by the two vertical dash lines.

Thus, the combined percentages of each soil, as shown on the upper and lower horizontal scales, lie between A = 47 percent to 22 percent, and B = 53 percent to 78 percent. Any combination outside these limits would not meet the specifications. If we use 40 percent of A and 60 percent of B, which lie between these limits, then the combined passing percentage for each sieve size would be as indicated by the vertical heavy solid line between A = 40 percent, B = 60 percent on the graph. Reading across horizontally to the left side Gradation scale, approximately ¾ inch = 83 percent, ⅜ inch = 60 percent, No. 4 = 46 percent, No. 10 = 35 percent, No. 40 = 24 percent, and No. 200 = 13 percent. This can also be checked from the original data:

¾ inch	= 95 x .40 + 75 x .60	= 83.0%	= 83%
⅜ inch	= 83 x .40 + 45 x .60	= 60.2%	= 60%
No. 4	= 75 x .40 + 26 x .60	= 45.6%	= 46%
No. 10	= 64 x .40 + 15 x .60	= 34.6%	= 35%
No. 40	= 52 x .40 + 5 x .60	= 23.8%	= 24%
No. 200	= 30 x .40 + 2 x .60	= 13.2%	= 13%

A thorough discussion of blending procedures, including examples of blending with two and three materials, is presented in Giummarra (2009).

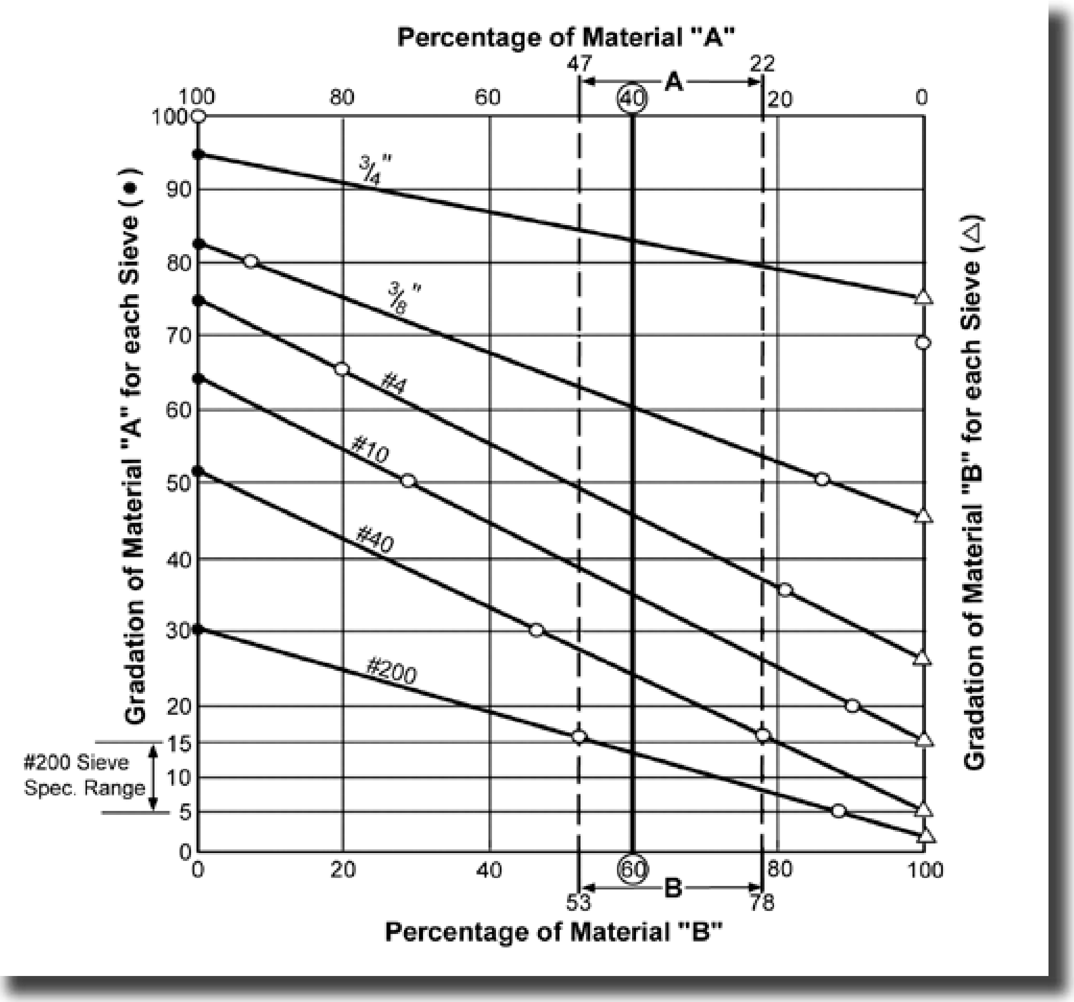


Figure 3-65—Graphical blending chart.

Unbound Aggregate Surfacing Use and Design

This section addresses how to combine knowledge of the materials characteristics with traffic information to ensure that the proper amount of aggregate surfacing is placed to minimize surface deformation.

As previously mentioned, the primary purpose of roadway surfacing is to support the traffic and minimize the amount of deformation in the roadway surface. Many natural soils are not strong enough to support traffic without excessive surface deformation and high vehicle operating costs. For this reason, a structural section is placed over the native materials to help distribute the load and provide a longer lasting surface that does not rut. Aggregate surfacing also is placed upon native soil surfaced roads to reduce dust and to control surface erosion. Many road repair and rehabilitation projects involve the application of aggregate on a road. Unbound aggregate is the most common type of improved surfacing on low-volume roads, mainly because it is the least costly alternative for road improvement. High traffic use roads are good candidates for other surfacing alternatives such as BST or pavements.

Use of poor quality aggregate, pit-run material, soil stabilization measures, or surface mulching should be considered, as discussed earlier. However, less expensive materials often are limited in volume and have hidden costs that must be evaluated, including higher exploration costs, higher maintenance costs, unknown performance, more road user discomfort, and other risks. As a result of these considerations, aggregate is the most commonly used forest road surfacing material. Also the technique of "spot rocking" is often used on low traffic volume roads where only poor, soft soil areas receive aggregate, or receive the most aggregate. Typically, aggregate depths are minimal (about 4 inches [100 mm]), and a soft area may receive subsequent applications of aggregate through road maintenance as the road deforms. Thus, in variable soil areas, the worst sections of road are stabilized.

There are many reasons to surface or resurface a roadway. These include and are not limited to the following:

- ❑ Repairing sections of damaged roads.
- ❑ Replacing aggregate lost through surface wear and time.
- ❑ Improving the structural capacity of the road.
- ❑ Improving the ride and comfort of the user.
- ❑ Reducing short-term maintenance and repair costs.
- ❑ Providing a long-term cost effective running surface.
- ❑ Minimizing the amount of sediment coming off the road surface.

Figure 3-66 outlines a flowchart that practitioners can follow to help determine if surfacing is needed to prevent excessive surface deformation (rutting) or to prevent resource damage from sedimentation. Typically, higher standard roads receive an aggregate surface course or some other improved surfacing. If road use is minimal, or if the road can be closed when wet, and if resource damage is minimal, then the road may be adequate with only a dust palliative or minor maintenance. Less expensive surfacing materials should always be considered as an alternative whenever possible, particularly on low traffic volume roads.

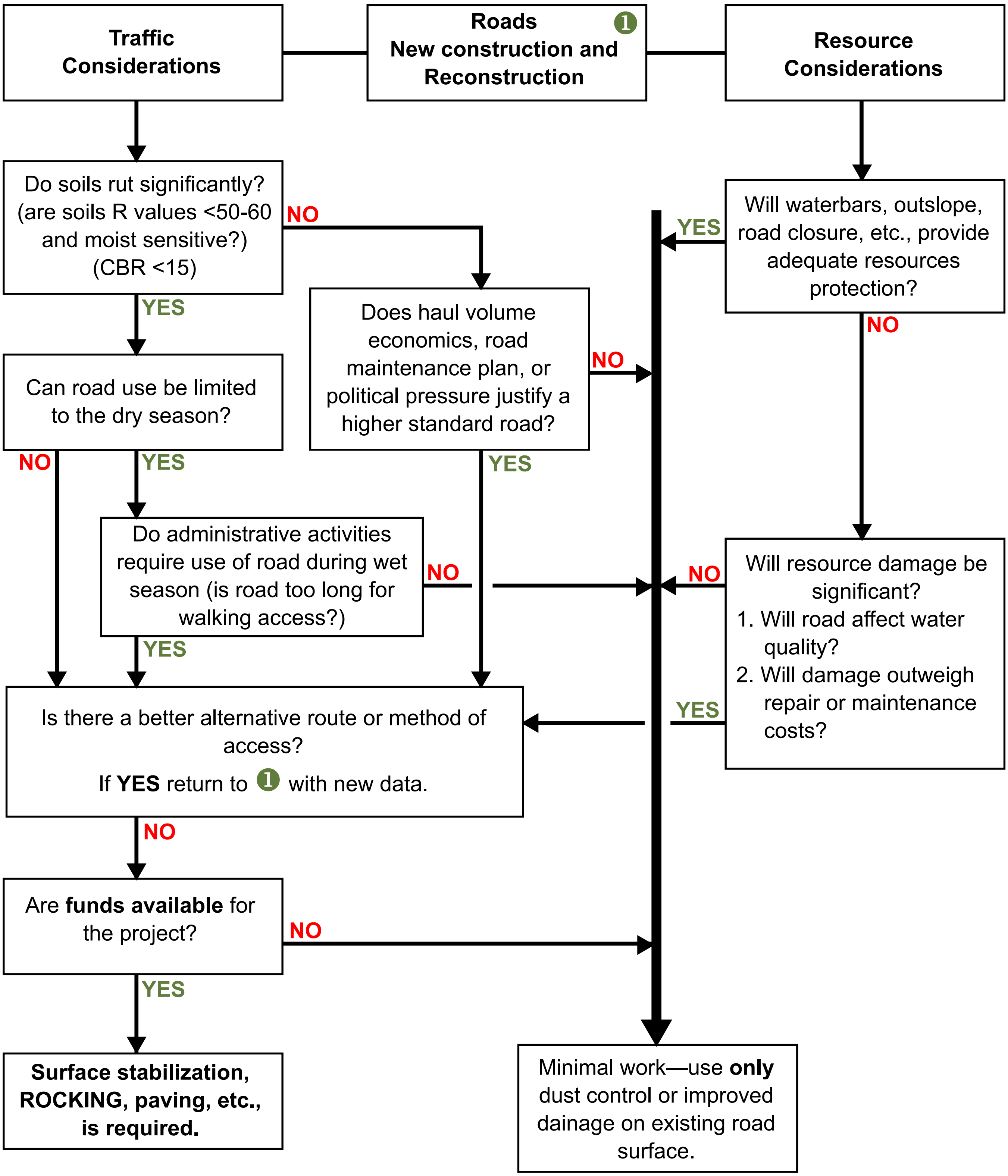


Figure 3-66—Flowchart for the logic of traffic and resource considerations for adding surface stabilization or aggregate on low-volume roads.

Surface deformation by traffic can take various forms. The primary surface deformation created by traffic is rutting in the wheel tracks. Rutting is the downward movement of the surface material with possible lateral or side heaving. The rutting takes place in either the surfacing material or in combination with the underlying subgrade material as shown in figure 3-67. An adequate thickness of aggregate eliminates rutting for a given traffic volume and soil. Thinner aggregate reduces, but does not prevent deformation, and it will fail with enough traffic.

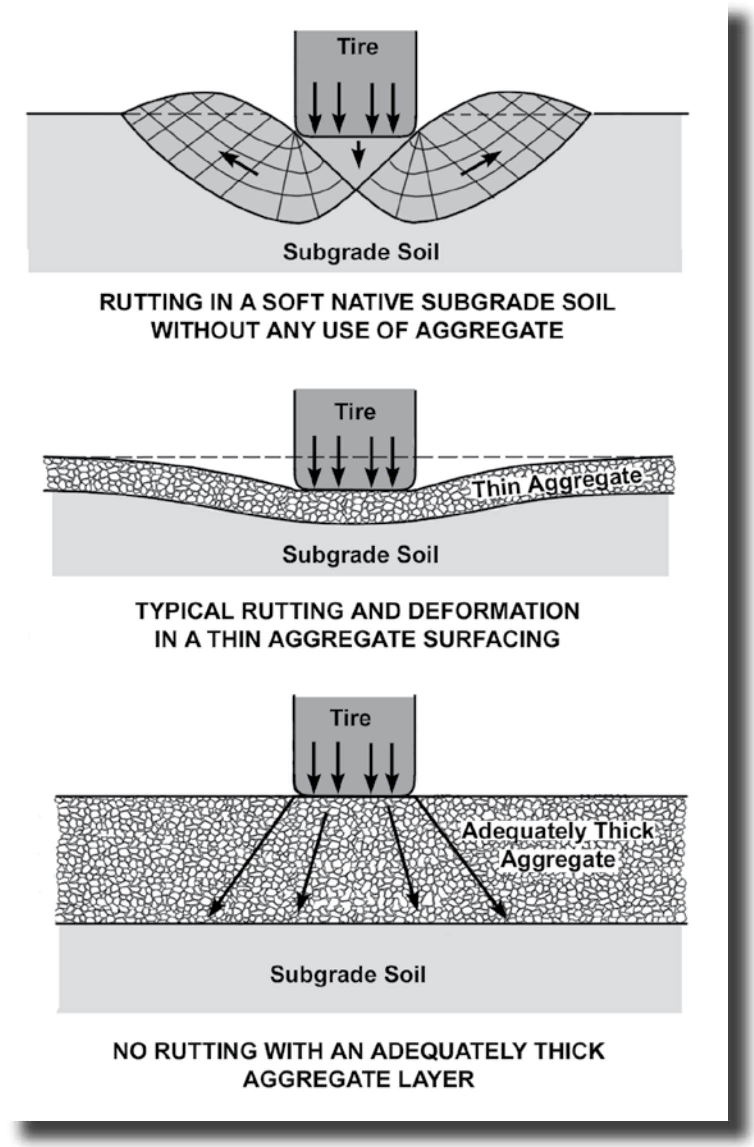


Figure 3-67—Rutting deformation in an aggregate surfaced road due to weak subgrade soil and inadequate aggregate depth (Courtesy of Pete Bolander).

Various methods are used to determine the proper amount of surfacing to prevent surface deformation. The Forest Service often uses the design algorithm developed by the U.S. Army Corps of Engineers in 1978. Today a rigorous mechanistic design approach can be used, but empirical methods are most often used on low-volume roads because they are easier. The philosophy of this surfacing design is to obtain a surface course thickness sufficient to provide acceptable performance for the expected traffic over a particular length of time. Several factors must be considered in the thickness design for aggregate-surfaced and earth roads, including:

- Subgrade strength.
- Traffic (vehicle weight and number of passes).
- Surface characteristics (gradation and quality).
- Weather (wet season versus dry season use).

Subgrade and Surface Aggregate Strength

The soil type and strength of the surface layer is an important factor in determining the aggregate thickness required. Initially, subgrade soil may be categorized into one of the following types:

- Granular soils (best for road subgrade).
- Fine-grained (or plastic) soils (variable quality for road subgrades).
- Organic soils (poor for road subgrades).

Generally, the higher the strength of the subgrade, the less surfacing is required. Subgrade strength is usually expressed in terms of CBR, though occasionally other values, such as the California R-Value are used. An excellent subgrade can have a CBR approaching 80, while that of a very poor subgrade can be 2 or less. There are a number of ways to estimate CBR values based on simple field tests or laboratory testing. Ideally soil samples are taken and the CBR test is run in a laboratory on specimens compacted to the anticipated design density. Field in-place CBR tests also can be run. The designer also may refer to CBR information from past projects in the area. When other information is not available, CBR values given in engineering tables may be used for varying soil types.

An easy and portable field tool used to determine in-place CBRs is the dynamic cone penetrometer (DCP). Figure 3-68 shows a typical correlation curve for CBR versus DCP values, expressed as blows per 100 mm of penetration, from a portable DCP drive probe. Information on use of the DCP can be found in appendix 6.4 of Bolander et al. (1996).

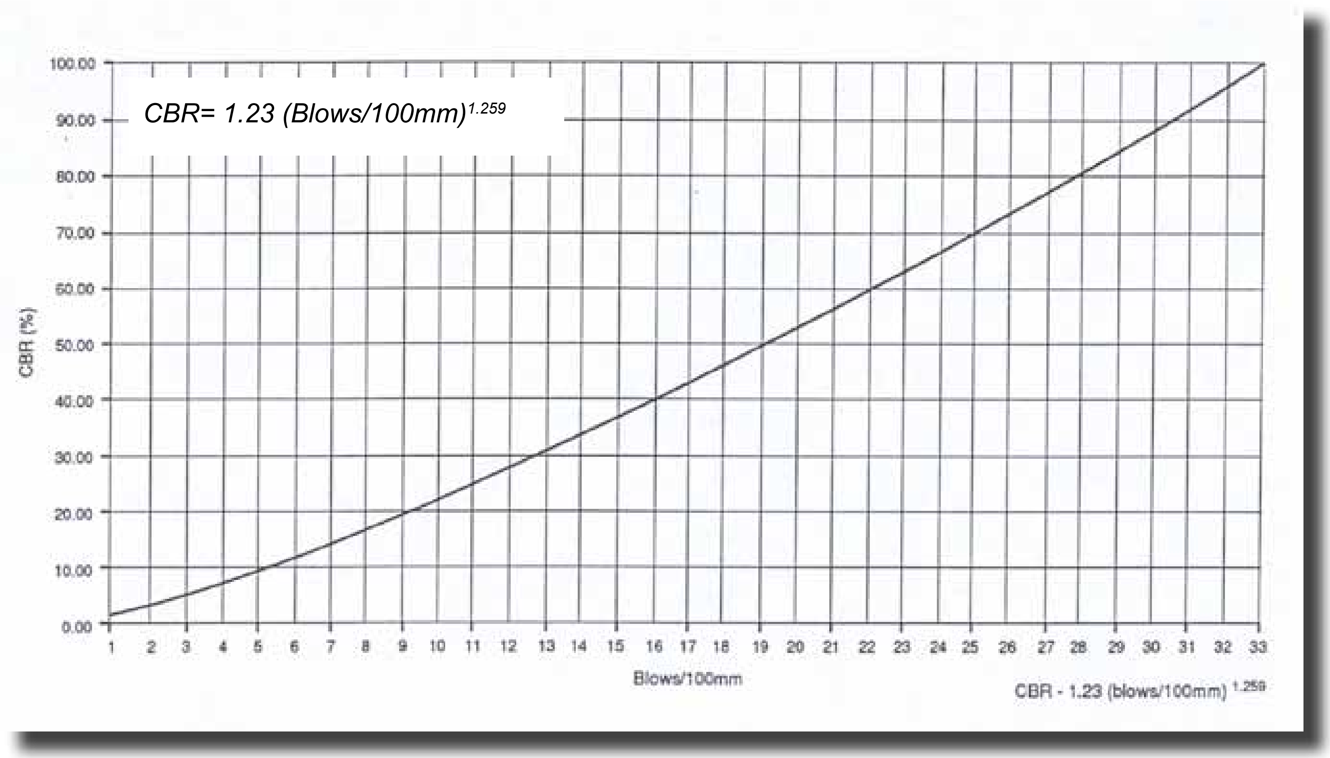


Figure 3-68—A correlation curve for in-place CBR versus DCP value from a portable DCP drive probe.

CBR values generally vary in a predictable manner with compaction or density for given soils. Generally speaking, the strength increases as the gradation becomes well graded, as the quality of the material increases, and as the density of the material increases. Table 3-19 provides guidelines for choosing a design CBR value for specific soil types, by the Unified Soil Classification System (USCS). This table provides typical CBR values for well-graded and poorly graded granular aggregate for various compaction levels. High quality aggregate is assumed to have a high strength (high CBR value, typically CBR > 50).

Table 3-19—CBR values for various USCS soil classifications (these values may be from laboratory or in-place field test).

USCS Classification	CBR Range (for % of T-99 Standard Proctor Maximum Density)			
Cohesive	**85% Maximum**	**90% Maximum**	**95% Maximum**	**100% Maximum**
GM_u	2.5-4	5-8	10-16	20-32
SM_u	1.0-2.5	2-5	4-10	8-20
ML	0.5-2.0	1-4	2-8	4-16
CL	0.5-2.0	1-4	2-8	4-16
OL	0.3-0.6	0.6-1.2	1.2-2.4	2.4-4.8
MH	0.5-2.0	1-4	2-8	4-16
CH	0.5-2.0	1-4	2-8	4-16
OH	0.3-0.6	0.6-1.2	1.2-2.4	2.4-4.8
Granular				
GW	17-33	22-43	29-56	37-73
GP	13-25	17-33	22-42	29-55
SP	4-17	5-22	7-29	9-37
Intermediate				
GM	8-12	14-20	23-35	39-59
GC	4-8	7-14	12-23	20-39
SM	3-8	5-14	9-23	15-39
SC	1-4	2-7	3-12	5-20

Note that maximum refers to maximum density that can be obtained at the optimum moisture content for that particular soil.

Traffic

The other important factor to be evaluated in the structural design of any roadway is the effect of loads as transmitted by vehicles (traffic). The vehicle type, volume, and mode of operation all affect the road design. Most design procedures employed in the United States classify traffic by the 18-kip (equivalent single-axle load [ESAL]). A kip is 1,000 pounds (454 kg). The ESAL depends on vehicle weight, tire and axle loads, configuration, and tire pressures. Tables to determine the number of ESALs as a function of vehicle type can be found in Bolander et al. (1996). The ESAL calculations for a typical 18-ton (80,000 pounds) gross vehicle weight (GVW) 18-wheel truck have been calculated and are shown in table 3-20 for different values of tire pressure.

Table 3-20—Typical 18-ton (80,000 pounds) GVW 18 wheel truck ESALs.

Tire Pressure, psi (kPa)	ESAL per vehicle (1)
70 (485)	2.33
80 (550)	3.17
90 (620)	4.30
100 (690)	5.30
110 (760)	6.57

Note (1): Assume 18-ton (80,000 pounds) GVW, 18 wheels (one axle single axle with single wheels at 2.25 tons, all others double wheels as two sets of tandem axles at 7.88-ton per tandem), and one pass of vehicle.

Aggregate Thickness Design Graph

Figure 3-69 presents a graph for the relatively simple determination of aggregate thickness needed on low-volume roads as a function of aggregate type (low or high quality), CBR, and ESALs. This procedure assumes a maximum rutting depth of 2 inches (50 mm) and is based upon U.S. Army Corps of Engineers test track data. As can be seen for most low-traffic volume roads, the needed aggregate thickness is in the range of 4 to 8 inches (100-200 mm). At high-traffic volumes and with poor soils, the needed aggregate thickness may vary from 12 to 24 inches (300 to 600 mm). At increased traffic volumes and thick aggregate depths, an improved surface such as paving can become cost effective.

The design procedure used to develop this chart, the algorithm details, and a companion program with user's manual, are found in the Forest Service publication "Earth and Aggregate Surfacing Design Guide for Low-Volume Roads" (Bolander et al. 1996). This publication contains information regarding aggregate surfacing design. It is available on the Association of Environmental and Engineering Geologist, Geoscience Library Web site under Section 5, Transportation Geology, Low-Volume Roads Collection, Roadway Materials and Sources Development (To access this site, one must initially register with them at <http://www.geoscilibrary.org)>.

Additional information on other aggregate thickness design procedures is found in Skorseth and Selim (2000). Link to the manual <http://www.t2.unh.edu/nltapa/Pubs/south_dakota_gravel_manual.pdf>.

Another publication with aggregate thickness design information and performance is Giummarra (2009). Link to the ARRB Web site <https://arrb.qnetau.com/documents/pubs/USRM%20flyer31Mar09_Lres.pdf>.

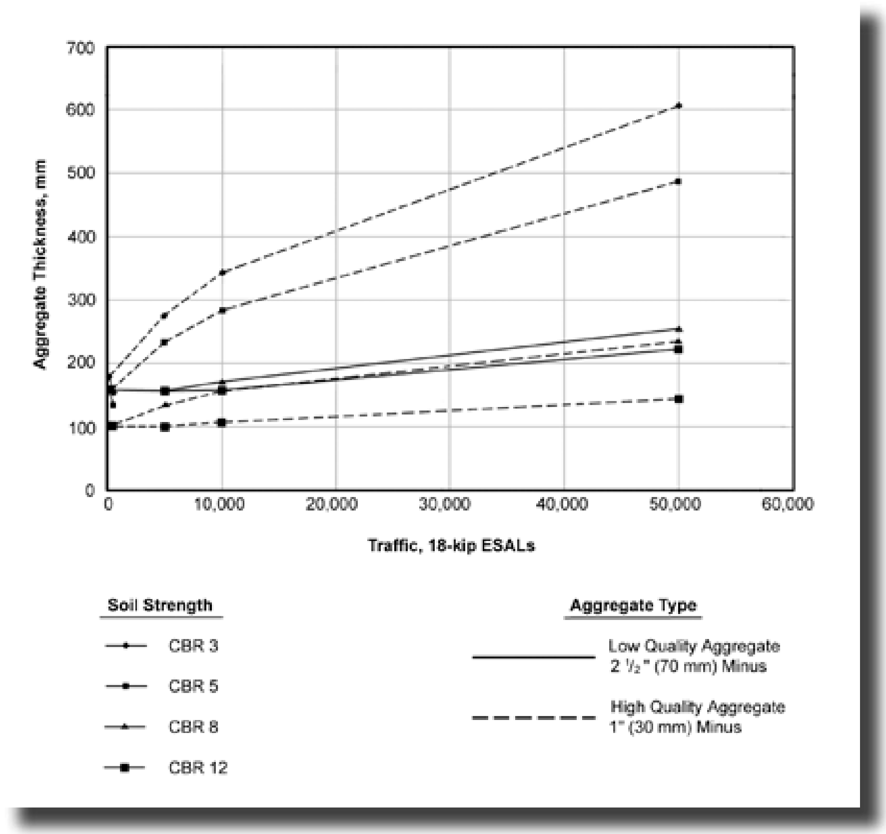


Figure 3-69—Aggregate surface design graph (Bolander et al., 1996).

3.3.1.4. In-Place Stabilization

Soil stabilizers can be used to treat the upper several inches of soil or aggregate surfaces of low-volume roads when the strength or other properties of the in-place soil do not meet the desired or required levels for anticipated traffic. Improving in-place soil offers an economical alternative to aggregate surfacing where aggregate is not available or it is excessively expensive. Soil can be modified or stabilized by many methods including chemical, mechanical, thermal, and electrical treatments. Modification is generally short term and includes benefits, such as improvement in workability (expediting construction and saving time and money). Stabilization generally results in a longer term strength gain. While stabilization improves the strength characteristics of the soil, often some sort of additional wearing surface course is still needed on the road.

Chemical stabilization is achieved by mixing chemicals, such as cement, lime, fly ash, bitumen, or combinations of these materials, with soil to form a stronger composite material. Selection of the type and percentage of additive is a function of the soil classification and the degree of improvement desired. Chemicals and/or emulsions can be used as:

- Compaction aids to soils.
- Binders and water repellents.
- Modifiers for clay to form a stronger composite material.

Chemical stabilization can aid in:

- Dust control.
- Water-erosion control.
- Fixation and leaching control.

Traditional Chemical Stabilizers

Traditional chemical techniques include:

- Cement (generally used as a base-course treatment and not as a surface treatment, but included because it is one of the standard traditional stabilizers).
- Lime.
- Fly ash.
- Bituminous materials.
- Combinations of the above.

Nontraditional Stabilizers

Nontraditional stabilizers are typically grouped into seven categories:

- Chlorides (chlorides, salts, calcium chloride, magnesium chloride, sodium chloride).
- Clay additives (clay additives, clay, filler, bentonite, montmorillonite).
- Electrolyte emulsions (electrolyte stabilizers, ionic stabilizers, electrochemical stabilizers, acids).
- Enzymatic emulsions (enzymatic emulsions, enzymes).
- Lignosulfonates (lignosulfonates, lignin, lignin sulfate, lignin sulfides).
- Synthetic-polymer emulsions (synthetic-polymer emulsions, polyvinyl acetate, vinyl acrylic).
- Tree-resin emulsions (tree-resin emulsions, tall-oil emulsions, pine-tar emulsions).

Mechanical modification/stabilization involves:

- Mixing (two or more soils to obtain a material of desired specification).
- Draining the soil.
- Compacting soil.
- Using reinforcing materials, such as geosynthetics/geocomposites/fibers that can be mixed in or physically placed with the geomaterial to improve strength.

Thermal stabilization involves heating or freezing soil.

- Heating the soil to 600 °C can irreversibly dehydrate or fuse soil particles.
- Freezing can strengthen the soil by solidifying water content.

Electrical stabilization involves applying a direct electrical current to the soil. This causes water to migrate out of the soil to an electrode.

For additional technical information about in-place stabilization consult the "Stabilization Selection Guide for Aggregate and Native-Surfaced Low-Volume Roads" (Kestler 2009). The guide provides information on available stabilizing agents, appropriate conditions for use, selection procedures, quantity determination, and contact information for manufacturers/suppliers. The guide focuses primarily on chemical and mechanical methods. Link to the document <http://www.fs.fed.us/eng/pubs/pdf/08771805.pdf>.

Monlux and Mitchell (2006) provide Federal, State, county and local road managers additional technical information on the performance and cost effectiveness of road mixing high applications of calcium and magnesium chloride, applied in a one-time construction process. Stabilization provides a much higher standard of road surface performance by improving ride quality and reducing dust, washboarding, and raveling. Link to the document <http://www.fs.fed.us/eng/pubs/pdf/06771805.pdf>.

3.3.1.5. Wood Aggregates, Chips, and Chunkwood for Road Stabilization

Consider relatively inexpensive materials whenever possible for road surfacing materials, particularly on low-standard roads. Using materials such as wood chips, chunkwood, or engineered road wood fiber may be cost effective. Wood chips are occasionally used as a lightweight road surfacing to cross a potentially unstable or wet area to minimize the weight of the fill. Wood particles ranging in size from chips to chunks (fist size and larger) have been used as a fill material for crossing soft soils or as a road surfacing and stabilization material.

Several advantages of using wood aggregate include:

- Wood is relatively abundant and can be less expensive than gravel.
- Low-grade unmerchantable wood that is normally left in the woods can be used. Low-grade wood can be easy and inexpensive to obtain in areas where no gravel deposits exist.
- Wood naturally biodegrades over time, so its application is realistic for temporary or short-term road use. Wood aggregate is not considered reusable.
- Wood insulates the ground, allowing hauling on frozen wood roadbeds to extend into the spring.
- Wood is a lightweight fill material.
- Wood interlocks to form a very strong roadbed suitable for crossing on very weak and wet roads. The interlocking prevents localized soil disturbance and soil compaction.

Disadvantages of wood include:

- Susceptible to fire.
- Short lifespan due to rot.
- Increased occurrence of saturated subgrades beneath the chips.

Wood aggregates like chunkwood and wood chips (figure 3-70) could be problematic if used near running water because of leachates produced as the wood deteriorates. Leachates can become an environmental pollutant if they enter a ditch, stream, or waterway. Some wood, such as aspen bark and hemlock tend to produce considerable leachates. Pine does not produce much leachate. Further investigation into use of wood aggregate is needed.

Chunkwood describes wood fragments produced from trees or logging residues by a wood chunking machine. Chunkwood was originally produced as an efficiently sized material for use as fuel, raw material for flakeboard, and pulp. Chunkwood-fragment size varies widely with typical maximum-size chunks about the size of a person's fist. This results in good particle interlock to form a relatively stable matrix, and the material has a high friction angle. Chunkwood weighs about one-fifth that of gravel and is an excellent lightweight fill material. Preferably, the chips are 2 to 4 inches (50 to 100 mm) in size, or graded from ½ to 4 inches (12 to 100 mm), and placed on top of the road in a layer approximately 6 inches (150 mm) thick (or thicker, if necessary in soft areas).

Figure 3-70—Wood aggregate (chunkwood) being used for temporary stabilization of a road surface over a soft, wet area.

Sawdust tends to break down under traffic loading. When sawdust is used in a section, deep ruts tend to occur. Planer chips do not compact very well; bark fibers tend to form a well-compacted layer. Wood aggregate products seem to perform best when placed in a good mixture of sawdust, planer chips, and bark fibers. Use wood aggregate with or without a geotextile underneath.

For additional information about chunkwood roads, see Karsky (1993). Another publication, Arola et al. (1991), has considerable information on chunkwood production, properties, use, and applications for forest roads. It can be accessed at <http://nrs.fs.fed.us/pubs/gtr/gtr_nc145.pdf>.

Today, Canada uses engineered road wood fiber. These shredded wood-fiber stabilized roads are strong, durable, and ecologically friendly. The material can be placed over rootwads and stumps to minimize site disturbance. Access information regarding engineered road wood fiber at <http://www.ecoroads.ca>.

3.3.2. Dust Prevention and Use of Dust Palliatives

Dust palliatives are the agents applied to various road surfaces to prevent dust clouds and their environmental impact. Most dust palliatives are spread directly on the road surface. They may be sprayed on as a liquid, spread as a powder, or mixed into the road surface 1 to 2 inches (25 to 50 mm) deep. Preparation can be minor but the road should be graded, properly shaped, and left with a thin loose surface prior to application of the palliative. Proper application involves a uniform cover of material, good penetration, a proper percentage of the desired solids, and final compaction of the surface. Depending upon road usage and weather conditions, a maintenance plan with subsequent applications is recommended.

How can dust emissions from the roadway be reduced or eliminated? Since fines act as a binder that holds the surface of the unpaved road together, retaining the fines is important. Sometimes clay can be added to the road surface material to maintain a tight surface, particularly if damp. An alternative is to apply a dust suppressant product. These products are not permanent and require further applications as the product's effectiveness decreases over time. Dust suppressants, or dust palliatives, work by either agglomerating the fine particles together (adhering/binding the surface particles together) or increasing the density of the road surface material. They reduce the ability of the surface particles to be lifted and suspended by either vehicle tires or wind. Figure 3-71 shows an application of a dust palliative on a forest road. Most dust palliatives are sprayed on the road surface as a liquid. Additional penetration and life may be gained by blading the products into the surface (figure 3-72) or by spraying the palliative into a windrow and then blading the windrow back onto the road surface, but these techniques typically require a higher application rate.

Products that are water soluble often need a reapplication after winter or after it rains. Some products produce a hard crust that is difficult to maintain and rework. Also the cost of products varies widely. Thus each product must be evaluated for its cost, application needs, and effectiveness.

To properly select the appropriate palliative one must understand the primary factors that generate dust. They include:

- ❑ Vehicle speed.
- ❑ Number of wheels per vehicle.
- ❑ Number of vehicles.
- ❑ Vehicle weight.
- ❑ Particle size distribution (gradation) of the surface material and plasticity index.
- ❑ Restraint of the surface fines (compaction cohesiveness/ bonding, durability).
- ❑ Surface moisture (humidity, amount of precipitation, amount of evaporation).

Figure 3-71—A calcium chloride dust palliative applied to a logging road.

Figure 3-72—A dust palliative application being blade-mixed into a road surface.

An excellent description of these factors that generate dust and how to analyze total long-term costs can be found in Foley et al. (1996) and UMA Engineering (1987). Selection of the proper dust abatement program must include an understanding of not only the above factors, but the total long-term costs and environmental impacts of that program. Long-term costs include road improvement, road preparation, application of the suppressant in conjunction with the number of times the palliative needs to be applied, and expected change in maintenance practices. A good dust abatement program reduces maintenance needs and decreases aggregate loss.

Environmental impacts include impacts to water quality, aquatic habitat, and the local plant community. Currently, considerable interest and research is directed towards better determining the environmental impacts of dust palliatives, particularly the nontraditional products on the market. Products should have a material safety data sheet and they should be applied in accordance with the manufacturer's recommendations. They should not be applied when there is a forecast for rain, or in a manner that allows the material to directly reach a water course.

Important benefiting factors (Langdon 1980) of dust palliatives that should be considered when evaluating and selecting the proper dust palliative include:

- ❑ Cohering the dust particles to themselves or to larger particles.
- ❑ Resisting wear by traffic.
- ❑ Remaining life on the road.
- ❑ Resisting aging.

Based on the above characteristics, the product selection chart shown in table 3-21 should aid in selecting the most suitable dust palliative (Foley et al.1996; UMA Engineering 1987; Bolander et al. 1997; Bolander 1999; Scholen 1992; Langdon 1980; Han 1992). When using this selection chart, first perform a soils analysis to classify the surface material. Some palliatives require a clay component or specific amount of fines to properly bind and/or agglomerate the material.

Table 3-21—Product selection chart (Bolander and Yamada 1999).

Dust Palliative	Traffic Volumes, Average Daily Traffic			Surface Material								Climate During Traffic		
				Plasticity Index				Fines (Passing 75 ③m, No.200, Sieve)						
	Light <100	Medium 100 to 250	Heavy >250 (1)	<3	3-8	>8	<5	5-10	10-20	20-30	>30	Wet &/or Rainy	Damp to Dry	Dry (2)
Calcium Chloride	A	A	B	C	B	A	C	B	A	B	C (3)	C (3,4)	A	C
Magnesium Chloride	A	A	B	C	B	A	C	B	A	B	C (3)	C (3,4)	A	B
Petroleum	B	B	B	A	B	C	B (5)	B	B (6)	C	C	B (3)	A	B
Lignin	A	A	B	C	B	A (6)	C	B	A	A	B (3,6)	C (4)	A	A
Tall Oil	A	B	C	A	B	C	C	B	A (6)	B (6)	C	B	A	A
Vegetable Oils	B	C	C	B	B	B	C	B	B	C	C	C	B	B
Electro-Chemical	A	B	B	C	B	A	C	B	A	A	A	B (3,4)	B	B
Synthetic Polymers	A	B	C	A	B	C	C	A	A (6)	C	C	B	A	A
Clay Additives (6)	A	B	C	A	A	B	A	B	B	C	C	C (3)	B	A

Legend: A = Good Performance B = Fair C = Poor Results

Notes:

(1) May require higher or more frequent application rates, especially with high truck volumes.

(2) Greater than 20 days with less than 40 percent relative humidity.

(3) May become slippery in wet weather.

(4) May leach out in heavy rain.

(5) SS-1 or CSS-1 with only clean, open-graded aggregate

(6) Road mix for best results.

For additional technical information about dust palliatives consult the "Dust Palliative Selection and Application Guide" Bolander and Yamada (1999). The publication helps practitioners understand and correctly choose and apply the dust palliative that is appropriate for their particular site, traffic conditions, and climate. In addition, this publication describes the expected performance, limitations, and potential environmental impacts of various palliatives. Link to the document <http://www.fs.fed.us/eng/pubs/pdf/99771207.pdf>.

Bolander (1997) discusses chemicals that serve as dust suppressants and stabilizers, but does not discuss chemicals that are used exclusively for dust control. Dust control is a side benefit of many of the stabilization techniques described. Link to the document <http://trb.metapress.com/content/v15402pu73460176/fulltext.pdf>.

For additional technical information about dust control monitoring, consult Taylor et al. (1987). The report describes the development, testing, and function of a prototypes design for a road dust monitor (an instrument intended to provide quantitative and reproducible measurements of road dustiness). Several recommendations are made in the report for refinement in design and instrumentation.

3.3.3. Frost Heave and Freeze Thaw Solution

Potential rehabilitation methods to reduce the impacts from frost heave and freeze-thaw problems include the following:

A. New or reconstruction techniques:

- ❑ Method 1- Use thick nonfrost susceptible fills, or, for localized bad spots, remove the frost susceptible materials and replace with nonfrost susceptible material.
- ❑ Method 2- Reconstruct an insulated road/pavement; for example, incorporate a layer of extruded polystyrene, or insulating material between the subgrade and base. This prevents frost from reaching frost susceptible subgrade, and consequently the subgrade does not undergo subsequent thaw-weakening when spring thaw comes. This requires a simple design procedure.
- ❑ Method 3- Use geosynthetics. Reconstruct using better drainage or incorporating a capillary barrier using a geosynthetic. Again, proper design is required.

B. Usage technique

- ❑ Method 4- Utilize spring load restriction practices.

Although relatively simple, method 1 is used mainly for high-volume roads/highways. Method 2 occasionally is more cost effective than method 1 (when there is a very long haul to get nonfrost-susceptible material). Method 3 generally requires excavating substantial material and essentially rebuilding the road. Alternately, damage to low-volume roads in seasonal frost areas can be kept to a minimum by implementing seasonal load restrictions, method 4.

Thaw Weakening and Spring Load Restriction

Interstates are constructed to withstand truck traffic during springtime. However, low-volume roads in seasonal frost areas are highly susceptible to damage from trucking during thaw-weakened periods (because it is not cost effective to design roads to withstand trucking year round). Placing and enforcing spring load restrictions keeps damage to a minimum if heavy loads are either limited or prohibited during damage susceptible spring thaw periods. Knowing when to place or remove load restrictions requires monitoring local conditions and varies from season to season.

In cooperation with other partnering agencies, the Forest Service has been evaluating several techniques for determining when to place and remove spring load restrictions. Four methods that appear promising include: (1) subsurface instrumentation for temperature and moisture, (2) portable or lightweight falling weight deflectometers, (3) the thaw index, and (4) the thaw predictor climatic model, which is a modification of the enhanced integrated climatic model. Technology and development efforts in each of these areas are completed for (1), nearing completion for (2) and (3), and currently underway for (4).

Additional technical information on the first three of these diagnostic techniques for determining when to place and remove spring load restriction is provided in "Determining When To Place and Remove Spring Load Restrictions of Low-Volume Roads" (Kestler et al. 2007). Link to the document at <http://trb.metapress.com/content/92571v6872784854>.

Kestler et al. (2000) and Berg et al. (2006) also provide useful information. Information on the fourth method is in preparation and will be available from the Forest Service when published.

3.3.4. Solutions for Asphalt Distresses

When faced with asphalt pavement distress, consider a range of management, maintenance, and rehabilitation options. However, first follow these steps:

1. Determine the type, extent, and severity of the distress.
2. Determine the cause of the asphalt distress.
3. Determine if the pavement has the necessary pavement structure to support current and future traffic.
4. Determine available funding and the most economical alternative based on life-cycle costing.

Typical management, maintenance, and rehabilitation options include the following six alternatives, as discussed in the following sections:

1. Living with the distress, do nothing.
2. Maintaining the road surface, **Corrective measures**.
3. Maintaining the road surface, **Preventative measures**.
4. Improving drainage.
5. Reconstructing the road surface.
6. Converting asphalt surface into aggregate surfacing.

Prior to deciding a course of action, one should evaluate the type, severity, and extent of the distresses on the asphalt road surface. Information and photographs about the types and severity of distresses in asphalt pavements can be found in the following guides:

- ❑ Miller and Bellinger (2003) <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=91>.
- ❑ Metropolitan Transportation Commission (1993) <http://www.mtcpms.org/publications/asphalt%20PCI%20book.pdf> or <http://www.mtcpms.org/products/index.html>.
- ❑ ASTM (2009) <http://www.astm.org/Standards/D6433.htm>.

Understanding the cause of the asphalt pavement distress also is important. Table 3-22 lists some of the common asphalt pavement distresses, their possible cause(s), and possible treatment options.

Other guides that not only cover the asphalt pavement distress types but also recommend treatments and treatment application tips include:

- Asphalt Institute (2009) Asphalt Pavement Distress Summary (Web page) <http://www.asphaltinstitute.org/public/engineering/Maintenance_Rehab/Distress_Summary.asp>.
- Asphalt Institute (2009a) MS-16 <http://www.asphaltinstitute.org/store_product.asp?inve_id=50)>.
- Johnson, A. (2000) Best practices handbook on asphalt pavement maintenance <http://www.mnltap.umn.edu/pdf/asphalt.pdf>.
- *Pavement Interactive* a Web-based information tool sponsored by various State and Federal agencies (November 2008) <http://pavementinteractive.org/index.php?title=Main_Page>.
- "Techniques for Pavement Rehabilitation" (1998), American Society of Civil Engineers, (Revision of National Highway Institute "Techniques for Pavement Rehabilitation," FHWA-NHI-131008 training course notes).

To determine if the current pavement structure, or if the proposed reconstructed pavement, will support traffic, follow AASHTO (1993). To determine if the pavement structure is adequate on very low-volume roads but with occasional very heavy loads, a mechanistic pavement design might be required. Mechanistic analysis and design are derived from mechanistic behavior of the pavement, where specific stresses and strains are examined in the pavement. Mechanistic analysis is most rigorous but requires a considerable amount of materials testing and computation to be used properly. Thus it is infrequently used for low-volume roads. Empirical methods are used more commonly.

To determine the thickness and quality of existing pavement, use the procedures found in "Handbook for Pavement Design" (1983) and in Bolander et al. (1996). Always consider present and future road use as part of the decision process. Tools, such as Forest Service Roads Analysis, Access and Travel Management, and Road Management Objectives are useful to aid in establishing the need and standard of a road, as well as justifying investments in the road.

The U.S. Department of Transportation, Federal Highway Administration (2009) has information on pavement structures at <http://www.cflhd.gov/materials/FLHFieldMaterialsManualJanuary2009.pdf>.

State of California (2003) has very useful information on many aspects of crack sealants, seal coats, and overlays. The link is found at <http://www.dot.ca.gov/hq/maint/MTA_Guide.htm>.

Table 3-22—Typical low-volume road asphalt pavement distresses, their causes, and treatments

Asphalt Surface Distress	Traffic or Load Related	Probable Cause	Repair Treatment by Distress Severity
Alligator Cracking	Yes	❑ Insufficient pavement structure due to weak base or weak subgrade (inadequate thickness or wet materials).	***Small and localized distress*** **Low:** Do nothing or fill cracks. **Medium and High:** Full depth patch. ***Large areas of distress*** **Low:** Chip seal. **Medium:** Chip seal with paving geotextile, cape seal, or overlay with paving geotextile (check if adequate pavement structure). **High:** Reconstruct (check if adequate pavement structure).
Bleeding (in an asphalt concrete mat without seal coat)	Yes	❑ Excessive asphalt binder in the asphalt concrete (high asphalt binder content). ❑ Low asphalt concrete air void content (not enough room for asphalt to expand into during hot weather) due to excessive asphalt binder or traffic densification of the asphalt concrete. ❑ Upward movement of asphalt in asphalt concrete (stripping of asphalt binder from aggregate). ❑ Temperature susceptibility of asphalt binder (softening of asphalt binder at high temperatures).	**Low:** Apply hot sand (blot surface). **Medium:** Apply coarse sand or place well-designed chip seal. **High:** Open-graded overlay, cold milling with or without chip seal or thin overlay, or heater-scarification/milling with chip seal or thin overlay.

Table 3-22—Typical low-volume road asphalt pavement distresses, their causes, and treatments. Continued

Asphalt Surface Distress	Traffic or Load Related	Probable Cause	Repair Treatment by Distress Severity
Bleeding (in seal coat or BST)	Yes	❑ Excessive application of asphalt binder during seal coat application ❑ Upward movement of asphalt in seal coat (stripping of asphalt binder from seal coat aggregate). ❑ Temperature susceptibility of asphalt binder (softening of asphalt binder at high temperatures).	**Low:** Apply hot sand (blot surface). **Medium:** Apply coarse sand or place well designed chip seal. **High:** Cape seal, thin overlay, or cold milling with or without chip seal or thin overlay.
Block Cracking	No	❑ Typically caused by inability of asphalt binder to expand and contract with temperature cycles because of asphalt binder aging in the mix.	**Low:** Seal cracks. **Medium:** Seal cracks then either a multilayer chip seal, rejuvenation seal, or chip seal with paving geotextile. **High:** Cape seal, scrub seal, or thin overlay.
Depressions/ Distortions	No	❑ Frost heave. ❑ Subgrade settlement resulting from inadequate compaction during construction. ❑ Organic material decomposing within embankment. ❑ Fillslope settlement or slope instability.	**Low:** Do nothing. **Medium:** Skin patch. **High:** Repair cause of depression (remove organic material, recompact fill, or deep patch (see section 3.2.2.3, Deep Patch).
Edge Cracking (within 2 feet of edge of asphalt pavement)	Yes	❑ Narrow shoulders and/or tight horizontal curve leading to wheels tracking along or going off the edge of the asphalt pavement. ❑ Poor drainage along edge. ❑ Frost heave along edge. ❑ Inadequate side/shoulder (lateral) support. ❑ Fillslope settlement or slope instability.	Assuming not a slope settlement or instability issue: **Low:** Fill cracks and improve shoulder drainage. **Medium:** Full depth patch. **High:** Reconstruct edge, improve shoulder drainage, extend road width.

Table 3-22—Typical low-volume road asphalt pavement distresses, their causes, and treatments. Continued

Asphalt Surface Distress	Traffic or Load Related	Probable Cause	Repair Treatment by Distress Severity
Longitudinal Cracking (within wheel tracks)	Yes	❑ Insufficient pavement structure due to weak base or subgrade (inadequate thickness or wet/ weak materials), may lead to alligator cracking.	***Small and localized distress:*** **Low:** Do nothing. **Medium and High:** Fill cracks. ***Large areas of distress:*** **Low:** Do nothing or chip seal. **Medium:** Fill cracks and chip seal or scrub seal. **High:** Fill cracks and then either chip seal with paving geotextile or overlay with or without geotextile to minimize reflection of cracks through overlay.
Longitudinal Cracking (outside wheel tracks)	No	❑ Poor joint construction. ❑ Volume change potential of foundation soil. ❑ Fillslope settlement or slope instability. ❑ Segregation due to paving machine. ❑ Other construction deficiencies. ❑ Reflection of underlying crack if an overlay.	***Small and localized distress:*** **Low and Medium:** Fill cracks. **High:** If volume change or fillslope issue repair cause (remove problem material, recompact fill, or deep patch (see section 3.2.2.3 Deep Patch), otherwise seal cracks. ***Large areas of distress:*** **Low:** Fill cracks. **Medium:** Fill cracks and then chip seal. **High:** Fill cracks and then either chip seal with paving geotextile, scrub seal, overlay with or without geotextile to minimize reflection of cracks through overlay, asphalt-rubber chip seal, or stress relieving granular layer (gravel interlay).
Patching	Yes	❑ A patch is considered a defect no matter how well it performs or why it was placed.	**Low:** Do nothing. **Medium:** Skin patch or mill edges to smooth transition. **High:** Remove and replace with full depth patch

Table 3-22—Typical low-volume road asphalt pavement distresses, their causes, and treatments. Continued

Asphalt Surface Distress	Traffic or Load Related	Probable Cause	Repair Treatment by Distress Severity
Transverse Cracking	No	❑ Hardening of the asphalt binder and cracking at low pavement temperatures (thermal cracking). ❑ Volume changes in the underlying base or subgrade material.	**Low:** Seal cracks. **Medium:** Seal cracks and rejuvenation seal coat. **High:** Remove and replace hardened asphalt concrete or volume changing material, or if overlaying a hardened oxidized asphalt concrete pavement first tack the pavement with a rejuvenation seal then seal the cracks and finally place geotextile over the cracks prior to the overlay.
Polished Aggregate	Yes	❑ Protruding rough, angular particles become polished. This can occur quicker if the aggregate is susceptible to abrasion or subject to excessive studded tire wear.	**Low:** Do nothing. **Medium:** Slurry seal or chip seal. **High:** Slurry seal, chip seal, or thin overlay.
Potholes	Yes	❑ As alligator cracking becomes severe, the interconnected cracks create small chunks of pavement that become dislodged as traffic passes.	**Low:** Do nothing or skin patch. **Medium:** Skin patch or full depth patch. **High:** Full depth patch.
Rutting	Yes	❑ Insufficient compaction during construction of any material layer in the pavement structure (asphalt concrete, base, or subgrade) with traffic further compacting the material. ❑ Incorrect asphalt concrete mix for traffic and climate.	**Low:** Do nothing. **Medium:** Thin overlay after milling or placing a leveling course; microsurfacing in ruts, or skin patch. **High:** Overlay after placing leveling course or remove and replace insufficiently compacted layer.
Shoving	Yes	❑ Usually caused by starting and stopping of traffic. ❑ Unstable asphalt concrete mix. ❑ Moisture in subgrade.	***Small and localized distress:*** **Low:** Do nothing. **Medium and High:** Full depth patch. ***Large areas of distress:*** **Low:** Do nothing. **Medium and High:** Remove shoving area and overlay.

Table 3-22—Typical low-volume road asphalt pavement distresses, their causes, and treatments. Continued

Asphalt Surface Distress	Traffic or Load Related	Probable Cause	Repair Treatment by Distress Severity
Raveling	No	❑ Low asphalt content. ❑ Excessive air voids due to insufficient compaction during construction. ❑ Hardening of the asphalt binder. ❑ Dust coating on seal coat aggregate. ❑ High use of studded tires at high traffic speeds.	**Low:** Fog or rejuvenating seal. **Medium:** Chip seal or slurry seal. **High:** Multiple chip seal, cape seal, or thin overlay.
Water Bleeding and Pumping	Yes	❑ Insufficient pavement structure due to wet base or subgrade, pumping action may be bring up fine material from the subgrade and/or base to the surface. ❑ High water table and/or poor drainage.	***Small and localized distress:*** **Low:** Do nothing. **Medium and High:** Full depth patch and improve drainage. ***Large areas of distress:*** **Low:** Chip seal. **Medium and High:** Overlay (check if adequate pavement structure) and improve drainage.
Loss of Cover Aggregate (in seal coat or BST)	Yes	❑ Coating of dust on seal coat aggregate during construction. ❑ Traffic speeds too high during seal coat construction. ❑ Insufficient amount of asphalt binder in seal coat. ❑ Too much aggregate in seal coat.	**Low:** Do nothing or apply ¼-inch (6 mm) coarse sand during warm weather. **Medium:** Hot coarse sand and then pneumatic roller or chip seal (can chip seal only in wheel tracks if necessary). **High:** Cold mill entire surface and apply new chip seal.
Longitudinal Streaking (in seal coat or BST)	No	❑ Incorrect height of spray bar during seal coat construction. ❑ Incorrect nozzle alignment and/ or size. ❑ Plugged spray nozzle. ❑ Plugged gate in aggregate spreader.	**Low:** Do nothing. **Medium:** ¼-inch (6 mm) maximum size chip seal. **High:** Cold mill entire surface and apply new chip seal.

The various treatments listed above have a range in application cost and expected longevity, so evaluating various alternatives should be considered as part of the decision process and weighed against available funding. Evaluate the various alternatives based on life-cycle costing to determine which alternative would be the most cost effective for the design life of the pavement.

The following publications provide guidance on how to perform a life-cycle cost analysis for a paved road as well as costs and expected life of each treatment:

- Hunt (1991) chapter 2.
- Johnson (2000) <http://www.mnltap.umn.edu/pdf/asphalt.pdf>.
- Hicks et al. (2000) <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=27>.

Many Federal, State, and local agencies have implemented a pavement management system (PMS). PMS is a tool that helps optimize use of available funds and can aid in choosing pavement maintenance or pavement rehabilitation activities. Part of the PMS tool is to rate the surface condition (distresses) of the asphalt pavement for each user-defined segment of road. The combined distress rating is commonly called a pavement condition index (PCI). The PCI does not measure structural capacity nor does it provide direct measurement of skid resistance or roughness. Continuous monitoring of the PCI is used to establish the rate of pavement deterioration, which permits early identification of major rehabilitation needs.

The remainder of this section addresses each asphalt maintenance repair and rehabilitation treatment.

3.3.4.1. Living With the Distress/Do-Nothing Option

The do-nothing alternative commonly leads to increased distress with time, slower traffic, more complaints from users, possibly less use, and possibly an increase in near-miss or accident rates due to driver avoidance of the distress by going outside the normal lane of traffic. Road user management techniques can be implemented to help manage future distress. One management technique is discussed in DeJean (1991) exhibit 6 at <http://www.fs.fed.us/r6/malheur/forest-prod/timber/documents/ecrd/round/road-rules-02.pdf>.

Another management technique is discussed in Kestler et al. (2007). These management techniques control heavy loaded traffic while the pavement is in its weakest state, thereby minimizing the deterioration of the pavement surface.

3.3.4.2. Maintaining the Road Surface–Corrective Measures

Corrective measures for maintaining/repairing the asphalt pavement road surface include crack sealing, pothole patching, and skin patching to improve the ride quality and seal defects to make that area more impermeable and/or resistant to wear and climate. Choosing the most practical and most cost-effective maintenance activity should be the goal of any road manager. Use table 3-22 and the following resources to help determine the treatment(s) with the greatest cost benefit:

- Hunt (1991).
- Asphalt Institute (2009a).
- Johnson (2000).
- Hicks et al. (2000).
- Washington State Department of Transportation (2009) flexible pavement design <http://training.ce.washington.edu/wsdot/modules/09_pavement_evaluation/09-7_body.htm>.

Once a maintenance activity is chosen, ensure it is applied correctly. Proper weather conditions are always essential for long-term performance of maintenance repairs. Some guidance on proper maintenance application techniques follows.

3.3.4.2.1. Crack Sealing and Filling Tips

Proper crack sealing and filling procedures for pavement requires three steps: (1) completely cleaning the crack, (2) using appropriate crack seal or filling material, and (3) following the manufacturer's application directions.

Cleaning the crack refers to removing all vegetation, removing any loose material, and drying the crack. The proper crack seal material is a function of whether you are sealing (allows the crack to expand and contract with the asphalt concrete as with transverse low-temperature cracks; also known as working cracks) or filling (cracks are not expected to move; also known as nonworking cracks) the cracks.

Smith and Romine (1999) <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=135> have an explanation and discussion of working versus nonworking cracks and maintaining these cracks. To conserve sealant materials, use a backer rod if the depth of crack is greater than ¾ inch (18 mm). To minimize traffic from tracking the sealant material, stop the sealant ⅛ to ¼ inch (3-6 mm) below the surface or use a squeegee to remove any sealant left on or above the pavement surface.

Some additional reference material for crack sealing and filling can be found at:

- Asphalt Institute (2009a).
- U.S. Department of Transportation, Federal Highway Administration (2001) <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=31>.

3.3.4.2.1.1. Working Cracks

Working cracks refer to cracks that have horizontal movement greater than 0.1 inch (2.5 mm). When sealing these cracks (allowing for expansion and contraction of the crack) use a product that expands and contracts with the asphalt concrete pavement. These crack sealant materials would be either a self-leveling silicon product (low modulus and applied cold typically in combination with a backer rod) or a low modulus rubberized asphalt product that meets American Society for Testing and Materials (ASTM) Specification D 6690, Type I, II, or IV <http://www.astm.org/Standards/D6690.htm> depending on the lowest expected pavement temperature that matches the local climatic conditions.

The U.S. Department of Transportation, Federal Highway Administration, Application Note Web site provides some guidance in selecting the appropriate crack sealing material <http://www.tfhrc.gov/pavement/ltpp/reports/03080/index.htm>. Studies have shown that for working cracks the preferred depth of crack sealant material should be twice the width of the crack when using silicone sealants and equal to the width of the crack when using rubberized asphalt sealants. To obtain the necessary depth-to-width ratio the crack might need to be sawn or routed.

Working cracks wider than 1 inch (25 mm) are difficult to seal effectively. It is recommended to either:

- Fill these cracks with material one might use for nonworking cracks (meeting the ASTM D 5078 requirements) when the pavement temperature is moderately cool (35 to 55 °F) (2 to 13 °C). If the crack depth is more than twice the width, fill the crack with loose sand to where the depth of the crack is the same as the width. Note that cracks treated with this method need to be sealed in a year or two with crack seal material that meets the requirements for a working crack.

- ❑ Cut out the crack and refill with asphalt concrete. When the pavement temperature is moderately cool, saw-cut at least 1 inch (25 mm) beyond the edge of the crack, remove the loose asphalt concrete, and then fill with new asphalt vconcrete. Note that cracks treated with this method also need to be sealed in a year or two with crack seal material that meets the requirements for a working crack. The cracks that develop will be narrower than the original.

Note that transverse low-temperature cracks, if they do occur, typically develop 5 to 7 years after construction. They commonly continue to open and close as the pavement temperature fluctuates. After a few years the cracks do not close anymore and the remaining gap just slowly widens until at some point it may stop, probably after it has gone through a couple of extreme hot-and-cold pavement temperature cycles. Paved roads that are not plowed commonly show less transverse low-temperature cracking since the snow insulates the surface from the extreme cold temperatures.

3.3.4.2.1.2. Nonworking Cracks

When filling the cracks (expansion and contraction of the crack not critical), a wide variety of crack fill materials can be used and the crack filling material would be more a function of the typical width of crack. Crack widths less than ⅛-inch (3 mm) are difficult to fill. Use undiluted slow-setting emulsion and squeegee the material into the crack. Some agencies don't even recommend trying to seal cracks less than ⅛ inch (3 mm) wide. For cracks widths between ⅛ and ¼ inch (3-6 mm) use undiluted slow-setting emulsions. For cracks between ¼ and 1 inch (6-25 mm) fill with a slow-setting emulsion and sand slurry, fiberized asphalt, or asphalt rubber meeting ASTM D 5078 requirements. A common recipe for the emulsion sand slurry is 20 percent CSS-1 emulsion, 2 percent cement, and 78 percent ¼ inch (6 mm) minus sand with water added as needed for workability. For crack widths greater than 1 inch (25 mm) consider an emulsion sand slurry, cold mix asphalt concrete, or hot mix asphalt concrete, again whichever costs least. Placing a band-aid of crack filler beyond the crack increases the life of the filled crack. The band-aid should be tightly squeegeed after filling the crack and not extend more than 1 inch (25 mm) beyond the edge of the crack.

3.3.4.2.2. Pothole Placement Tips

Proper pothole patching procedure for pavement requires four steps: (1) removing the broken asphalt surface and base to firm support while keeping the sides near vertical, (2) applying a coat of tacking material to the sides, (3) placing a full-depth patch of asphalt concrete, and (4) compacting and finishing the patch so it is level with surrounding pavement. Not following these procedures can result in unnecessarily expensive and frequent pothole repair.

The ‘throw-and-roll’ procedure has been shown to be effective if using good quality patching material, which commonly includes polymer-modified binders and graded, crush-quality aggregate that are quality assurance tested. Many States maintain a qualified products list of patching materials that meet these requirements. Patching work should be performed during warm and dry weather (50 °F [10 °C] and above).

Some additional reference material for pothole placement can be found at:

- Asphalt Institute (2009a).
- Wilson and Romine (1999) <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=139>.
- Eaton et al. (1985) <http://www.erdc.usace.army.mil/pls/erdcpub/docs/erdc/images/Pothole_Patching_Resources.pdf>.

3.3.4.2.3. Skin Patching Tips

Proper skin patching procedure for pavement requires four steps: (1) cleaning the surface, (2) tacking the surface, (3) compacting the mix (while hot if it is a hot-mix asphalt concrete and before the emulsion breaks if it is cold-mix asphalt concrete), and (4) sealing the edges with emulsion and clean fine sand. Not following these procedures can result in peeling patches, rough edges, and frequent skin patch repair. Rough edge problems also can be mitigated by the use a of a well-graded asphalt mix with a maximum aggregate size of ½ inch (12.5 mm) and good edge feathering techniques. Perform patching work during warm and dry weather (50 °F [10 °C] and above).

Some additional reference material for skin patching placement can be found in Asphalt Institute (2009a).

3.3.4.3. Maintaining the Road Surface–Preventative Measures

Preventative or preservation measures to protect and maintain the road surface include very thin pavement overlays, seal coats, microsurfacing, rejuvenating seals, and edge crack repairs. Each helps seal defects to make the road surface more impermeable and/or resistant to wear and climate.

3.3.4.3.1. Very Thin Hot-Mix Asphalt Overlay

The type of asphalt mix for initial construction and/or thin overlays in low-volume trafficked roads is important. Highway mixes, common with State and some county roads, are formulated to be rigid to support high volume and high wheel loaded traffic. Therefore, these mixes have low asphalt content. This provides a mix that resists fatigue failure, which leads to alligator cracking. These low asphalt content mixes may ravel with time as they age. Low trafficked roads commonly do not need to be designed for rigidity but for flexibility. Flexibility requires higher asphalt content and would tend to rut if subjected to high volumes and/or high wheel loads, which is not the case in many typical low-volume roads. The key asphalt mix design parameter that controls the asphalt content is the percent air voids, which for low trafficked road should be between 3 and 3.5 percent.

Thin hot-mix asphalt overlays need to follow good construction practices since the lift is thin and cools quite rapidly. Federal Highways Administration (2002d) provides some additional construction guidance <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=41>. Also refer to the National Asphalt Pavement Association (2009) publication <http://store.hotmix.org/index.php?productID=696>.

3.3.4.3.2. Seal Coat Options

Seal coat options include fog seals, chip seals, slurry seals, and microsurfacing and rejuvenation seals. Proper seal coat procedures for pavement requires five key criteria: (1) proper weather, (2) a clean asphalt surface, (3) dust-free aggregate, (4) a uniform and adequate application of asphalt and aggregate, and (5) an adequate cure period prior to allowing traffic. Not following these criteria can result in poor seal coat adhesion to the existing surface.

Asphalt seal coat treatments commonly are a preventive maintenance procedure applied to the asphalt pavement surface to prevent or delay costly corrective measures. They are designed to seal and protect the asphalt pavement from harmful environmental conditions, such as sunlight, rain, and snow. In addition, they also are applied to enhance the wearing properties and improve the traction between the pavement and vehicle tires.

Surface treatments work well where the distresses are limited to pavement surface deterioration, or where cracks are not severe. The seal coat limits water from infiltrating through the pavement into the underlying material. Asphalt seal coat treatments do not cure problems beneath the pavement, such as a base failure, or if the base aggregate is not structurally sound. If the material beneath the asphalt pavement has deteriorated, treating the surface of the pavement does not solve the problem.

Various seal coat options are available for use in maintenance practices. A BST is a multiple layer application of chips placed on a compacted and primed aggregate base (figure 3-73) and is the most common asphalt surface treatment for low-volume roads.

BSTs are summarized in “Asphalt Seal-Coat Treatments” (Yamada 1999) <http://www.fs.fed.us/eng/pubs/html/99771201/99771201.htm>.

Another reference describing seal coats and their uses is “Seal Coat Options: Taking the Mystery Out” (Bolander 2005). This paper is available at <http://onlinepubs.trb.org/onlinepubs/circulars/ec078.pdf> and <http://pubsindex.trb.org/view.aspx?id=775181>.

The Washington State DOT (1987) document “Asphalt Seal Coats” has information on seal coats. Link to the document <http://www.wsdot.wa.gov/Research/Reports/100/136.1.htm>.

Texas DOT (2006) also has useful general seal coat information. <http://onlinemanuals.txdot.gov/txdotmanuals/scm/scm.pdf>.

Figure 3-73—A BST (chip seal) operation with chips being spread on an emulsified asphalt over base aggregate.

Some additional reference material for seal coats can be found at:

- Asphalt Institute (2009a).
- Asphalt Institute (2009b) <http://www.asphaltinstitute.org/store_product.asp?inve_id=53>.

3.3.4.3.2.1. Fog Seals

A fog seal is an application of diluted asphalt emulsion sprayed on the road surface without a sand application. It provides some minor waterproofing and surface sealing and retards pavement oxidation. In addition to the Asphalt Institute publications, the U.S. Department of Transportation, Federal Highway Administration (2002b) has some placement tips for fog seals <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=15>.

3.3.4.3.2.2. Chip Seals

A chip seal BST is commonly used on low-volume roads. A chip seal is an application of asphalt followed by an aggregate cover. A double chip seal is a layer of asphalt followed by an aggregate cover and followed by another layer of asphalt with another layer of aggregate cover. A triple would be adding another layer of asphalt and cover aggregate. The applied asphalt can be hot asphalt cement, cutback asphalt, emulsified asphalt, or some modified emulsified asphalt. Aggregate is immediately applied over the sprayed asphalt before the hot asphalt cement cools or the asphalt emulsion breaks. Use of hot asphalt is uncommon, but it does allow traffic back on the road quickly and it has good aggregate retention. An asphalt emulsion such as cationic rapid set-2 (CRS-2) is commonly used and is less expensive than other products. Use a pneumatic roller to reorient or seat the aggregate particles and tighten the rock matrix after each course of aggregate.

For a multilayer chip seal, the size of the following chip application typically is one-half the size of the previous application. The asphalt should fill approximately two-thirds of the voids in the chips (figure 3-74). Note that low-volume road asphalt-application rates are less than those associated with higher traffic since there is less traffic to further compact the chips. However, low-volume roads that are older and have a more pitted and oxidized surface need more asphalt to help hold the chips. Less asphalt does not properly bind the aggregate to the road surface. More asphalt runs the risk of the treatment bleeding as it compacts and as the weather warms. Occasionally one has to adjust the asphalt application to account for changes in the surface texture of the existing surface; for example, a pitted surface requires more asphalt than a smooth surface, before any asphalt is available to retain the aggregate chips.

Other key components of a properly constructed chip seal are that the asphalt distributor nozzles are all the same size and correctly angled and that the height of the spray bar is adjusted so that the road surface gets a triple coverage of asphalt (each spot on the road receives asphalt from three nozzles). This helps prevent streaking in the final surface.

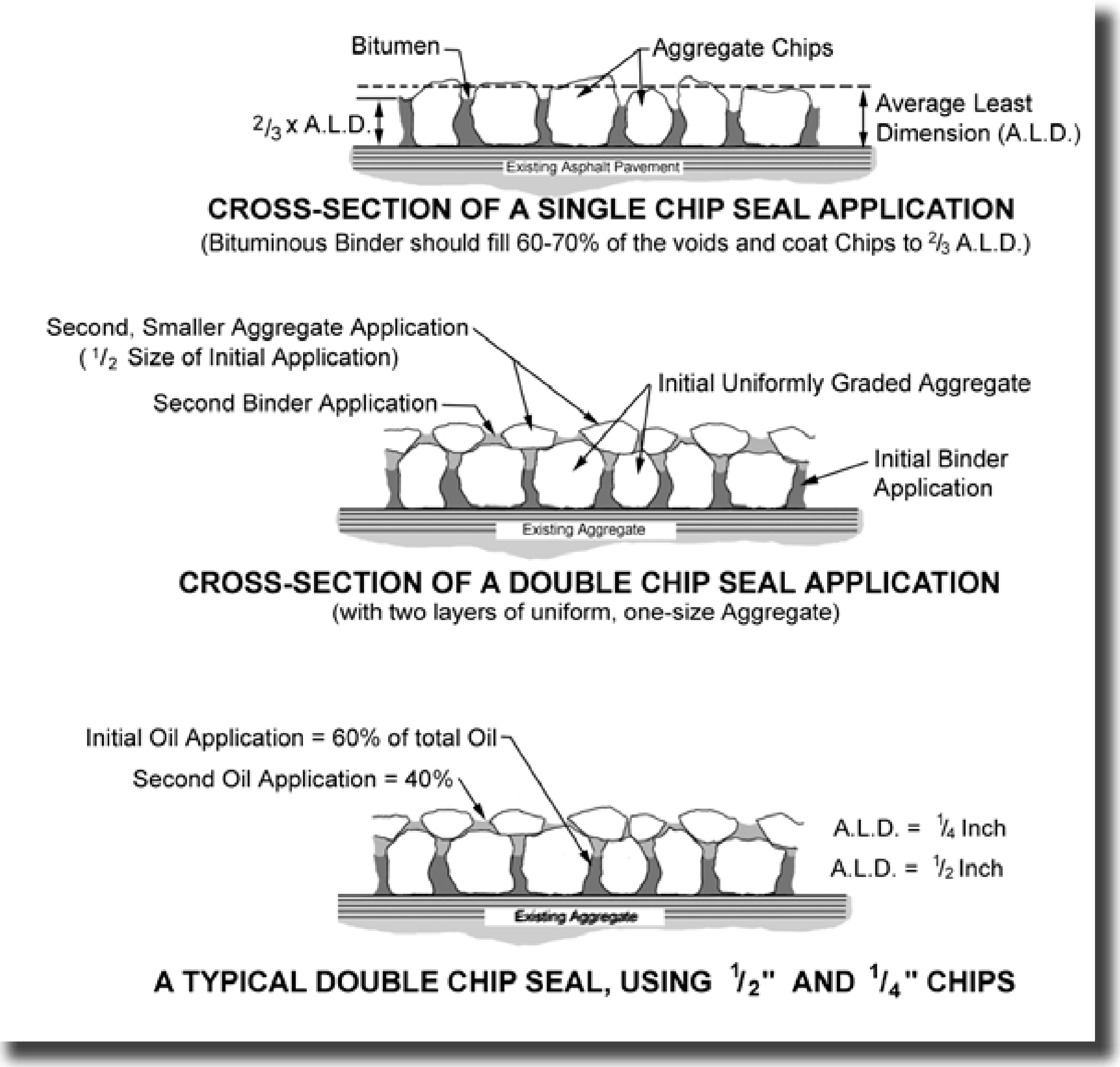


Figure 3-74—Characteristics and typical requirements for chip seals.

Selecting the correct asphalt for the chip seal can increase the chance for a successful seal coat. It is generally recommended to use a rapid setting CRS-2 asphalt emulsion for chip seals and BSTs unless special conditions exist on the project. Some special conditions and potential resolutions are addressed in table 3-23.

Table 3-23—Special chip seal situations and possible resolutions

Situation	Possible Resolution
Steep grades (> 6 percent)	Use polymer modified or polymer modified high float emulsions or use hot asphalt cement.
Tight horizontal alignment	Use polymer modified or polymer modified high float emulsions; or increase asphalt rate up by 0.05 gallons per square yard (gal/yd²) (0.23 L/m²); place a fog seal on the completed chip seal (CSS-lh mixed 50/50 with water at 0.10 to 0.15 gal/yd² (0.45-0.70 L/m²)); choke; fog seal with choke the final surface; more tightly control the traffic (speeds <15 mph) (24 k/h); increase the percentage of fractured faces in the aggregate; or use hot asphalt cement.
Cross slope > 6 percent	Use polymer modified or polymer modified high float emulsions or use hot asphalt cement.
Heavy tree canopy or other situations where low temperatures and high humidity would deter evaporation of the standard emulsions	Use polymer modified or polymer modified high float emulsions; increase asphalt rate up by 0.05 gal/yd² (0.23 L/m²); place a fog seal on the completed chip seal (CSS-lh mixed 50/50 with water at 0.10 to 0.15 gal/yd² (0.45-0.70 L/m²)); choke; fog seal w/choke the final surface; more tightly control the traffic (speeds <15 mph) (24 k/h); increase the percentage of fractured faces in the aggregate; use hot asphalt cement; or use rapid set low temperature emulsion[1].
Dusty aggregate chips	Wash the aggregate, use cutback asphalt, use high float emulsion or use CMS-2, or precoat the aggregate chips.
Construction before June 1 or after September 15	Place a fog seal, choke, or fog seal w/choke on the completed chip seal; use polymer modified or rapid set low temperature emulsions[1]; or use hot asphalt cement.
Need early chip retention	Use polymer modified or polymer modified high float emulsions or use hot asphalt cement.
Areas with foot traffic during hot weather	Use harder base h-designated emulsions or use hot asphalt cement.
Nonuniform surface	Sand seal the necessary areas a few weeks prior to chip sealing to provide a more uniform textured surface or adjust the asphalt application rate longitudinally using different size nozzles; note the aggregate rate also can be adjusted longitudinally by adjusting the chip spreader gates; these methods need close coordination between the inspector and the contractor to ensure the proper application rates.
Recently placed patches	Pretreat the patches with a fog seal (CSS-l mixed 50/50 with water at 0.10 to 0.15 gal/yd² (0.45-0.70 L/m²)); can check porosity of the existing patch versus the surrounding area by observing the relative absorption rate of drops of motor oil placed on the surface.

(1) Rapid-set low temperature emulsions are designed to chemically break at temperatures as low as 40 °F (4 °C). They still need warm temperatures (60 to 70 °F) (16 to 21 °C) to cure completely.

When placing a BST, tie the chip seal to the underlying base by priming the base course prior to placing the first layer of the BST. Instead of priming prior to the first shot of asphalt, some practitioners just increase the first asphalt application rate of the BST. This may work but is not recommended in that the emulsions commonly used for chip seal application are not made to penetrate into the underlying material; they are made to break (asphalt cement comes out of solution) when they contact the aggregate or asphalt surface. Use any of the following methods to prime the base course:

1. Loosen the top 1 inch (25 mm), spray diluted slow-setting emulsion (1 part emulsion to 1 part water) at 0.60 gal/yd^2 (2.7 L/m^2); ideally the surface needs to be damp and the emulsion mixed with the water at the plant.
2. Blade mix the top 1 to 1.5 inches (25-38 mm) with the diluted slow-setting emulsion (method 1) but apply at 0.50 gal/yd^2 (2.3 L/m^2) if the surface is tight.
3. Mix slow-setting emulsion in the water used for compacting the base course, typically mix 1 part emulsion to 6 parts water.
4. Spray MC-250 liquid asphalt at 0.50 gal/yd^2 (2.3 L/m^2); ideally the surface needs to be damp or dry; note: may need to blot surface if traffic needs immediate access; use MC-70 if the surface has a high amount of fines, or reduce the quantity of MC-250 to 0.35 gal/yd^2 (1.5 L/m^2).
5. Loosen the top 1 inch (25 mm), spray medium-setting emulsion (CMS-2s) that has a minimum of 5 percent oil at 0.60 gal/yd^2 (2.7 L/m^2); use higher amount of oil if there is a high amount of fines in the surface.

Due to the variability in every aggregate surface texture, it is recommended that a test section be used to determine the correct priming application rate. The test section should be at least 500 feet (150 m) in length.

Besides the Asphalt Institute publications, the following publications have design and construction information concerning chip seals:

- U.S. Department of Transportation, Federal Highway Administration (2002a) <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=39>.
- U.S. Department of Agriculture, Forest Service (1999).
- ASTM (2005a) <http://www.astm.org/Standards/D5360.htm>.
- Minnesota Department of Transportation (2006) <http://www.dot.state.mn.us/materials/researchsealcoat.html>.

3.3.4.3.2.3. Slurry Seals

A slurry seal is a mixture of quick-setting asphalt emulsion, fine aggregate, mineral filler, additives, and water. The mix is spread with a squeegee. It fills small surface cracks, has good skid resistance, and is smoother than a chip seal. The following publications have design, guideline specifications, and construction information concerning slurry seals:

- ASTM (2007) <http://www.astm.org/Standards/D3910.htm>.
- International Slurry Surfacing Association <http://www.slurry.org/>.
- U.S. Department of Transportation, Federal Highway Administration (2005d) <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=358>.

3.3.4.3.2.4. Microsurfacing

Microsurfacing is similar to a slurry seal but cures faster and can be placed thicker than slurry. It can fill wheel ruts and can allow traffic back on the road quickly. Both Asphalt Institute publications and these publications have design and construction information concerning microsurfacing:

- ASTM (2005b) <http://www.astm.org/Standards/D6372.htm>.
- U.S. Department of Transportation, Federal Highway Administration (2002c) <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=44>.

3.3.4.3.2.5. Rejuvenation Seals and Pavement Dressings

A rejuvenation seal is an application of a modified asphalt emulsion that covers the entire road like a seal coat. Wetting agents allow penetration into the existing pavement to help soften the aged pavement. There are a variety of rejuvenation seals and pavement dressing seal coats. The Forest Service publication Bolander (2005) discusses these options that address some of the various seal types, breaks down the components of the seals, and also provides construction tips.

3.3.4.3.3 Edge Cracking Repairs

As noted in table 3-23 the treatment for edge cracking could be crack sealing, removing and placing a full depth patch, reconstructing the edge, and/or improving drainage. Follow proper crack sealing and patching techniques as noted above for nonworking cracks. When considering reconstructing the edge, ensure that sufficient pavement structure is placed to withstand the vertical traffic load and also resist the lateral side forces. Some success has been obtained by placing a minimum 4-inch (100 mm) plug of asphalt concrete on the outer 2 feet (0.7 m) of the pavement. Prior to placing the asphalt concrete plug, ensure that this technique does not stop the lateral drainage of water out from underneath the pavement. A highly permeable aggregate (clean 2- or 3-inch (50-

75 mm) minus) wedge along the edge of the pavement assists the lateral drainage of water away from the under the pavement. Management techniques to mitigate further edge cracks would include placing pavement markers (fiberglass composite utility markers or break-away posts) just off the edge to keep traffic back from riding on the edge. In administrative sites with low traffic speeds, boulders or other similar devices just off the edge of the pavement tend to shift traffic away from the riding along the edge of the pavement.

3.3.4.4. Improving Drainage

Draining water away from the asphalt pavement unquestionably leads to a longer lasting pavement with less surface distress. There are two ways to improve drainage: (1) drain water off the asphalt surface; and (2) drain water away from underneath the pavement and pavement edges.

To help the surface drain, the minimum cross slope should be 2 percent. Even up to 4 percent has more benefits but if the road gets occasional black ice or packed snow, a 4 percent crown might lead to vehicles sliding off to the side of the road. If the surface does not have the minimum cross slope and pooling of water has been observed consider the following surface improvements:

- ❑ Mill/profile the surface.
- ❑ Place a thin overlay.

To prevent water from saturating the underlying pavement material and to keep it from the shoulders, consider the following improvements:

- ❑ Improve the ditch capacity by removing vegetation, deepening the ditch, widening the ditch, or increasing the slope of the ditch.
- ❑ Install more frequent cross drains.
- ❑ Identify the source of the water (for site specific drainage issues) and consider placing a longitudinal underdrain (excavated trench first lined with a filtration drainage geotextile and then back filled with permeable aggregate and commonly a collection pipe placed at the bottom of the trench).

See Carpenter et al. (1992) for some additional drainage design techniques <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=599>.

3.3.4.5. Reconstructing the Road Surface

Reconstructing the road surface could entail one of these options:

- ❑ Placing an asphalt overlay (with or without a geotextile).
- ❑ Recycling the existing asphalt concrete surface.
- ❑ Pulverizing the existing surface and placing a new asphalt surface.

When the time comes to reconstruct the road surface, investigate the current asphalt pavement and engineer the new pavement structure to ensure a cost-effective, long-term pavement surface.

3.3.4.5.1. Placing a New Asphalt Overlay (With or Without a Geotextile)

The depth of a new asphalt overlay should be a function of the pavement design if reconstruction is being considered because (1) the pavement shows signs of distress due to inadequate pavement strength or (2) an increase in traffic is expected. Prior to placing an overlay, high severity pavement distress areas should be repaired using the table 3-22 as a guide.

In areas of medium to high severity alligator cracking, placing a water-proofing paving geotextile or a stress-reducing geotextile might be cost effective. Water-proofing paving geotextiles have been used for many years to minimize reflective cracking and to enhance waterproofing in asphalt overlays. Placing water-proofing paving geotextiles does not stop crack reflection but only delays when the cracks reflect up through the overlay. To help stop reflective cracking, high-strength, low-elongation (reinforcement) paving geotextiles, such as polyvinyl-chloride coated fiberglass-reinforced geogrids have been developed. Figure 3-75 shows the placement of a high-strength, low-elongation paving geotextile to mitigate cracks reflecting through the planned asphalt overlay.

Some manufacturers have combined the water-proofing capability with the high-strength, low-elongation properties into one paving geotextile product. Therefore, it is important to define and clearly specify the objectives and necessary properties of the paving geotextile as part of the project since paving geotextiles are expensive. Water-proofing geotextile should, as a minimum, retain 0.20 gal/yd² (0.9 L/m²) of asphalt cement (ASTM D 6140) and have a grab strength of 110 pounds (50 kgs) (ASTM D 4632). Based on limited experience, pavement reinforcement geotextiles should, as a minimum, have a tensile strength of 550 pounds per inch (97 kg/cm) at strains less than 5 percent (ASTM D 6637) in the direction perpendicular to the crack.

Figure 3-75—Placement of a high-strength, low-elongation paving geotextile prior to an asphalt overlay. Photo courtesy of Gordon Hanek.

Sprague et al. (1998) presents the results of laboratory testing of various geotextiles used for asphalt overlay reinforcement <http://trb.metapress.com/content/7rq0u06p83724140/fulltext.pdf>.

Holtz et al. (2008) provides information on the use and design of waterproofing geotextiles <http://www.fhwa.dot.gov/engineering/geotech/library_listing.cfm>.

Ultimately there will be times that an overlay needs to be placed over a pavement that has a large amount of high severity, transverse low-temperature cracking. Various options exist to help minimize cracks from reflecting up through the new asphalt overlay. American Society of Civil Engineers (2006) chapter 3 lists some of these options along with their effectiveness and limitations. The following is an expanded list of options:

- ❑ Mark the transverse cracks, place the overlay, saw cut exactly over the marked transverse cracks, and then crack seal.
- ❑ For the hot inplace process, recycle the top 1 inch (25 mm) of existing pavement before the overlay is placed. Increase the overlay thickness.

- Place an unbound stress-relieving granular layer (gravel interlay) on the existing pavement before the overlay is placed (Washington DOT 1991) <http://www.wsdot.wa.gov/research/reports/fullreports/226.1.pdf>.
- Place paving geotextiles over the cracks with or without using an asphalt mastic layer prior to the overlay.
- Place a stress-absorbing membrane interlayer before the asphalt overlay; the stress-absorbing membrane is a thick rubber or polymer modified asphalt layer placed on the original pavement at the crack locations and covered with chip aggregate. See the fact sheet at <http://www.ces.clemson.edu/arts/SAMI.pdf>.
- Spray the pavement with a rejuvenation seal, seal the cracks, and then place a high-strength, low-elongation paving geotextile over the cracks prior to the overlay.

3.3.4.5.2. Recycling the Existing Asphalt Concrete Surface

If the asphalt distresses are associated with poor asphalt concrete materials (bleeding or block cracking), the existing asphalt concrete could be recycled inplace. Inplace recycling is accomplished by either a cold process or a hot process. The cold process involves milling part of the distressed asphalt layer (typically the top 2 to 3 inches (50-75 mm)) with a milling machine and then mixing additional asphalt, additives, and mineral filler (occasionally), and then relaying the mixed material all in a continuous operation on the road (figure 3-76). The hot process also is continuous but the existing asphalt concrete is first softened by infrared heating. In both cases, a seal coat or a thin lift overlay is applied on top of the recycled asphalt concrete.

Various user groups and publications are available for information. They include:

- Asphalt Recycling and Reclaiming Association <http://www.arra.org/>.
- Dunn (2001) <http://www.asphaltinstitute.org/store_product.asp?inve_id=404>.
- U.S. Department of Transportation, Federal Highway Administration (2005a) <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=357>.
- U.S. Department of Transportation, Federal Highway Administration (2010) Web Page <http://www.fhwa.dot.gov/pavement/recycling/cir/>.

- U.S. Department of Transportation, Federal Highway Administration (2005c) <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=356>.

Figure 3-76—Milled asphalt being reused on a forest road.

3.3.4.5.3. Pulverizing the Existing Asphalt Surface and Placing a New Asphalt Surface

If the area of asphalt distress (alligator cracking, bleeding, block cracking, edge cracking, longitudinal or transverse rutting) is large and the condition severe, one option to rehabilitate the area is to pulverize the existing asphalt surface using a travelling rotary mixer and then place a new asphalt surface. If additional pavement structure is needed to support future traffic or the base course aggregate is contaminated with too many fines, then the pulverized material could be treated with asphalt emulsion, flyash, and/or Portland cement. A rotary mixer can pulverize asphalt material and aggregate to a depth of 12 inches (300 mm), some up to 16 inches (400 mm), but it can be set at any depth in between. It is recommended to pulverize only 1 to 2 inches (25-50 mm) below the asphalt pavement but at a minimum depth of 4 inches (100 mm). Do not follow these recommendations if it would involve pulverizing wet high fines material unless the material is treated with one of the above mentioned additives.

Asphalt pavement is generally completely removed either by milling it off in layers or by full-depth removal using heavy equipment. Milling entails removing the pavement surface using a milling machine, which can remove up to a 2-inch (50 mm) thickness in a single pass.

Further information can be obtained from the following:

- Carpenter et al. (1992) volume 1 <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=599>.
- Carpenter et al. (1992) volume 2 <http://www.fhwa.dot.gov/pavement/pub_details.cfm?id=588>.
- Kestler (2009) <http://www.fs.fed.us/eng/pubs/pdf/08771805.pdf>.

3.3.4.6. Converting Asphalt Surface Into Aggregate Surfacing

As undesirable as it may seem, some asphalt surfaces are being ripped up and converted back to an aggregate surfaced road. This may be a short-term fix based upon economic constraints and lack of funds. Alternatively, it may be based on changing road use and the fact that many roads are not being used as much today as they were during the period of heavy timber haul.

Converting an asphalt surface into aggregate can be accomplished as follows:

1. Rip and break the pavement in place using a rhino horn on a bulldozer, pneumatic pavement breaker, or heavy grid roller. Blade and compact the resulting material after removing any pieces larger than 2 inches. Depending on how well the material breaks into a well-graded material, the surface may or may not suffice as surfacing material. Depending on the type and depth of asphalt pavement, the surface temperature may play a large role in how well the material breaks down. Cold mixes are more likely to soften with increasing pavement temperatures. Soft asphalt pavement does not break into a well-graded material easily.

2. Rip and transport removed asphalt concrete to a central facility for processing. At this facility, the asphalt material is processed by crushing and screening, or if there is sufficient space and a firm level area, the material can be grid-rolled. The remaining underlying aggregate would be the new surfacing material, or the reprocessed material could be

hauled back and used for the new surface. Some potential pitfalls if using the reprocessed material for surfacing are discussed below. Again, the temperature of the asphalt pavement determines how well the material breaks into a well-graded material. Also consider the gradation of the base material under the asphalt pavement. If it is an open-graded material or if it has a high amount of fine material, it may not suffice as surfacing material. In this situation, new material or some of the reprocessed asphalt material might have to be added and/or mixed to the base material.

3. Pulverize the asphalt pavement with a travelling rotary mixer. It is recommended to pulverize only 50 percent more than the depth of the asphalt pavement but at a minimum depth of 4 inches (100 mm).

Double chip seal surfaced roads also have been converted back to a gravel road on occasion. The process has been accomplished relatively easily by ripping up the road with multiple passes of grader ripper bits or "teeth" and running over the ripped material with a "cat" tractor. After six to eight passes with the equipment, the road has resembled a normal gravel road. There are some minor stabilization benefits from the old oil in the mix.

Reclaimed asphalt pavement (RAP) is the removed and/or reprocessed pavement materials containing asphalt and asphalt-coated aggregates. There are pitfalls if using straight RAP as surfacing. In 100 percent RAP, the asphalt portion of the old pavement can soften during the summer months and compact under traffic. The resulting surface will have the characteristics of a weak pavement and often develops potholes and could be hard to maintain with simple blade maintenance. To help overcome these characteristics, mix the RAP 50/50 with virgin aggregate. This provides a material that still has good binding characteristics, but remains workable for maintenance and reshaping.

Some guidance on when to pave a gravel road that might be of assistance when one is evaluating whether to change a paved road back to gravel is found in appendix D of Skorseth et al. (2000). Link to this document <http://www.epa.gov/owow/nps/gravelroads/appd.pdf>.

Another reference on upgrading aggregate roads is "To Pave or Not to Pave" (Minnesota LTAP 2006) <http://www.mnltap.umn.edu/publications/factsheets/documents/paveornot/brochure.pdf>.

3.4. TREATMENT FOR ROAD SURFACE AND SUBSURFACE DRAINAGE ISSUES

Surface drainage moves water efficiently off the roadway and into a natural drainage before it erodes, infiltrates and weakens, or damages any portion of the road structure. It also removes water from the surface as quickly as possible to minimize the concentration of water and to minimize the amount and velocity of surface flow. Control of the road grade, use of insloping, outsloping, crown surface, rolling dip cross drains, waterbars, frequent leadoff ditches and downdrains, surface armoring, subsurface drainage measures, and good maintenance all contribute to good roadway surface drainage and minimize sediment loss from the road. The road surface, shoulders, and cut and fillslopes are a relatively large area that has the potential to produce significant sedimentation and erosion if drainage is not properly controlled. Figure 3-77 summarizes many of the measures used in road surface and subsurface drainage.

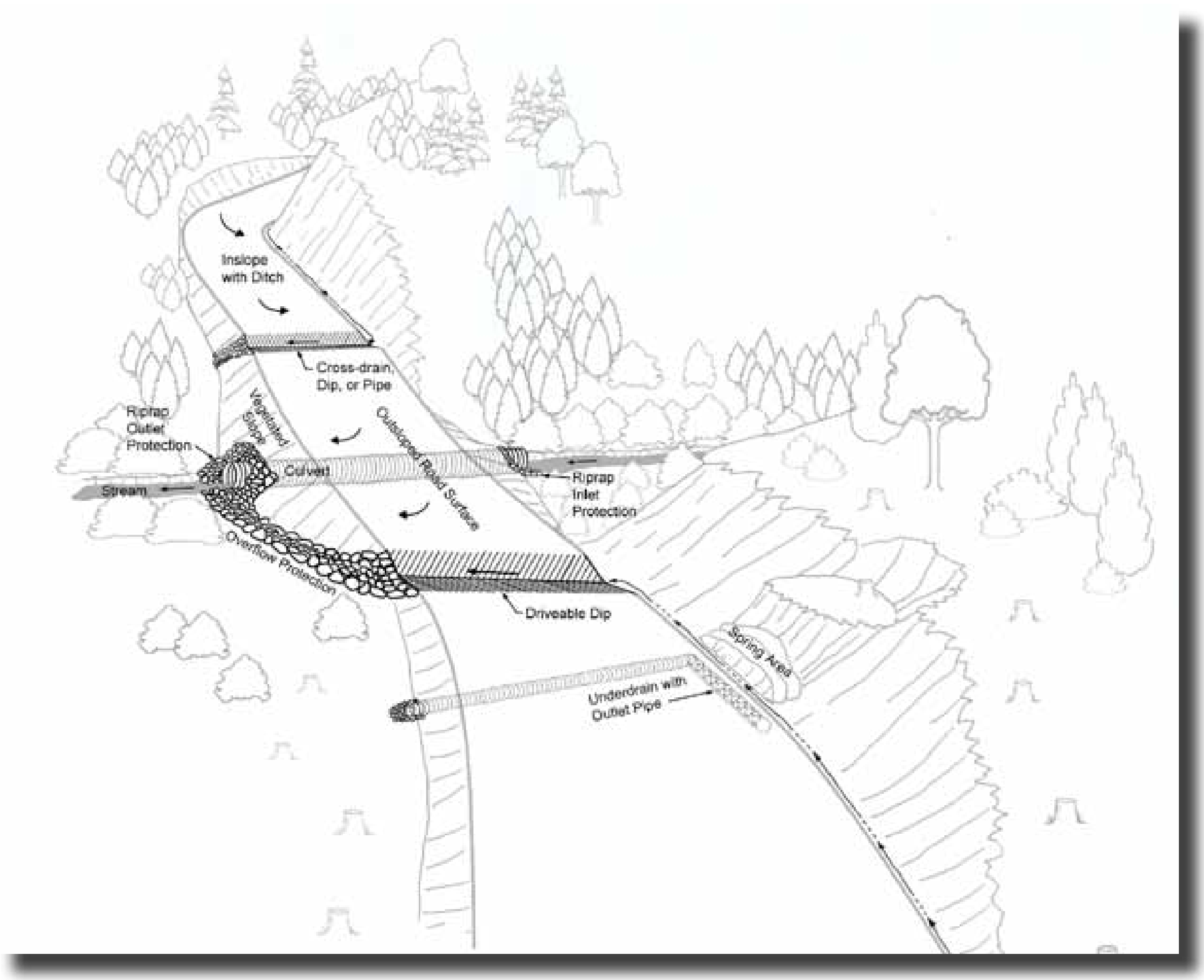


Figure 3-77—Summary of road drainage measures.

The most essential thing to understand in treatment of road surface and subsurface drainage is to maintain the proper shape of the cross section and ditch to drain water away from the roadside. Culverts and bridges at the right location and elevation also are essential for carrying water away from the road. It is said that the three most important aspects of road design are drainage, drainage, and drainage.

Effective surface drainage is the best way to prevent water damage on a road and thereby reduce maintenance and repair costs. Water affects the entire function of a road. Water allowed to remain on top of the road weakens the surface and, when combined with traffic causes potholes and cracking. Once the correct shape is established on a roadway and drainage matters are taken care of, attention can be given to obtaining and properly placing good gravel. Once proper shape for drainage is established and good surface gravel is placed, many gravel road maintenance problems simply go away and road users are provided the best service possible from gravel roads (Skorseth et al. 2000).

Adequate road drainage requires careful attention to detail. One must study drainage conditions and patterns on the ground. Also, one should observe drainage during rainy periods to see how the water is actually moving, where it is concentrated, what damage it may cause, and what measures are needed to prevent damage and keep the drainage systems functioning properly. Since the surface layer is directly exposed to surface moisture, it must be drained quickly to retain adequate strength to resist traffic loads.

The San Dimas Technology and Development Center (SDTDC) has produced an excellent video “Forest Roads and The Environment” (available on DVD) (U.S. Department of Agriculture, Forest Service 2006a), which documents many good road maintenance practices important to keep a road surface well drained and water moving rapidly off the road, as well as for protecting the road and the environment.

The SDTDC Water/Road Interaction Technology (WRIT) Series (U.S. Department of Agriculture, Forest Service 2000b) identifies information and methods on developing, operating, and managing forest roads and dealing with surface drainage. Link to the Web site <http://www.stream.fs.fed.us/water-road/>.

The purpose of the WRIT series is to:

- ❑ Provide an illustrated field-going guide of observable water/road interaction problems damaging to road, watershed condition, water quality, aquatic life, or public safety.
- ❑ Increase awareness of how road location, design, maintenance, and management affect interactions with rainfall, runoff, and ground water.
- ❑ Facilitate communication on water/road interaction problems among professionals and technicians in a variety of physical and biological science disciplines and fields of engineering.
- ❑ Improve the recognition of basic road drainage problems, the ability to identify and verify likely causes, and present solutions.
- ❑ Increase awareness of possible alternative treatments to mitigate existing problems.
- ❑ Develop knowledge and experience required to conceptualize road segment characteristics that provide desired safe access with minimal effect to watershed, water resources, and aquatic life.
- ❑ Help inform and improve management decisions.

Other references on general road drainage can be found in the following documents:

- ❑ State of California DOT (2003) <http://www.dot.ca.gov/hq/oppd/hdm/pdf/chp0830.pdf>.
- ❑ Moll (1999) <http://stream.fs.fed.us/water-road/w-r-pdf/Min_water_displace.pdf>.
- ❑ Keller and Sherar (2003) <http://www.fs.fed.us/global/topic/welcome.htm#8>.
- ❑ Orr, D (2003 Update) “Roadway and Roadside Drainage” <http://www.clrp.cornell.edu/workshops/pdf/drainage_08_reprint-web.pdf>.

3.4.1. Surface Drainage Solutions

Surface drainage provides for the interception, collection, and removal of water from the road surface and slope areas. Water left on the surface may interfere with traffic or cause erosion, and if allowed to infiltrate, can soften and cause damage to the subgrade.

Surface shaping includes maintaining a crown on double lane roads or a positive inslope or outslope on single lane roads; constructing broad base dips or waterbars to divert water off the road; and rolls in the road profile and grade (twisting the road from an inslope template to outslope and back again) to avoid concentrating water. Other devices to divert water off the road include open top or slotted culverts, metal waterbars, and rubber water diverters. Surface drainage measures also include modest road grades to be able to control surface flow.

Summary of Recommended Practices for Roadway Surface Drainage Control

- ❑ Design and construct roads so that they move water rapidly off the road.
- ❑ Avoid steep road grades. Road grades less than 10 to 12 percent are easiest for control of surface flow.
- ❑ Maintain positive surface drainage with an outsloped, insloped, or crown roadway section.
- ❑ Roll grades or undulate the road profile frequently to prevent concentration of water.
- ❑ Use frequently spaced leadoff ditches to prevent accumulation of excessive water in the roadway ditches.
- ❑ Use roadway cross-drain structures (rolling dips, pipe culverts, or open top culverts or flumes) to move water across the road from the inside ditch to the slope below the road. Space the cross-drain structures frequently enough to remove all surface water.
- ❑ Protect cross-drain outlets with rock (riprap), brush, or logging slash to dissipate energy and prevent erosion, or locate the outlet of cross drains on stable, nonerosive soils, rock, or in well vegetated areas.
- ❑ Construct rolling dips rather than culvert cross drains for typical low-volume, low-speed roads with grades less than 12 percent. Construct rolling dips deep enough to provide adequate drainage but long enough to pass vehicles and equipment. In soft soils, armor the mound and dip with gravel or rock. Also armor the dip's outlet.
- ❑ Use culvert cross drains on roads with an inside ditch and moderately fast vehicle speeds. Install culvert cross drains with an angle of 0-30 degrees perpendicular to the road, using an outslope of 2 percent greater than the ditch grade to prevent plugging.
- ❑ Construct waterbars on infrequently used roads or closed roads to control surface runoff.

- ❑ Use catch-water ditches (intercept ditches) across the natural ground above a cutslope only in areas with high intensity rainfall and overland flow. These ditches capture overland sheet flow before it pours over the cutslope and erodes or destabilizes the cut. However, be aware that catch water ditches that are not properly maintained can become a counterproductive pool for water above the slope, increasing the probability of a slope failure.
- ❑ Avoid the use of outside ditches, along the outside edge of the road, except in specific areas that must be protected from sheet flow off the road surface. Use berms as needed.

3.4.1.1. Reshaping the Template

Traveled way surface shape (outslope, inslope, or crown) is used to drain concentrated surface flow off the traveled way. Outslope directs flow to-and-over the downhill shoulder, while inslope directs flow toward the backslope toe or ditch and requires a ditch relief culvert or rolling dip to remove water off the road. A crown is half inslope and half outslope, breaking surface water concentration into two parts. See SDTDC WRIT series document “Traveled Way Surface Shape” (Moll et al. 1997) for more information. Link to the Web site <http://www.stream.fs.fed.us/water-road/>.

Advantages of an outsloped road are that the roadway template is as narrow as possible (not requiring a ditch); construction is least expensive; and water is dispersed off the road, avoiding concentration. Thus an outsloped road can be the most desirable roadway template to use. However a significant problem with outsloping can be safety if the road surface is slippery. Drivers can feel unsafe and fear that they will slide off the mountain. In steep terrain where the road surface may be slippery or have snow and ice, it is safer to use an insloped road template. Better to slide into the ditch than off the hillside!

One advantage of an inslope road is that water is better controlled by moving it into a ditch; the ditch can be discharged into a stable, nonerosive location. Also it can be safer to prevent a vehicle from sliding off the road. The disadvantages of an inslope road with ditch are the need for additional road width, concentrated flow in the ditch, and the need for ditch relief cross drains or leadoff ditches.

A crown-shaped road surface divides the drainage area in half, reducing the flow distance as well as the amount of water off each side of the road. It is the most common form of surface drainage on two-lane roads. Note that a crown shape is difficult to achieve or maintain on a single-lane road, thus, on narrow roads, insloping or outsloping is used. Also note that it is quite expensive to convert an existing insloped road to an outsloped road template. The typical road surface drainage options are shown in figure 3-78.

Traveled way shaping may not effectively remove surface water on steep grades (10 percent or greater on unsurfaced roads) or on rutted surfaces, necessitating use of surface cross drains. Surface cross drains, such as open top drains, metal waterbars, precast concrete troughs, rubber water diverters, or rolling dips (section 3.4.1.6), are all designed, spaced, located, and armored to prevent water from draining down the road and releasing it as well as possibly minimizing effects to adjacent areas and watersheds. Note that open top drains often clog with soil and gravel, so they require frequent maintenance. See SDTDC WRIT Series documents on surface cross-drains (Gonzales 1998) <http://www.fs.fed.us/eng/pubs/pdf/w-r/98771804.pdf> and Copstead et al. (1998) <http://www.stream.fs.fed.us/water-road/w-r-pdf/crossdrains.pdf> for more information about surface drainage devices.

Recommended Practices

- ❑ Design and construct roads such that they move water rapidly off the road surface to keep the surface drained and structurally sound.
- ❑ Avoid steep road grades in excess of 12 to 15 percent. It is very difficult and expensive to properly control drainage on steep grades.
- ❑ Maintain positive surface drainage with an outsloped, insloped, or crown roadway section using 4- to 6-percent cross slopes (figure 3-78).
- ❑ Roll grades or undulate the road profile frequently to disperse water, particularly into and out of stream crossings.

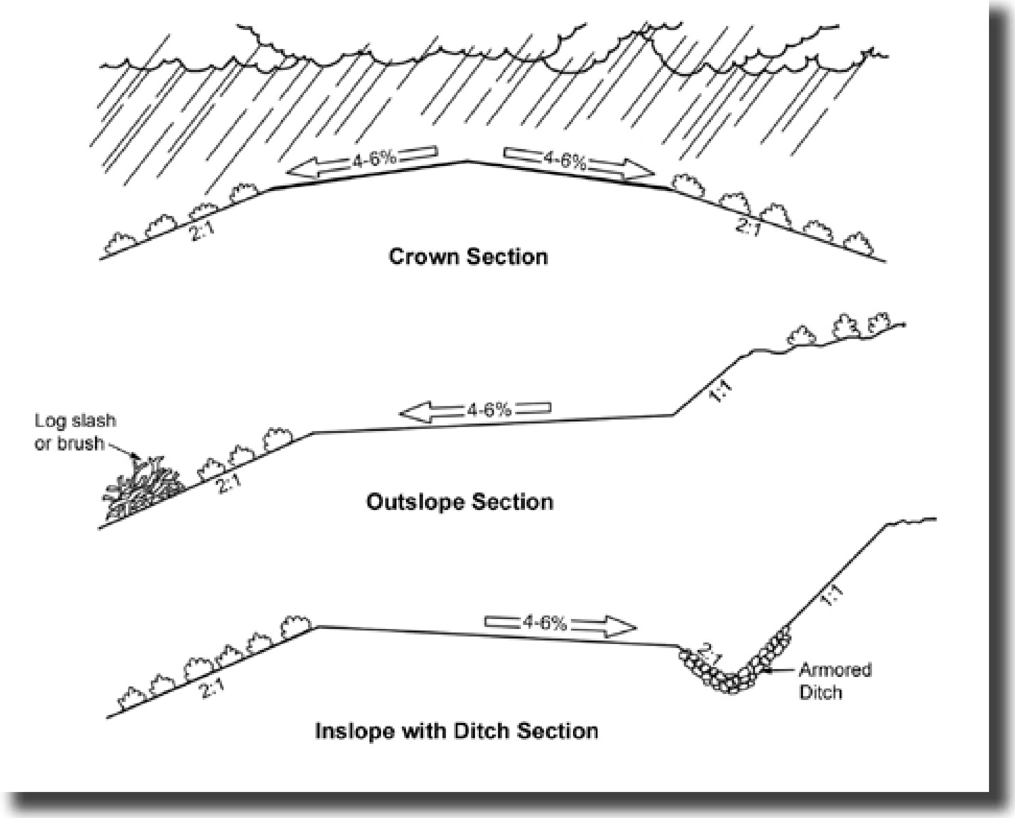


Figure 3-78—Typical road surface drainage options.

Establishing proper crown in the road surface probably generates more controversy than any other aspect of good maintenance. How much crown is enough? Can one get too much? What is a recommended crown? Problems develop quickly when a road has no crown or cross slope. Water quickly collects on the road surface during a rain and softens the crust. This leads to rutting, which can become severe if the subgrade also begins to soften. Even if the subgrade remains firm, traffic quickly pounds out smaller depressions in the road where water collects and the road develops potholes (figure 3-79).

Figure 3-79—Potholes in the road surface pond water, weaken the roadway structural section, accelerate surface damage, and make driving difficult.

An operator also can build too much crown into the road surface (figure 3-80). This can lead to an unsafe condition in which the driving public does not feel comfortable staying in their lane or simply staying on the right side of the road. Because of the excessive crown, drivers begin to feel a slight loss of control of the vehicle as it wants to slide towards the shoulder. For these reasons drivers tend to drive right down the middle of the road regardless of how wide it is.

Figure 3-80—A gravel road with a 26-foot (9 m) driving surface, yet everyone drives in the middle. (Courtesy of South Dakota LTAP, Ken Skorseth)

The reasons include excessive road crown, excessive road width, and driver comfort (Skorseth et al. 2000).

The most common problem encountered is a road constructed with no crown, or too little crown to maintain drainage once the road wears for a period of time. Thus it is desirable to build a crown (or cross slope) a bit radical initially, or to the 6-percent limit, so that as the road wears with time or as shallow ruts develop, some surface drainage still occurs. Figure 3-81 shows a well-maintained two-lane road with a distinct crown. Figure 3-82 shows a single-lane road that is outsloped.

Figure 3-81—A road with a good crown, where the road is half insloped and half outsloped, breaking surface water concentrations into two parts.

Figure 3-82—An outsloped single-lane road template, directing flow to and off the downhill shoulder.

See Skorseth et al. (2000) for more information on traveled way drainage needs and maintenance. The manual helps provide a better understanding of what makes good surface gravel and how to maintain and drain it. Link <http://www.t2.unh.edu/nltapa/Pubs/south_dakota_gravel_manual.pdf>.

Another reference on roadway drainage measures is “Introduction to Highway Hydraulics” (Schall et al. 2008). Schall et al. address many aspects of road drainage and the theory behind it. Link <http://www.fhwa.dot.gov/engineering/hydraulics/pubs/08090/HDS4_608.pdf>.

Flat, Entrenched Roads

With time, wear, and poor maintenance practices, many roads in very flat terrain become entrenched, effectively becoming a bathtub. Once this occurs, the road can be a pond or ditch where adequate drainage is very difficult or impossible to achieve (figure 3-83).

To avoid entrenched road problems and ensure good surface drainage, raise the roadway elevation above the elevation of the adjacent ground. Either fill the old road with imported material to raise the grade, or reconstruct a turnpike section where ditches are dug and the excavated material is used to elevate the roadway (figure 3-84). Often local excavated material is used and then capped with imported select material. Once the roadway elevation is raised above the local terrain, then water can be dispersed off the road. Also roadway ditches help separate the elevation of the road and local water level.

Figure 3-83—An entrenched road where water cannot be diverted off the road.

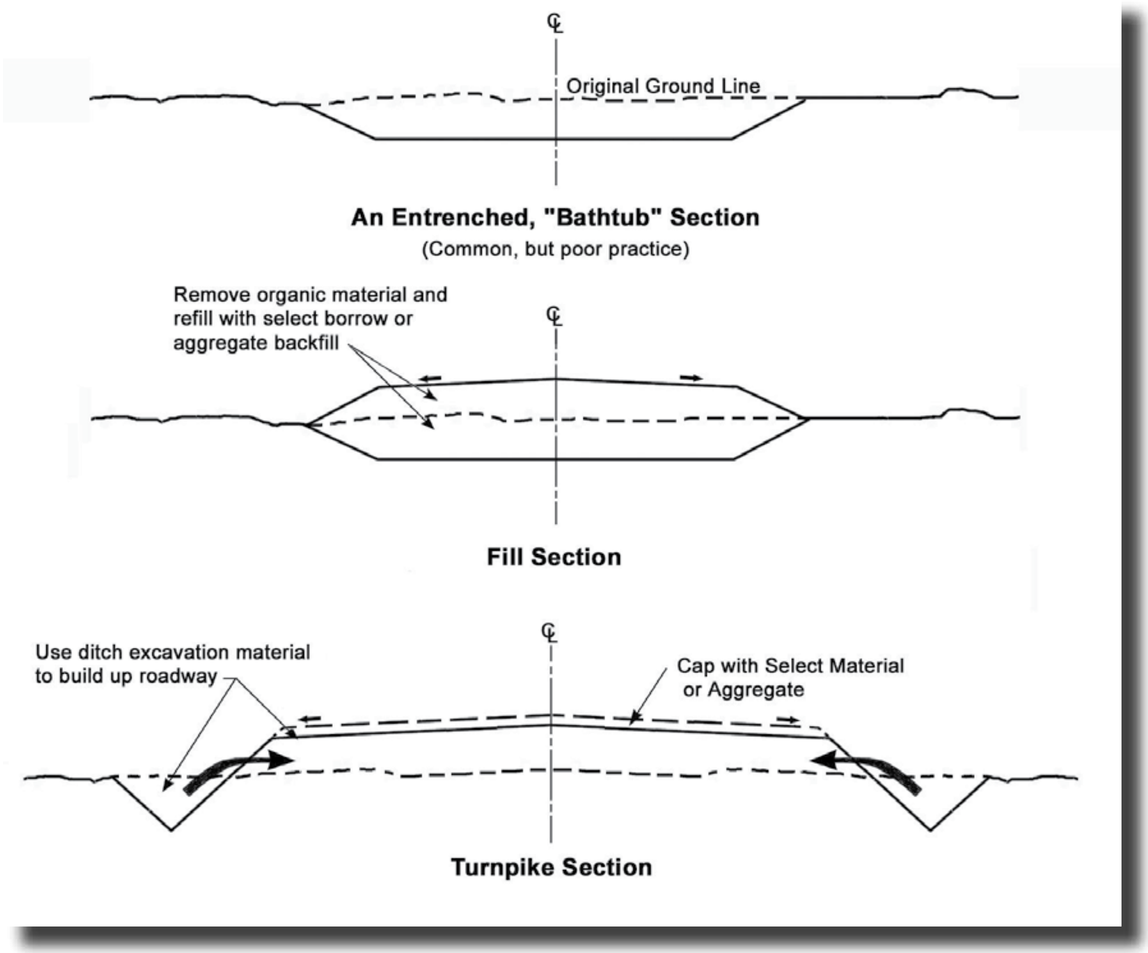


Figure 3-84—Methods for raising the roadway out of an entrenched bathtub section.

3.4.1.2. Culvert Cross Drains (Relief Culverts)

Culvert cross drains (relief culverts) move ditch water across the road. They are conduits buried beneath the road surface to discharge ditch water from the toe of the cut to the outside edge of the road. They are crucial on most insloped and crown roads to prevent excess concentration of water in the ditch. They are the most common type of road drainage ditch relief, and are most appropriate for high standard roads where a smooth road surface profile is desired. They also are very common on low standard roads anywhere a ditch is constructed. However cross-drain pipes are another expense and relatively small culvert pipes used for cross drains are susceptible to plugging.

Construct relief culverts with circular or arch pipes, or rectangular concrete or wood boxes. An 18-inch (500 mm) minimum diameter round culvert is most often used for ditch relief to help prevent failure from debris blockage. Smaller pipes plug very easily. If the pipe has plugged, then install a larger pipe, such as a 24-inch (650 mm) culvert. Also consider additional cross-drain pipes, thus reducing the spacing between the pipes. Calculate pipe size and spacing by using the rational formula with the small road watershed and local rainfall intensity-duration data. However, pipe size and spacing are more commonly based on local experience or on a recommended spacing from tables. Table 3-24 lists criteria for spacing ditch relief cross drains. Actual spacing can depend on ditch capacity to prevent overflow or limiting the volume of water to prevent erosion or formation of a gully at the outlet.

Install culvert cross-drain pipes with an ideal angle of 15 to 30 degrees perpendicular to the centerline of the road, using a minimum outslope of at least 2 percent, and an outslope at least 2 percent greater than the ditch grade to reduce siltation and prevent debris from plugging the culvert. Usually a berm or ditch-block structure is needed in the ditch immediately beyond the cross drain to insure that water turns and enters into the pipe. The pipe should exit at ground level to prevent a waterfall and erosion. In some cases, place rock armor at the outlet for energy dissipation and erosion control. Excess sediment in the ditch or pipe may be evidence of upslope instability that needs to be addressed by experts.

Table 3-24—Guidelines for maximum ditch relief cross-drain spacing in feet, based on ditch soil type (by VSCS).

Road Grade (percent)	Group 1 GW, GP, Aggregate Surfacing (feet)	Group 2 GM, GC (feet)	Group 3 CH, CL (feet)	Group 4 MH, SC, SM (feet)	Groups 5 and 6 SW, SP, ML (feet)
2	400	300	250	170	95
4	340	275	210	150	85
6	300	230	180	130	75
8	250	200	150	110	65
10	200	160	130	90	55
12	160	130	100	75	45
14	130	110	85	60	35

Conversion: 1 meter = 3.28 feet

The above guidelines should be adjusted according to the following (Packer and Christenson 1964):

1. Reduce the spacing by 15 feet (5 m) if the road is located in the middle one-third of a slope.
2. Reduce the spacing by 35 feet (11 m) if the road is located in the bottom one-third of a slope.
3. Reduce the spacing by 10 feet (3 m) if the road is on an east or west exposure.
4. Reduce the spacing by 20 feet (6 m) if the road is on a south slope.
5. If the resulting spacing after items 1 through 4 falls below 55 feet (17 m), use relief culverts at 55-foot (17 m) spacing and apply aggregate surfacing and erosion protection measures, such as vegetative seeding to ditches, road surface, fills, shoulders, and embankments.

Recommended Practices

- ❑ Use roadway ditch relief cross-drain structures (either pipes or rolling dips) to move water across the road from the inside ditch to the slope below the road. Space the cross-drain structures often enough to remove all surface water. Table 3-24 gives recommended cross-drain spacing.
- ❑ Install culvert cross drains with an angle of 0 to 30 degrees perpendicular to the road, using an outslope of 2 percent greater than the ditch grade to prevent plugging (figure 3-85).
- ❑ Use culvert cross drains on roads with an inside ditch and moderately fast vehicle speeds.

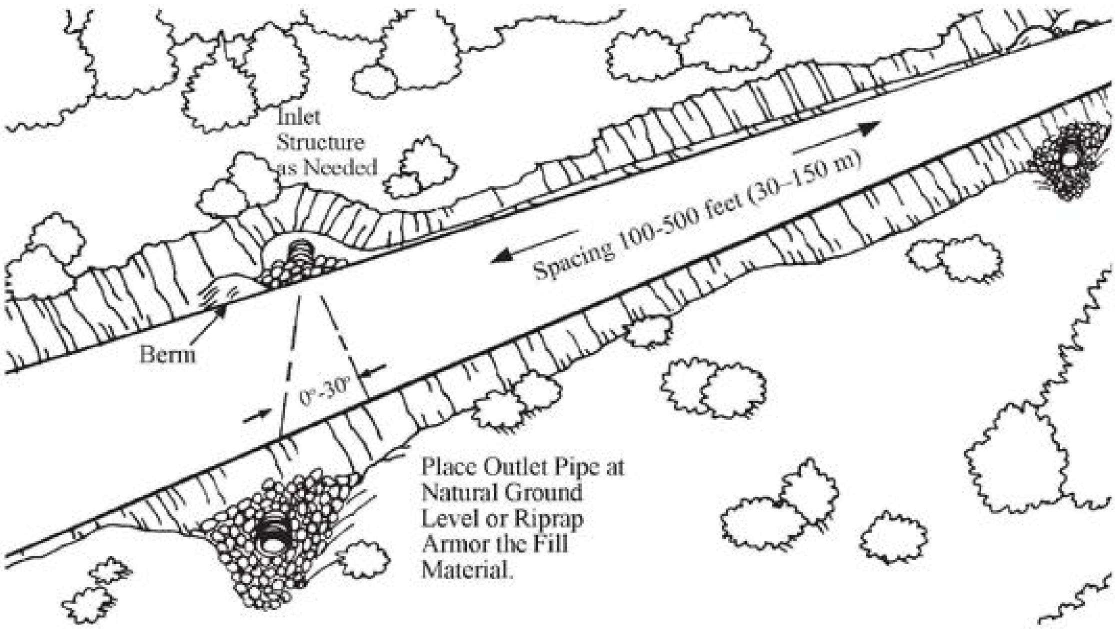


Figure 3-85—A typical culvert cross-drain installation.

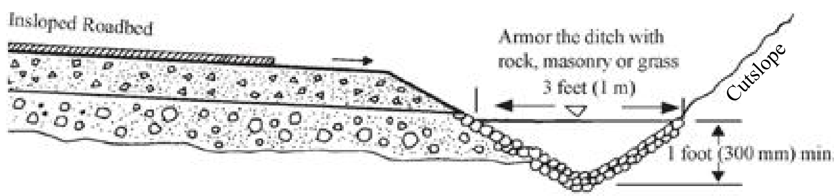
For additional technical information about cross-drain relief culverts, consult SDTDC WRIT publication Johansen et al. (1997) <http://www.fs.fed.us/eng/pubs/pdf/w-r/97771812.pdf> and chapter 7 of Keller and Sherar (2003). Link to the Web site <http://www.fs.fed.us/global/topic/welcome.htm#8>.

3.4.1.3. Ditches

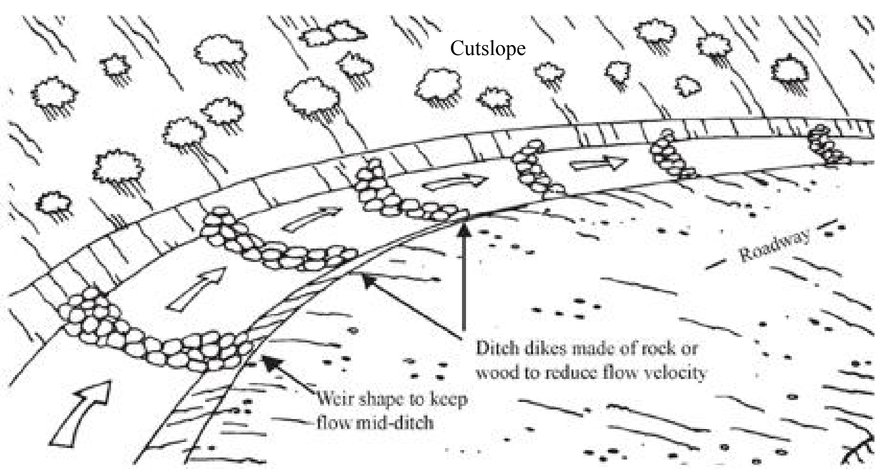
Ditches and channels should be hydraulically efficient, easy to maintain, safe for vehicles accidentally leaving the traveled way, and move water without erosion or damage to the adjacent land. The most efficient channel shape is a semicircle; a trapezoidal shape is ideal as a compromise between hydraulic efficiency and ease of construction and maintenance. However, a V-shaped ditch is most often used because of ease of construction and ease of maintenance with a motor grader. Avoid abrupt changes in ditch alignment or grade. A sharp change in alignment presents a point of erosion for the flowing water, and abrupt changes in grade cause deposition of transported material when the grade is flattened or scour when grade is steepened.

Systematic maintenance is essential to any drainage channel. Without proper maintenance, a well-designed channel can become a downcut ditch or gully. Consider maintenance methods in the design of ditches so that the channel sections are suitable for the methods and equipment used for their maintenance. Also on very flat grades, an unmaintained ditch can fill with sediment and debris or pond water allowing water to infiltrate, saturate, and damage the road subgrade.

Ditches, catch basins, ditch dams, and special inlet structures direct flow into relief culverts, which are spaced and located as dictated by ditch or culvert capacity or by site conditions. In erosive soils, reduce the ditch velocity with ditch dikes (check dams), or by armoring the ditch with rock riprap, grouted riprap, pavement, concrete, or masonry (figure 3-86). Although ditch lining is often necessary to control erosion, it also can make maintenance more difficult. Discharge from ditches along the road near drainages should be into vegetation or a stable area rather than directly into the drainage (figure 3-91).



a. Typical Ditch Armoring and Shape



b. Use of Ditch Dikes

Figure 3-86—Ditches with armoring and ditch-dike structures.

Catch-water ditches (intercept ditches) are used occasionally above a cutslope to intercept surface runoff and overland flow, particularly after forest fires. These ditches are useful to capture overland flow before it pours over the cutslope and erodes or destabilizes the cut. However, catch-water ditches are one more thing to maintain and, if not properly maintained, can pond water above the slope, increasing the probability of a slope failure.

Ditches are occasionally constructed along the outside edge of the road to prevent sheet flow off the road surface and protect specific areas below the road. This use is infrequent. Berms also may be used to keep water from flowing over the fillslope or to prevent roadway sediment from entering an adjacent stream. Note that either an outside ditch or a berm necessitates additional road width.

Recommended Practices

- ❑ Use frequently spaced leadoff ditches to prevent accumulation of excessive water in the roadway ditches.
- ❑ Use drop inlet structures with culvert cross drains to prevent ditch downcutting or, where space is limited, against the cutbank. Alternately, use catch basins excavated into firm soil.
- ❑ Discharge culverts and cross-drain dips at natural ground level, on firm, nonerosive soil, or in rocky or brushy areas. If discharged on the fillslopes, armor outlets with riprap or logging slash, or use down-drain structures. Extend the pipe 0.5 to 1.0 meters beyond the toe of the fillslope to prevent erosion of the fill material.
- ❑ Armor roadway ditches and leadoff ditches (in erosive soils) with rock riprap, masonry, concrete lining or, at a minimum, grass. Use ditch-dike structures to dissipate energy and control ditch erosion (figure 3-86).
- ❑ Discharge roadway drains in an area with infiltration capability or into filter strips to trap sediment before it reaches a waterway. Keep the road and stream hydrologically disconnected.

3.4.1.3.1. Control at Inlets and Outlets

Culvert Inlet Control Structures. Culvert inlet control structures (drop inlets) occasionally are placed in the inside ditchline at the location of a culvert cross drain. They commonly are constructed with concrete or masonry boxes or from round metal or concrete pipe. They typically are used where the ditch is eroding and downcutting, so that the structure controls the elevation of the ditch. Inlet structures also are useful to change the direction of water flowing in the ditch, particularly on steep grades, and they can help stabilize a steep cutbank behind the pipe inlet structure. To control the grade or elevation of the ditch, either the top of the pipe, or a concrete wall, or a window cut in the tube is set at the desired ditch elevation (figure 3-87). Thus, flow has to go over this edge at this elevation, preventing further ditch downcutting.

Figure 3-88 shows a drawing with drop inlet details for drop inlets using either corrugated metal pipe or a masonry inlet structure with a sand trap.

Figure 3-87—Typical drop inlet structure.

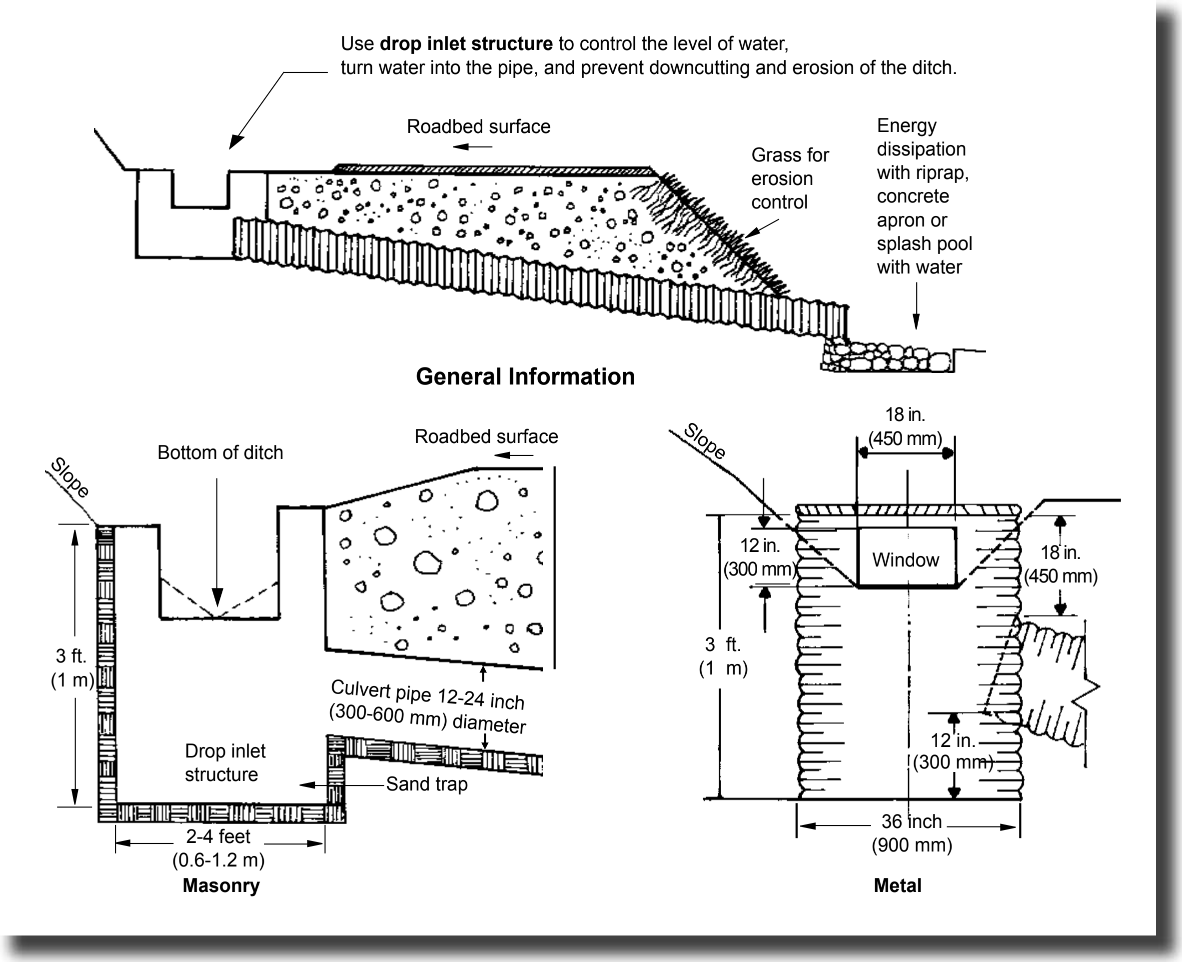


Figure 3-88—Drop inlet design and installation details.

Use culvert inlet structures that are large enough to prevent debris accumulation and that are easy to clean and maintain. Concrete box inlets are particularly useful to stabilize the ditch elevation before entering the culvert, as well as the excavation backslope. Additionally concrete and masonry box structures often have a bottom set below the cross-drain pipe elevation so that this area or reservoir serves as a trap for sediment. Then the trapped sediment can be cleaned out periodically.

If inlet control structures or drop inlets are not used, then earthen catch basins excavated into the surrounding soil normally are used to concentrate the flow and funnel it into the cross-drain pipe. This type of catch basin is simple to excavate and inexpensive, but will not hold the elevation of the ditch in erosive soils. Also since the catch basin is several feet (at least 2 m) in diameter, it can be difficult to construct in rocky terrain, on steep slopes, and on very narrow roads.

Outlet Energy Dissipators. The pipe and dip outlets ideally are located in a stable, nonerosive soil area, or in a well-vegetated or rocky area, away from a live stream. The accelerated velocity of water leaving a roadway ditch or culvert pipe can cause severe erosion or gullying if discharged directly onto erosive soils. Stabilize the pipe, dip, or drain outlet, and dissipate the water's energy by discharging the water onto a few cubic yards (1-2 m³) of a graded rock riprap (figure 3-89). Other energy dissipation measures include stilling basins, reinforced splash aprons, gabion baskets, or dense vegetation, logs, boulders, or bedrock.

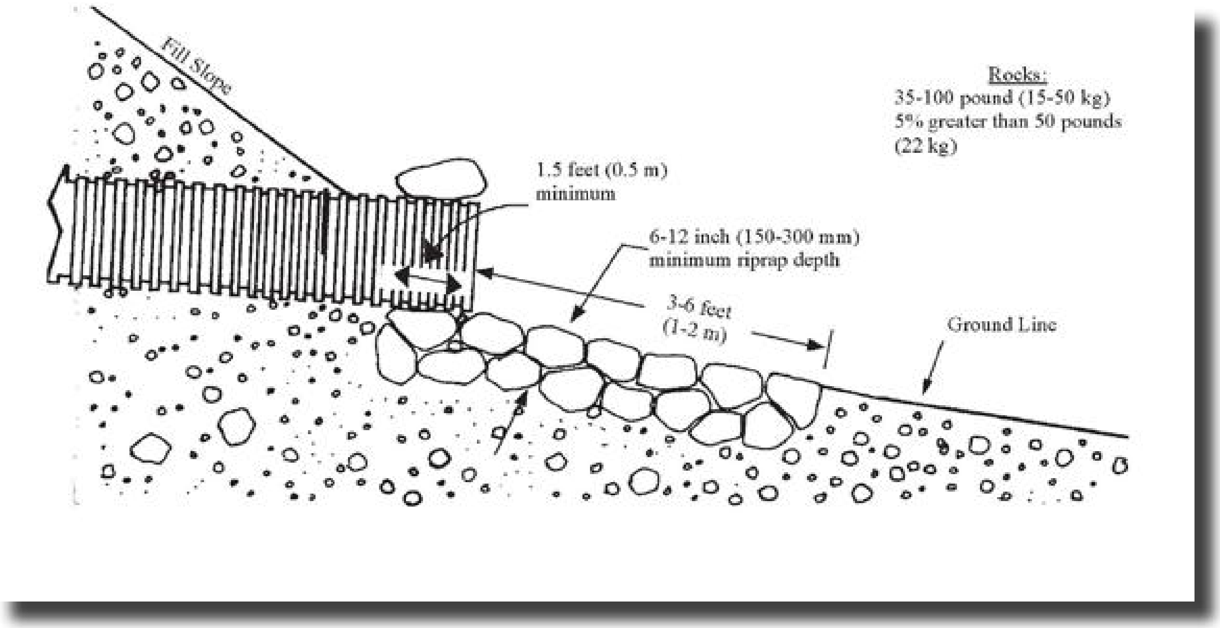


Figure 3-89—Drawing for riprap pipe outlet protection and slope stabilization.

Discharge Location. Align and discharge culverts and cross-drain dip-drainage structures at the natural ground level and in stable areas, such as an existing natural channel, rocky area, or well-vegetated area. Alternatively, discharge the water onto slash and limbs, imported riprap, or any material that dissipates the water's energy. When using slash, press the material into good contact with the ground, or mix with varying sizes of debris to provide a ground surface protection layer.

A pipe should discharge beyond the toe of any fillslope. Extend the pipe 2 to 3 feet (0.6 to 1.0 m) beyond the toe of the fillslope to prevent erosion of the fill material. In high fills one might need a down-drain pipe or armored channel to safely convey the water to the toe of the fill. Figure 3-90 shows the ideal way to bury a cross-drain pipe under the fill and exit at the toe of a fill.

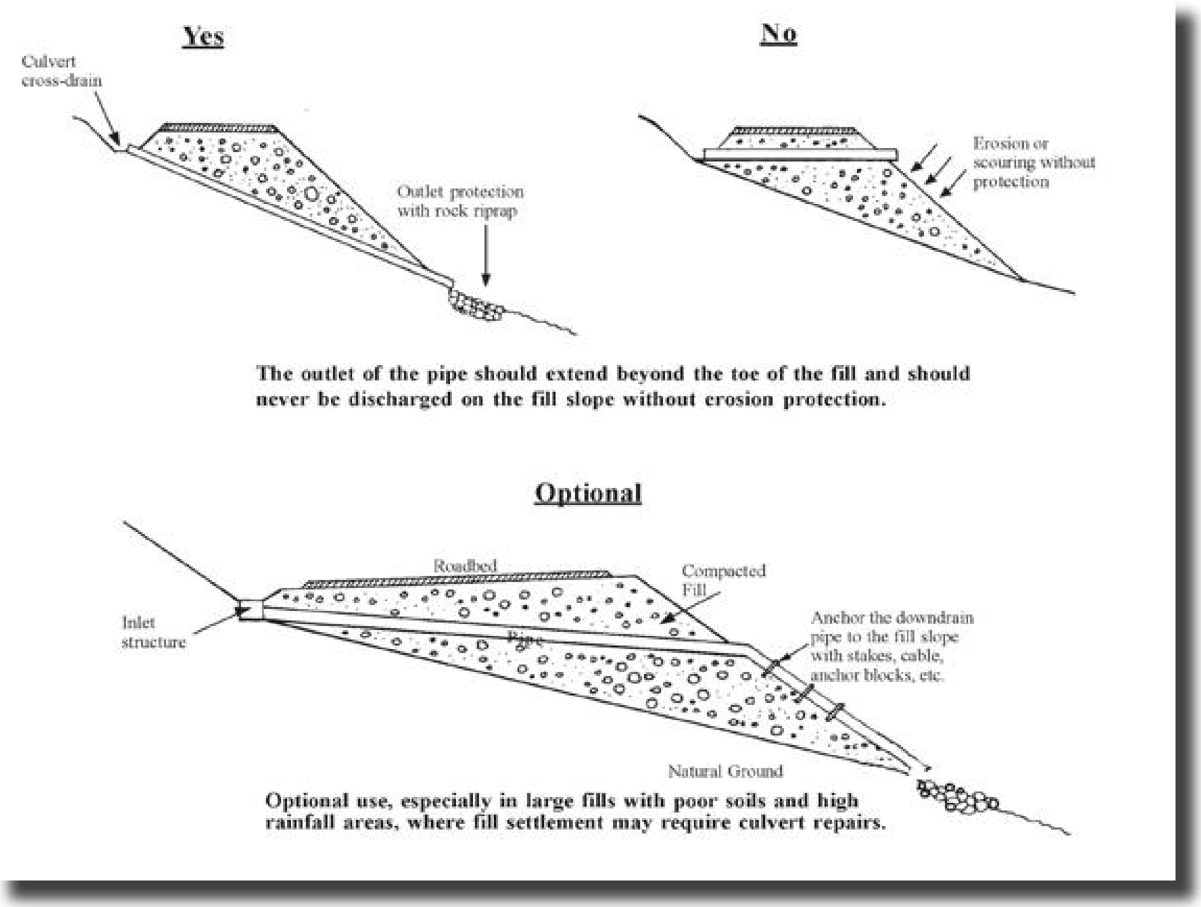


Figure 3-90—A cross-drain pipe should exit at the toe of a fill.

Ideally, discharge roadway cross drains and leadoff ditches into an area with infiltration capability or into filter strips of vegetation (figure 3-91) to trap sediment before it reaches any waterway. Keep the road drainage system and streams hydrologically disconnected.

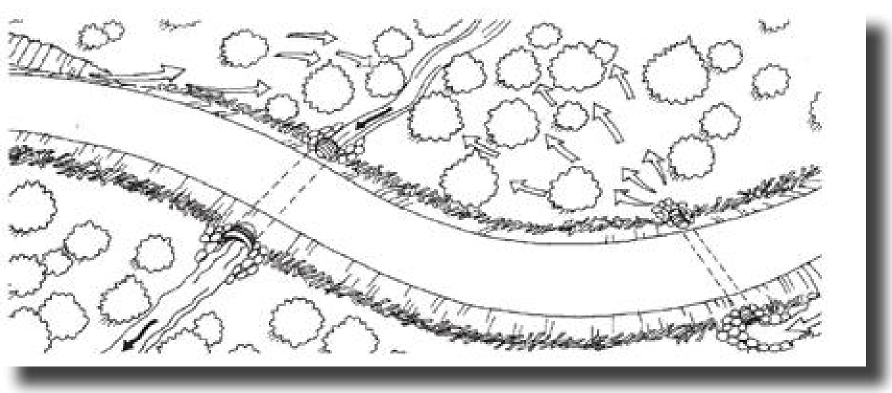


Figure 3-91—Basic road surface drainage with leadoff ditches and culvert cross-drains exiting into a vegetated buffer area before entering the stream. (Adapted from Montana State University 1991)

If replacing cross-drain culvert pipes, grade should be such that it maintains the velocity of the water entering the culvert. If the water velocity slows at the pipe inlet, bedload deposition occurs. If the velocity is increased, scouring occurs at the exit with a possible hydraulic jump and siltation. The critical slope for corrugated metal pipe (CMP) with inlet control is less than 4 percent. Any increase in slope does not increase capacity, but increases velocity. Use Manning's formula to calculate velocity.

3.4.1.3.2. Ditch Leadoffs

Ditch leadoffs (or leadoff ditches, or turnouts) are another way to discharge water and prevent accumulation of excess water in the roadway ditches (figure 3-92). They are an inexpensive alternative to culvert cross drains and should be used at any opportunity possible where the terrain is suitable.

They are used in flat terrain where there is not a cutbank at approaching drainage crossings, and at fill areas across a swale or ravine. As with rolling dips or culvert cross drains, they should be discharged in nonerosive areas or protected outlets. Discharge the water into the forest or a vegetated area before the ditch reaches a live stream.

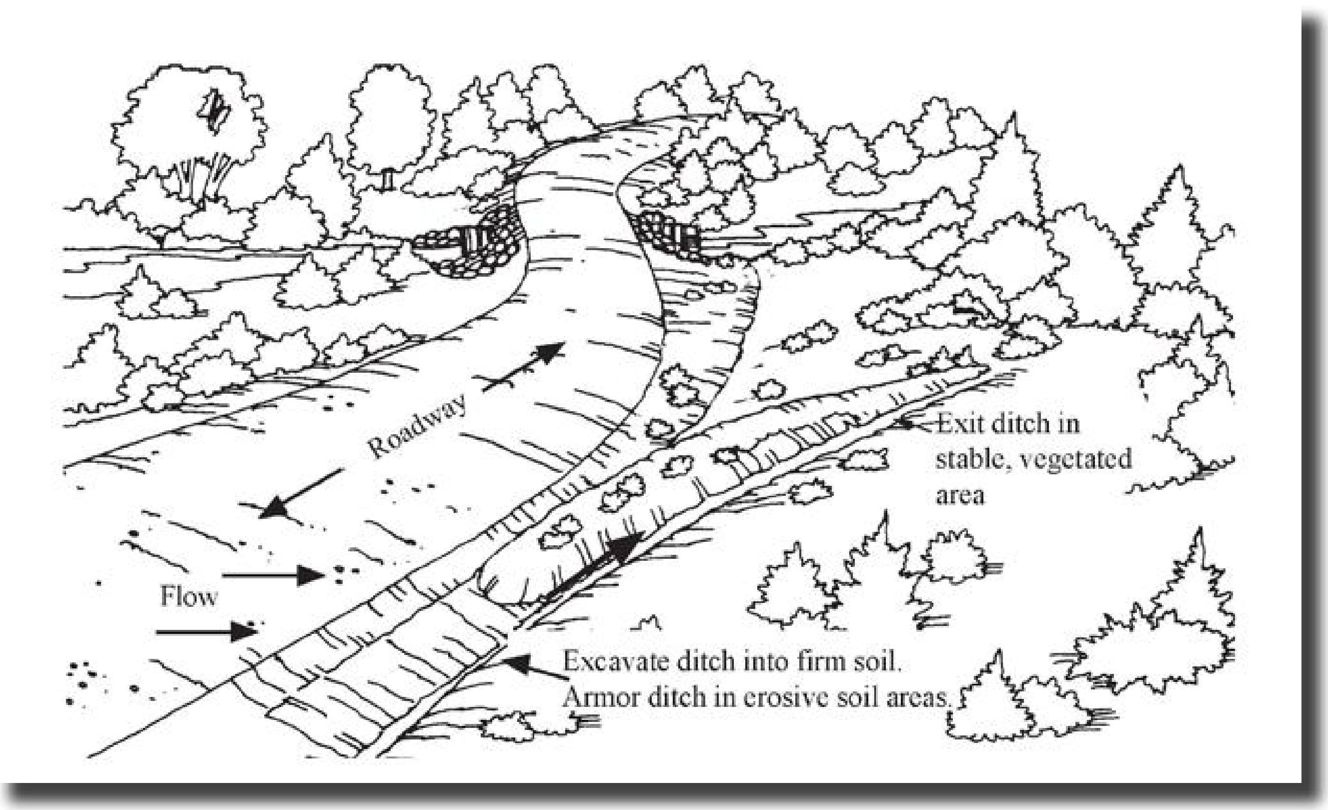


Figure 3-92—Ditch layout and leadoff near a stream (Adapted from Wisconsin's Forestry 1995 Best Management Practices for Water Quality).

3.4.1.3.3. Ditch Rock Check Structures (Dams)

Rock check dams that are built into a ditch or gully can be made with many types of materials, including sand bags, loose rocks, masonry or concrete, branches and straw or brush, logs, live vegetation, gabions, posts and brush, and other material combinations. Of all these materials, loose rock is one of the most commonly used and most effective designs (figure 3-93). Try to use local native materials whenever possible for practical and cost considerations.

Check dams decrease the velocity of water moving down the ditch or gully. By decreasing the velocity, silt and debris are deposited in the ditch instead of additional bed material being eroded away. Reducing the effective gradient of the channel decreases the water's velocity. By constructing a series of check dams along a ditch, a channel of relatively steep slope, or high gradient, is replaced by a stair-stepped channel. Water successively flows on gentle slopes between structures, and then cascades over the stabilized structure.

The California Division of Forestry (1968) presents some criteria for spacing of check structures in roadside ditches, as a function of ditch grade and assuming check structures are 12 inches (300 mm) high.

- ❑ For grades less than 4 percent, spacing is 50 to 100 feet (15 to 30 m).
- ❑ For grades 4 to 7 percent, spacing ranges from 25 to 50 feet (8 to 15 m).
- ❑ For grades 7 to 10 percent, spacing ranges from 12 to 25 feet (4 to 8 m).
- ❑ For grades over 10 percent, spacing is generally less than 12 feet (4 m).

These spacing values are approximate, and can be proportionally greater in a deep ditch with 18-inch-high (450 mm) dike structures. Adjust spacing for local soil and rainfall conditions, particularly based upon field performance of the structures and maintenance frequency.

Rock check structures need maintenance to remove sediments and they are labor intensive to build, but they are very effective in reducing flow velocity and trapping sediment. Depending on spacing and location, they can be difficult to maintain. They are dam-like structures, so they have design details that are needed to make them function properly. They are weirs, so they need a V shape over the top to keep the flow in the middle of the ditch and prevent an end run around the structure that can cut into the road. Also the structures need to be placed firmly against or into the soil.

Figure 3-93—Rock check structures in the ditch (Oroville-Quincy Highway).

3.4.1.3.4. Vegetative-Lined Ditches

Vegetative-lined ditches, typically using grasses, offer ground cover, root strength, and soil erosion protection with inexpensive and aesthetic natural vegetation, as well as help to control water and promote infiltration (figure 3-94). Ideally one selects grasses for good growth properties, hardiness, dense ground cover, and deep roots to stabilize the ditch. Vegetative ditches are common but need periodic maintenance to remove sediments.

Grasses are the ideal ditch liner on gentle slopes or nearly flat ground. It often is suitable on ditch slopes of up to 5 to 10 percent, depending on soil and grass type, and climate. On steeper slopes grasses may be inadequate and more durable ditch protection is needed, such as a turf reinforcing mat, rock riprap, a masonry liner, and so forth. Also vegetative-lined ditches can be difficult to maintain. On flat slopes with a lack of maintenance, the vegetation (as well as other debris) can block the flow and pond water, thus saturating the adjacent road.

Figure 3-94—A vegetative-lined ditch.

3.4.1.3.5. Rock-Armor Ditch

Water that runs in the ditch can erode and move large quantities of soil and debris. One can armor an eroding ditch with graded rock to decrease the velocity of water, prevent erosion and downcutting, and allow the deposition of sediment (figure 3-95). Use small rock riprap as a lining material. A graded 3- to 6-inch (75 to 150 mm) rock size is ideal. One also can place a geotextile under the rock as a filter to separate the rock from the soil and keep soil from eroding under the rock.

By decreasing the velocity, silt and debris are deposited in the ditch instead of additional bed material being eroded away. Increasing the roughness of the ditch decreases the velocity of water. Rock-armor ditches are common but need periodic maintenance to remove sediments. They are labor intensive to build initially and can be difficult to clean and maintain.

Figure 3-95—A rock-armored ditch to control the waterflow and prevent downcutting of the ditch.

3.4.1.4. Berm and Downdrains

Use berms on the downhill shoulder of the traveled way to direct surface flow away from erosive fillslopes or sensitive areas, and to move water to a downdrain (figure 3-96) and (figure 3-90, optional design). Restrict berms to areas of need, as they require increased road corridor width and excavation quantities, while adding weight to fills, and concentrating the water somewhere else. In very erosive soils and new fill construction, use berms along the outside edge of the road to prevent initial erosion of the fill. However once the fill has stabilized and become vegetated after a few years, remove the berm and allow water to sheet off the road (assuming the road has a crown or is outsloped).

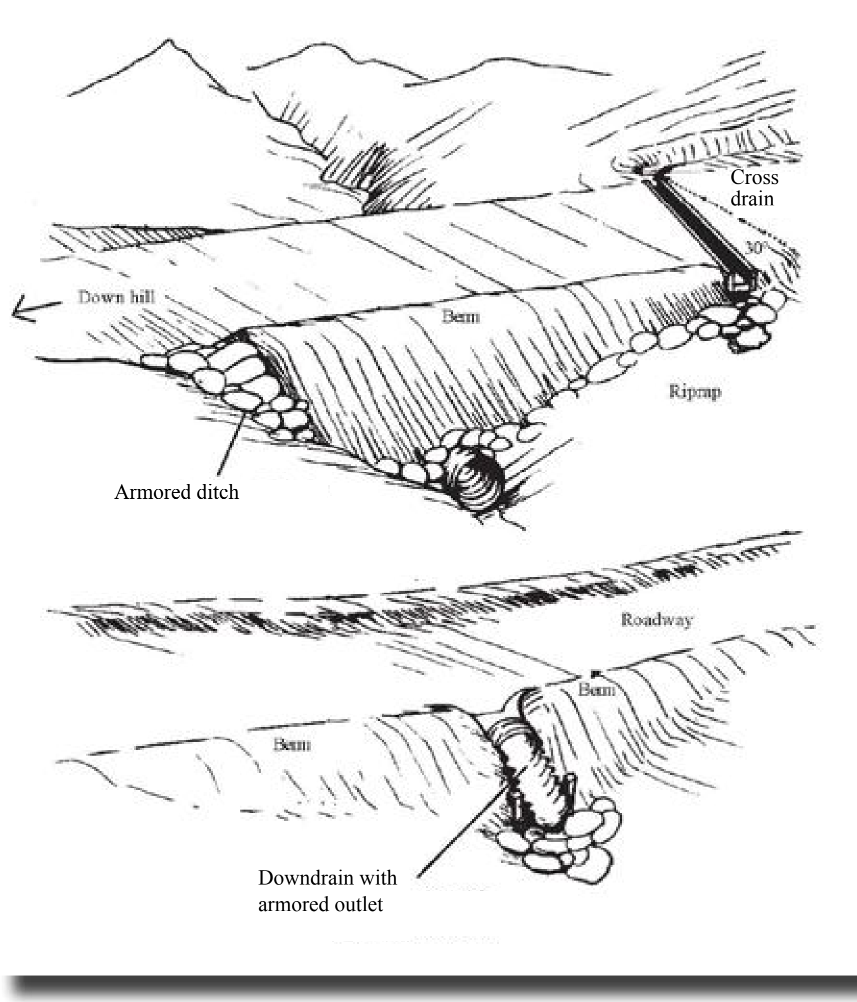


Figure 3-96—Berm and downdrains to protect the fillslope.

Road maintenance equipment operators often create and perpetuate berms in their road grading work (figure 3-97). However, only use berms based on input from a specialist who indicates that the berms are required, not berms created by poor road maintenance practices.

Figure 3-97—A berm formed at the edge of the road, typically by poor grader maintenance practices.

Use downdrains in conjunction with berms and curbs to move water down a fillslope or erosive embankment in a protected channel. Downdrains are made of many materials including pipes, half-round pipes, metal flumes, large rubber hoses, rock-lined channels, and concrete and masonry structures. The key advantage of downdrains is that water moves to the toe of a fillslope or to a specific erosion-resistant area in a protected channel. Thus downdrain location depends on the local soils and site conditions.

The disadvantage of a downdrain is that it requires installation detail to ensure that water gets into the downdrain without eroding or washing out around the downdrain entrance. Many downdrain units wash out because water gets behind or under the inlet. Good compaction or stabilized soil, concrete, or asphalt is needed around the inlet area (figure 3-98). Also pipe and flume downdrains need to be well anchored to the slope and their outlet protected with an energy dissipator (figure 3-90, optional design for downdrains). They too require occasional maintenance.

Figure 3-98—A downdrain used to move water to the toe of the fill.

3.4.1.5. Waterbar

Waterbars gather and block surface water running down a road, firebreak, or trail; prevent concentrated water flow from accelerating down a sloping road; prevent excessive erosion until natural or planted revegetation can become established; and divert water off a road. Waterbars are typically used on roads that are closed or limited-use roads and trails. It is an excellent method of closing or decommissioning roads and trails as well as abandoned roads where surface water running down the road may cause erosion of exposed mineral soil.

Waterbars commonly are used on closed, inactive roads, or skid trails and may be fairly high and deep to prevent traffic from crossing over them. Spacing may be quite close, depending on road grade and soil type, such that erosion does not occur between waterbars. Waterbars are installed on grades up to 30 percent or more.

Drivable waterbars, as shown in figure 3-99, have the same function as normal waterbars (to impede waterflow down a road) but are constructed in a manner such that high-clearance vehicles or 4-by-4 vehicles can reasonably drive over them. Drivable waterbars are occasionally used on inactive roads, and 4-wheel drive roads that receive little use yet occasionally need to pass vehicles. Spacing of waterbars is much closer than spacing of rolling dips or cross drains. Most drivers do not like waterbars and tend to blade them out during periods of road use, such as a fire or log haul. Once use of the road is finished, then reinstall the waterbars.

Recommended Practices

- Construct waterbars on infrequently used roads or closed roads to control surface runoff.
- Construct waterbars angled at 0 to 25 degrees to the direction of the road; with an outslope of 3 to 5 percent; and a height of 1 to 2 feet (300 to 600 mm) (figure 3-99). Waterbars are not dams, and water can usually drain out from behind them. Waterbars intercept and/or divert surface water runoff.
- Space waterbars between 30 and 150 feet (10 to 50 meters), as shown in table 3-25. Spacing may be farther apart on flat, rocky terrain. Nondrivable waterbars may be closer together on very steep skid trails.
- Spacing for waterbar construction on forest roads, trails, and firebreaks must be site specific and adapted to existing soil and slope conditions.

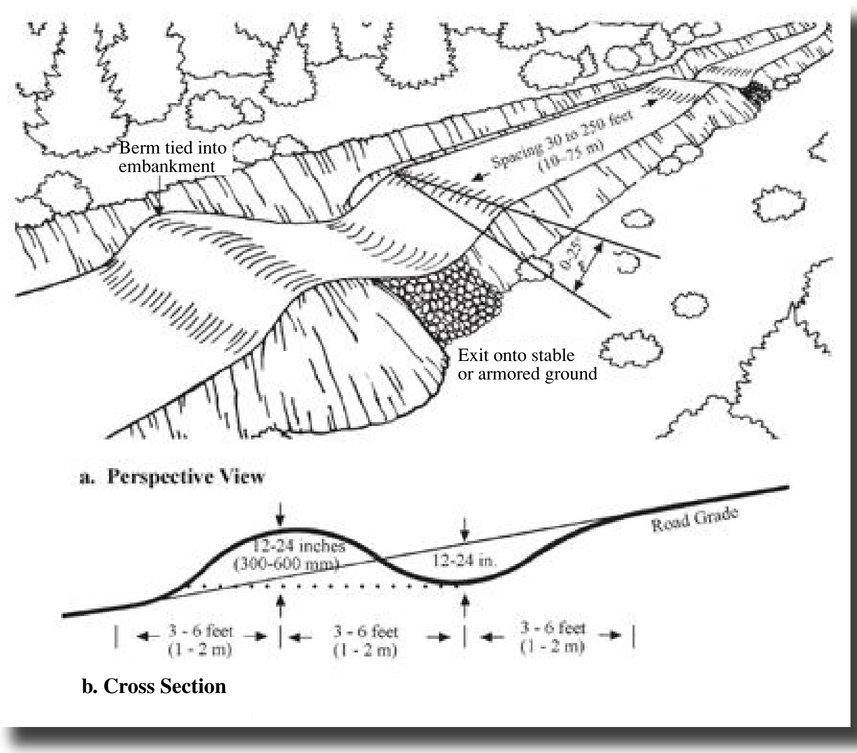


Figure 3-99—Drivable waterbar construction. Adapted from Wisconsin's Forestry Best Management Practices for Water Quality (1995).

Table 3-25—Recommended waterbar spacing (feet).

Recommended Waterbar Spacing (feet)		
Road/Trail Grade %	Low to Nonerosive Soils (1)	Erosive Soils (2)
0-5	250	130
6-10	200	100
11-15	150	65
16-20	115	50
21-30	100	40
30+	50	30

Note:
(1) Low erosion soils = coarse rocky soils, gravel, and some clay.
(2) High erosion soils = fine, friable soils, silt, fine sands.
Conversion: 1 meter = 3.28 feet
Adapted from Packer and Christensen (1964); Copstead et al. (1998).

3.4.1.6. Rolling Dips (Broad-Based Dips)

Rolling dips, or broad-based dips, are designed and constructed in new and existing low-speed roads, for diverting and removing water off the road surface, as well as draining any roadway ditch. They are designed to divert water safely off the road while allowing the passage of traffic. Figure 3-100 and figure 3-101 show the form of two different rolling dips. Rolling dips are a cross between a waterbar and a grade break. They have a reverse grade to direct water off the road rather than on down the road. Like waterbars, they rely on a mound of soil at the downhill side to stop the water. Rolling dips are an alternative to conventional ditch relief cross-drain culvert pipes, but they have the added advantage that they drain the roadway surface as well as the ditch.

Figure 3-100—Rolling dip (broad-based dip) cross drains.

Figure 3-101—Rolling dip cross drains are not susceptible to plugging when shaped properly.

Rolling dips cost less, require less maintenance, and are less likely to plug and fail than culvert cross-drain pipes. Rolling dips are ideal on low-volume, low- to moderate-speed roads (15 to 30 miles per hour (25 to 50 kilometers per hour)). Other roadway surface cross-drain structures occasionally used to divert water off the road surface are open-top box wood or metal flumes, and rubber water deflectors.

Do not construct rolling dips on road grades over about 12 percent. Rolling dips occasionally are constructed on steeper road grades, but the excavation becomes significant with construction of a canyon in the road to adequately turn the water off the roadway. Consequently, sight distance is poor and they are not practical or cost effective on steep grades.

Use rolling dips just downslope of a drainage crossing to prevent stream diversion in case the drainage crossing culvert plugs and sends water down the road. With a dip, water can be diverted back into the natural drainage before flowing down the road and causing damage.

Information on diversion potential, using culvert overflow protection, or diversion prevention dips is presented in section 3.5.1.2 and in Furniss et al. (1997). Link to the document <http://www.fs.fed.us/eng/pubs/pdf/w-r/97771814.pdf>.

Construct rolling dips either perpendicular to the road, or at a maximum skew of 25 degrees to minimize damage to truck frames driving through them (figure 3-102). The bottom of the dip should have a 2- to 5-percent outslope to ensure positive drainage. The entire structure should be long enough, typically 50 to 200 feet (15 to 60 m) long, to comfortably pass vehicles and equipment. They need to be moderately deep to function properly, have a distinct reverse slope into the dip to properly drain water off the road, and constructed using a hand level, rod, and tape (or other simple survey instruments) to establish the proper grades. Armor the mound and dip with gravel or rock, particularly in soft soils, to maintain the shape of the rolling dip after traffic use. Also armor the dip's outlet.

During an active log haul, rolling dips are often graded out or smoothed out to facilitate driving over them. However, they may not work for water diversion during this interim period. Once haul is completed, reconstruct the rolling dips into the road. On most low-volume forest roads, rolling dips are very desirable and are a very cost-effective way to achieve good road surface drainage, whether the road is new or being rehabilitated!

Recommended Practices

- ❑ Use rolling dip (broad-based dip) cross drains to move water off the road surface efficiently and economically, without the use of culvert pipes.
- ❑ Construct rolling dips rather than culvert cross drains for typical, low-volume, low-speed roads with grades less than 12 percent.
- ❑ Construct rolling dips deep enough to provide adequate drainage, angled 0 to 25 degrees from perpendicular to the road, with a 4- to 6-percent outslope, and long enough (50 to 200 feet (15 to 60 m)) to pass vehicles and equipment (figure 3-102).
- ❑ In soft soils, armor the mound and dip with gravel or rock, as well as the dip's outlet.
- ❑ For recommended rolling dip spacing, see table 3-26. Adjust these distances using judgment and site-specific conditions.
- ❑ See figure 3-103, a drawing for rolling dip designs used for different vehicle types.

The recommended spacing varies widely among professionals. Spacing for maximum distance between rolling dips cross-drain construction on forest roads must be site specific and adapted to existing soil and slope conditions. The spacing (distances) presented in table 3-26 are typical values used in erosive and nonerosive soils to minimize rilling in the road surface. To ensure that the location will not erode or form a gully, visit the site and adjust the specific spacing and discharge location. Ideal dip or cross-drain exit locations are in brushy areas, rocky areas, or natural drainage areas or ravines.

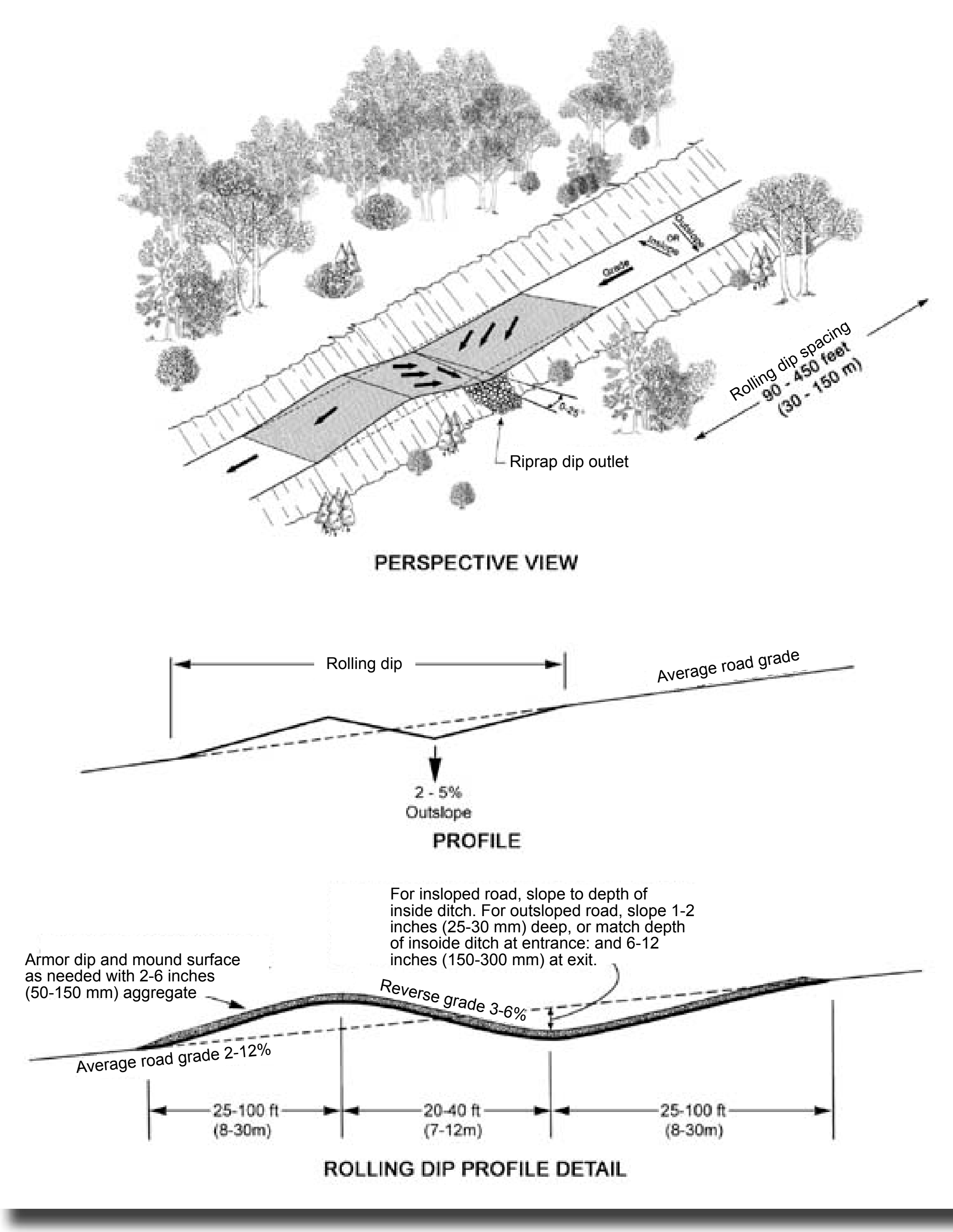


Figure 3-102—Rolling dip perspective and profile form.

Table 3-26—Recommended maximum distance between rolling dip cross drains (feet).

Recommended Maximum Distance Between Rolling Dip Cross Drains (feet)		
Road Grade %	Low to Nonerosive Soils	Erosive Soils
0-3	400	150
4-6	325	125
7-9	250	100
10-12	200	75
12+	150	50

Conversion: 1 meter = 3.28 feet

Adapted from Packer and Christensen (1964); Copstead et al. (1998)

Different design vehicles have different rolling dip geometric requirements so that the vehicle can drive over the dip without damaging the dip or the vehicle. High-clearance vehicles can pass over short, deep rolling dips or drivable waterbars. Low-clearance vehicles, particularly “low-boys” and chip vans, require a longer, shallower dip and a more gentle transition into and out of the dip. Figure 3-103 presents a typical drawing with construction requirements for three different design vehicles (low-boy, logging truck, and pickup truck). A Forest Service engineer in region 6 has developed an Excel spreadsheet program useful for rolling-dip design. The design vehicle type and its dimensions can be entered to determine the needed dip dimensions and distances. This program is available through the Forest Service’s regional engineering office in Portland, OR.

For additional technical information about cross drains, consult “Introduction to Surface Cross Drains” (Copstead et al. 1998) and chapter 7 of Keller and Sherar (2003).

Link to the Copstead et al. document <http://www.fs.fed.us/eng/pubs/pdf/w-r/98771806.pdf>.

Link to the Keller and Sherar Web site <http://www.fs.fed.us/global/topic/welcome.htm#8>.

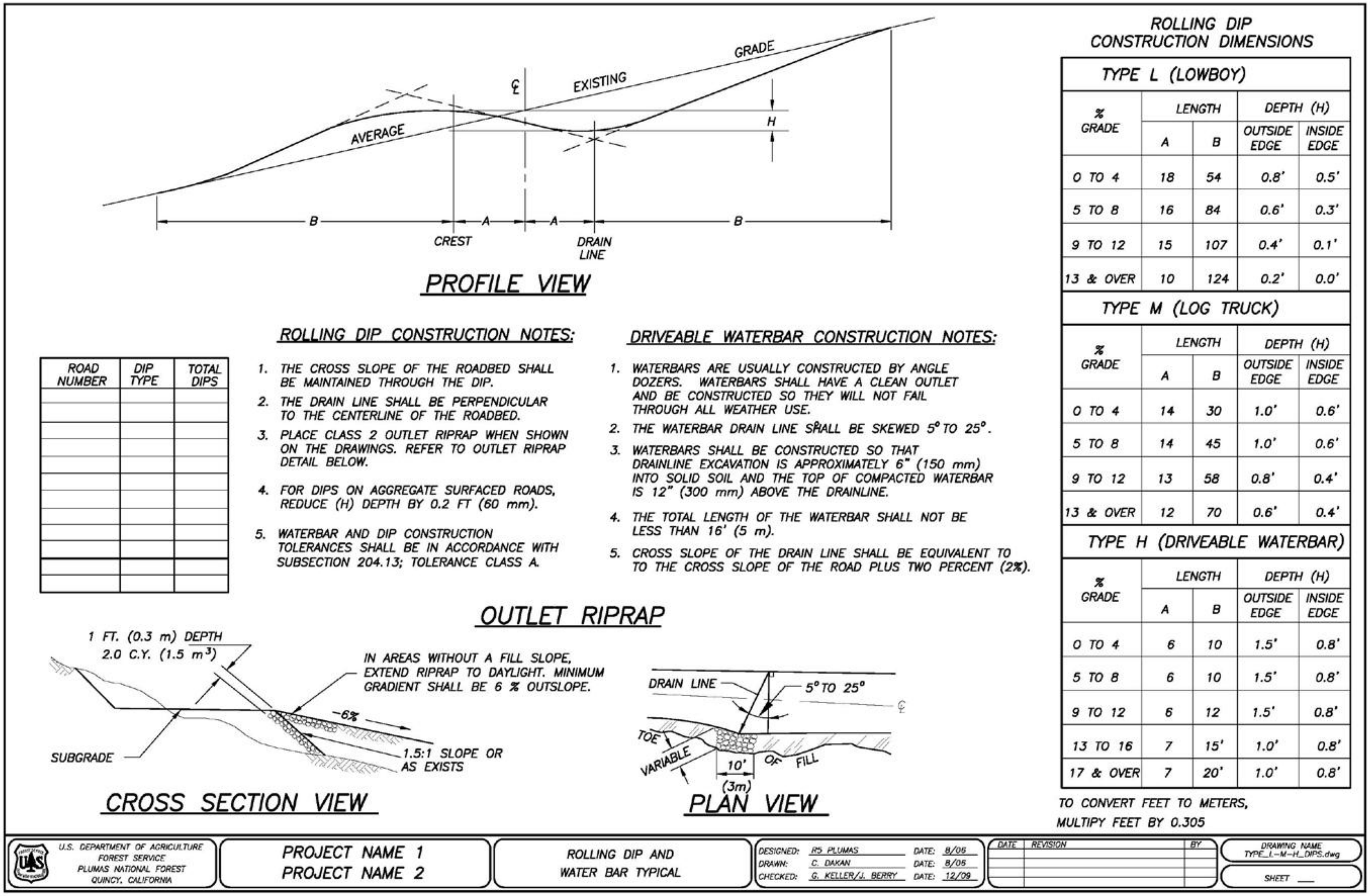


Figure 3-103—Rolling dip drawing. (Note that dimensions are in feet. To convert to metric multiply feet by 0.3.)

Dip cross-drain spacing also can be determined based upon sediment yield. The X-DRAIN model is a user-friendly computer program based upon the water erosion prediction project (WEPP) developed to predict an estimate of sediment yield from roads, landings, or trails, depending on climate, local soils, and road conditions. Use X-DRAIN to determine the optimum cross-drain spacing for a given acceptable amount of sediment yield, or estimate the sediment yield from a given segment of road. Information on the use of X-DRAIN is found in the WRIT publication Elliot et al. (1998).

Link to the document <http://www.fs.fed.us/eng/pubs/pdf/w-r/98771801.pdf>.

Rolling Grades (Grade Breaks)

Rolling grades, or constructed grade breaks, are a method of undulating or changing the road profile and slope frequently to prevent the concentration of water and facilitate frequent dispersion of the water for the road surface (figure 3-104). Ideally the road profile can take advantage of natural grade brakes in the terrain and the road can conform to the terrain, thus minimizing the height of cuts and fills. This practice is only recommended for relatively low-speed, low-volume roads but is highly desirable as fundamentally built-in water concentration prevention.

Build rolling grades into the road initially during new construction. However, use every opportunity to roll the grades during any road repairs or road reconstruction.

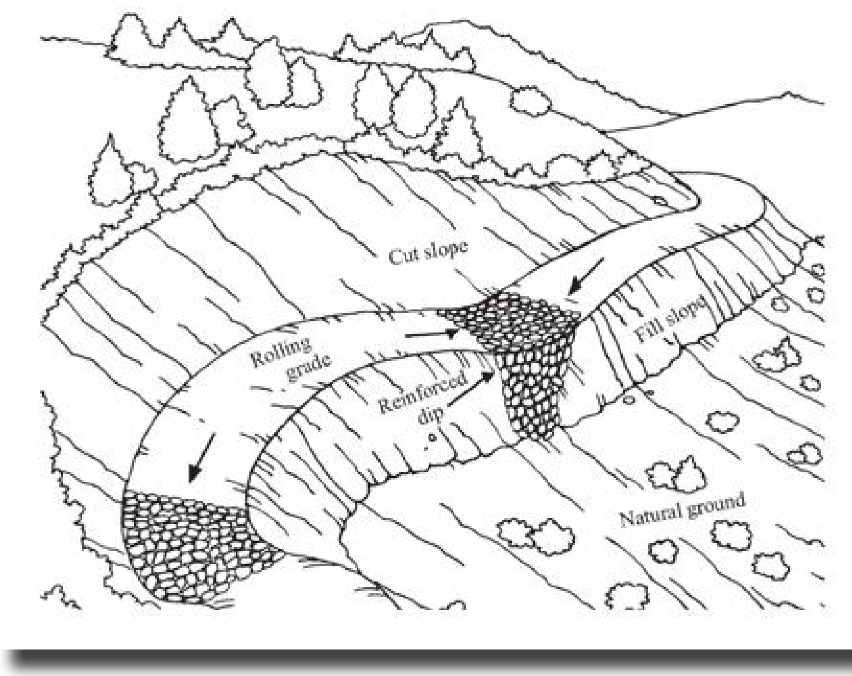


Figure 3-104—Basic road surface drainage with rolling grades and reinforced dips.

3.4.2. Subsurface Drainage Solutions

Subsurface drainage intercepts, collects, and removes ground water that may flow onto the roadway, into the subgrade, or into cut and fillslopes. Drainage can lower the ground water table or drain specific pockets of water, spring areas, and so forth.

Water may be present under the road surface because of infiltration of surface and ground water. Water can seep down through unsealed surfaces or move laterally along fractures or the top of impervious soil or rock layers. Ground water may pond above impervious strata to form a perched water table, exiting in local spring areas. Subsurface drainage is recommended when there is significant ground water, and the potential for pore pressure buildup. Without proper drainage, subsurface water weakens the soils, particularly if clay or silt rich, causing slope stability problems or soft spots in the road. Under repeated loading from traffic, moisture pumps to the surface, further reducing the structural capacity of even relatively good soils.

There are several methods of removing subsurface water from the road subgrade or structural section. Subsurface drainage, through use of underdrains or aggregate filter blankets, is commonly used along a road in localized wet or spring areas, such as a wet cutbank with seepage, to specifically remove the ground water and keep the roadway subgrade dry.

Properly designed and maintained surface drainage systems, such as ditches, may reduce the need for special subsurface drainage structures. However if ground water is encountered, either an underdrain or a filter (drainage) blanket is needed. Horizontal drains also may be used, but typically are installed to solve specific slope stability problems. In a soft roadway subgrade area, the road may be repaired with the application of a thicker structural section, such as more rock, but it usually is more cost effective to drain the area.

Useful information on subsurface drainage measures as well as all aspects of drainage can be found in the classic text “Seepage, Drainage and Flow Nets” (Cedergren 1997). A digital version is available at <http://books.google.com.mx/books?id=xD4ouHFvp_wC&printsec=frontcover&dq=cedergren,+Drainage&source=bl&ots=v6xgyGVsVz&sig=_HL_FODLXaEYGI-K8nJVVQVT7NQ&hl=es&ei=702BS_yZC4H-sgOKmY2SBA&sa=X&oi=book_result&ct=result&resnum=1&ved=0CAkQ6AEwAA#v=onepage&q=&f=false>.

Information for monitoring ground water levels and determining the effects of roads or other management activities on ground water resources can be found in the WRIT series publication Hartsog et al. (1997). The document is available at <http://www.fs.fed.us/eng/pubs/pdf/w-r/97771804.pdf>.

3.4.2.1. Underdrains (With or Without Pipe)

Construct underdrains by digging a trench that intercepts the ground water, installing a perforated pipe in the bottom of the trench, and backfilling the trench with a drain rock (free-draining coarse sand or gravel). Surround the pipe and gravel with a geotextile to serve as a filter to drain the water yet retain the soil and keep the filter rock from getting contaminated with soil, and losing its permeability. Water is removed from the area in the perforated (and then solid) drain pipe that crosses the road in a trench and daylights on the fill side of the road. Figure 3-105 shows the design and installation details of a vertical trench underdrain. Geocomposite drains also are used today, as explained in the following section.

Most underdrains are excavated 4 to 6 feet (1.3 to 2 m) deep, especially if excavated in the ditchline or shoulder of the road. This seems deep enough to intercept most water that saturates a roadway subgrade. However, in a slide area some underdrains have been dug to over 15 feet (5 m) deep to intercept deep ground water. These can be very effective for drainage, but are difficult to construct safely, and caving of deep trenches is a problem. Shoring is required or the pipes or geocomposite drains have to be preassembled and lowered into the trench with ropes. Note that excavations over 4 feet (1.3 m) deep require shoring in unstable ground for safety and Occupational Safety and Health Administration compliance (figure 3-106).

French drains, as they are traditionally called, are an underdrain without a drain pipe. They are filled with coarse rock that collects and moves water in the trench to its daylight point. Because of the inherent low transmissibility of aggregate compared to a pipe, most French drains are not long. For filtration, French drains are constructed with fine rock on the perimeter of the drain and coarse rock in the middle. Today, with geosynthetics that can surround and filter the rock, uniform permeable gravel can be used. However conventional underdrains are generally more desirable, less likely to plug, and have more flow capacity than a French drain.

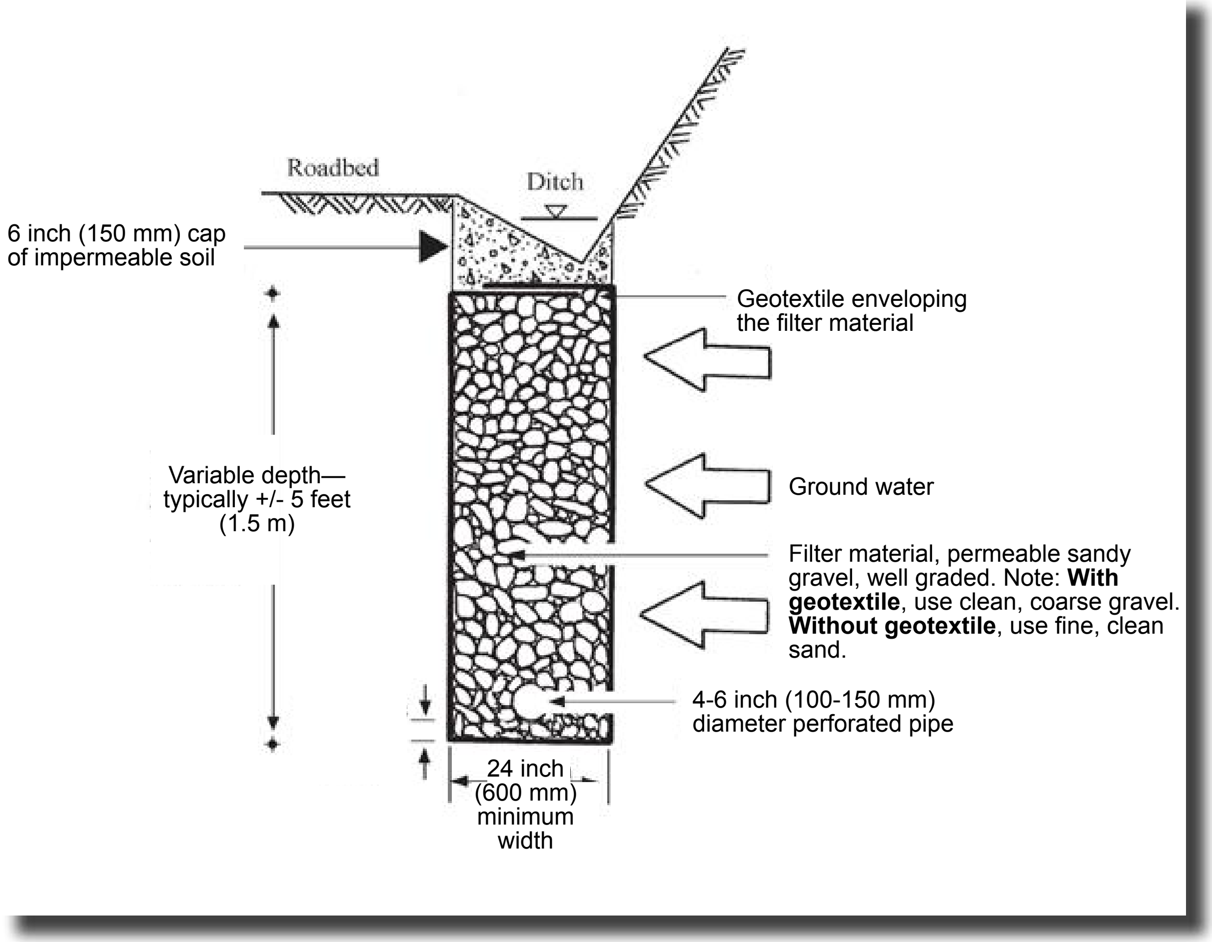


Figure 3-105—Typical road underdrain used to remove subsurface water.

Figure 3-106—Construction of an underdrain with shoring (courtesy of FHWA).

3.4.2.2. Geocomposite Drains

Geocomposite drains are a specific type of underdrain made of geotextile wrapped around a core material (typically plastic). They are capable of transmitting water in a plane downward into a slotted pipe. Water is removed in a pipe that exits the drain trench and daylights on a slope, similar to a conventional underdrain (figures 3-107 and 3-108).

Many geosynthetic product manufacturers have geocomposite drains available. Use them in areas where graded aggregate is not available or is very expensive. They are commonly used today because of their ease of installation. Suggested design requirements for geocomposite drains are: (1) the geotextile must satisfy the needed filter criteria for the surrounding soil; (2) the core material must have a minimum crushing strength of 4,000 pounds per square foot (19,484 kg/m^2); and (3) the drain must have a minimum flow capacity of 1 gallon per minute per lineal foot under a gradient of 1.0. These underdrains also are commonly installed in vertical applications behind retaining walls or in drained excavations.

Use local backfill material to fill the trench behind the drain. Gravel backfill is better, but more expensive. Lightly compact the backfill to avoid damage to the geocomposite core.

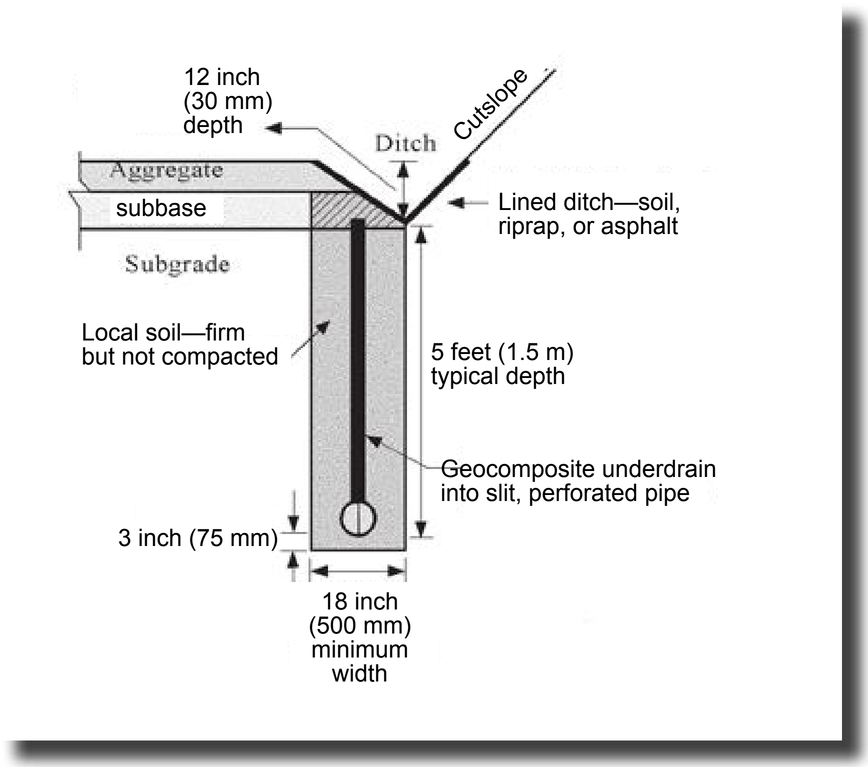


Figure 3-107—Geocomposite underdrain.

Figure 3-108—A geocomposite underdrain during installation.

3.4.2.3. Horizontal Drains

Horizontal drains are subsurface drainage used in slope stabilization. Slope stabilization is discussed in section 3.2.1.3.

3.4.2.4. Drainage Blanket (Filter Blanket)

Drainage blankets, or filter blankets, occasionally are installed to repair a section of damaged road caused by a spring or wet spots in the existing road. They also may be placed under a fill to prevent it from becoming saturated (see section 3.2.1.3, figure 3-20). As opposed to an underdrain that is usually vertical, a filter blanket is usually laid on a relatively flat area to intercept water that is rising up under the road. It consists of a layer of gravel filter material, typically at least 6 inches (150 mm) thick, with one or more perforated drain pipes to remove water (figure 3-109). It should be wrapped in a geotextile or other filter layer to keep the gravel free draining. The filter material and drain pipe daylight to the road edge or the surface of the fill to ensure full drainage.

Try not to place fills over a wet or spring area since the embankment fill material can become saturated and fail. Drain fills in wet areas initially with a rock filter or drainage layer at the bottom of the fill to remove the water and prevent the fill from becoming saturated. If the fill has already failed and the road is being repaired, then consider a filter blanket before reconstructing the roadway embankment. Alternatively construct a rock fill, or place a drained buttress at the toe of the embankment to stabilize it, as discussed in section 3.2. Coarse rocky fill material that is free draining does not need a drain. Figure 3-110 shows the construction of a filter blanket over a spring area in the road to drain the road subgrade. Note that a filter layer of geotextile is placed above and below the gravel drainage layer.

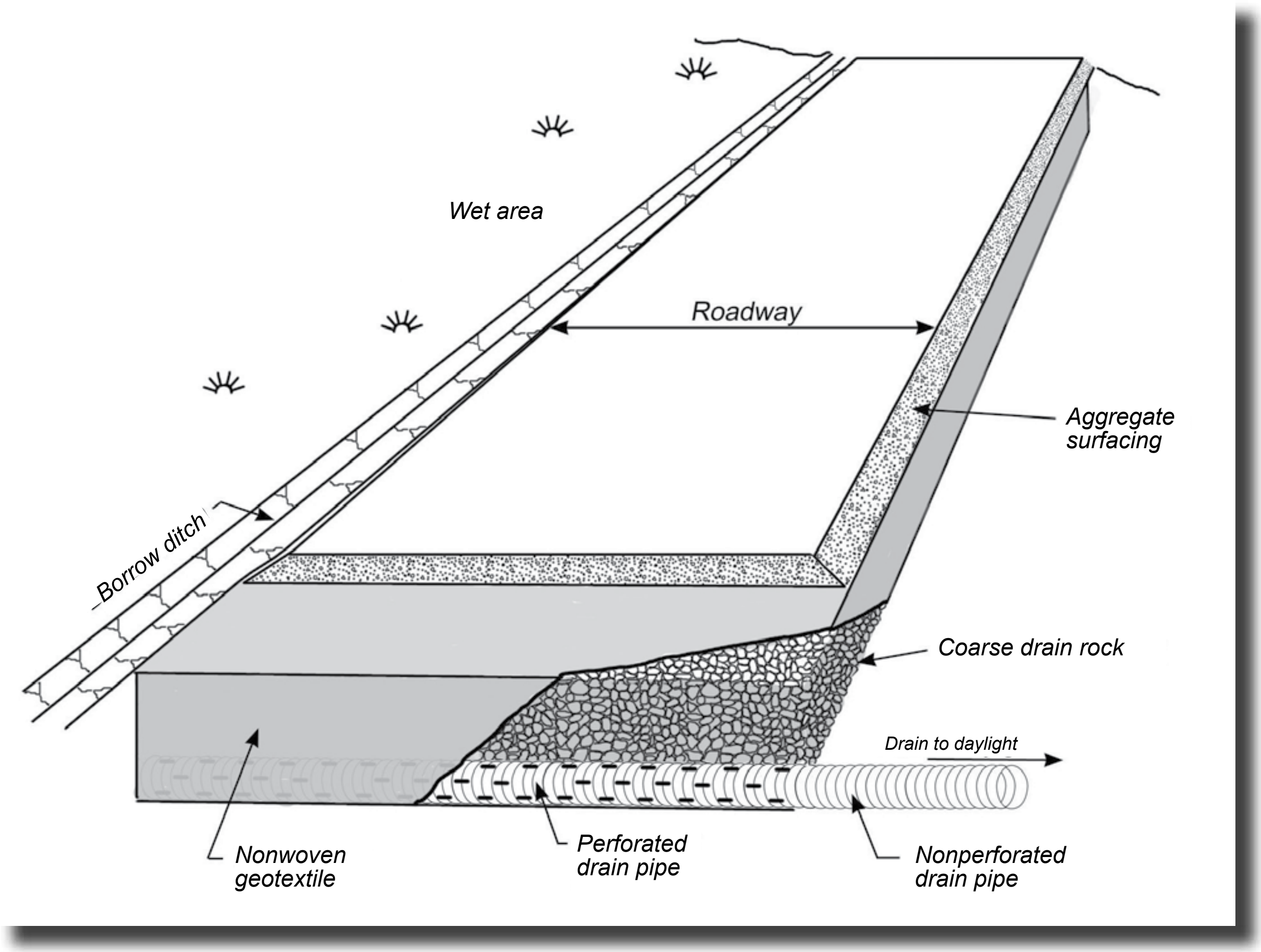


Figure 3-109—Filter blanket drain.

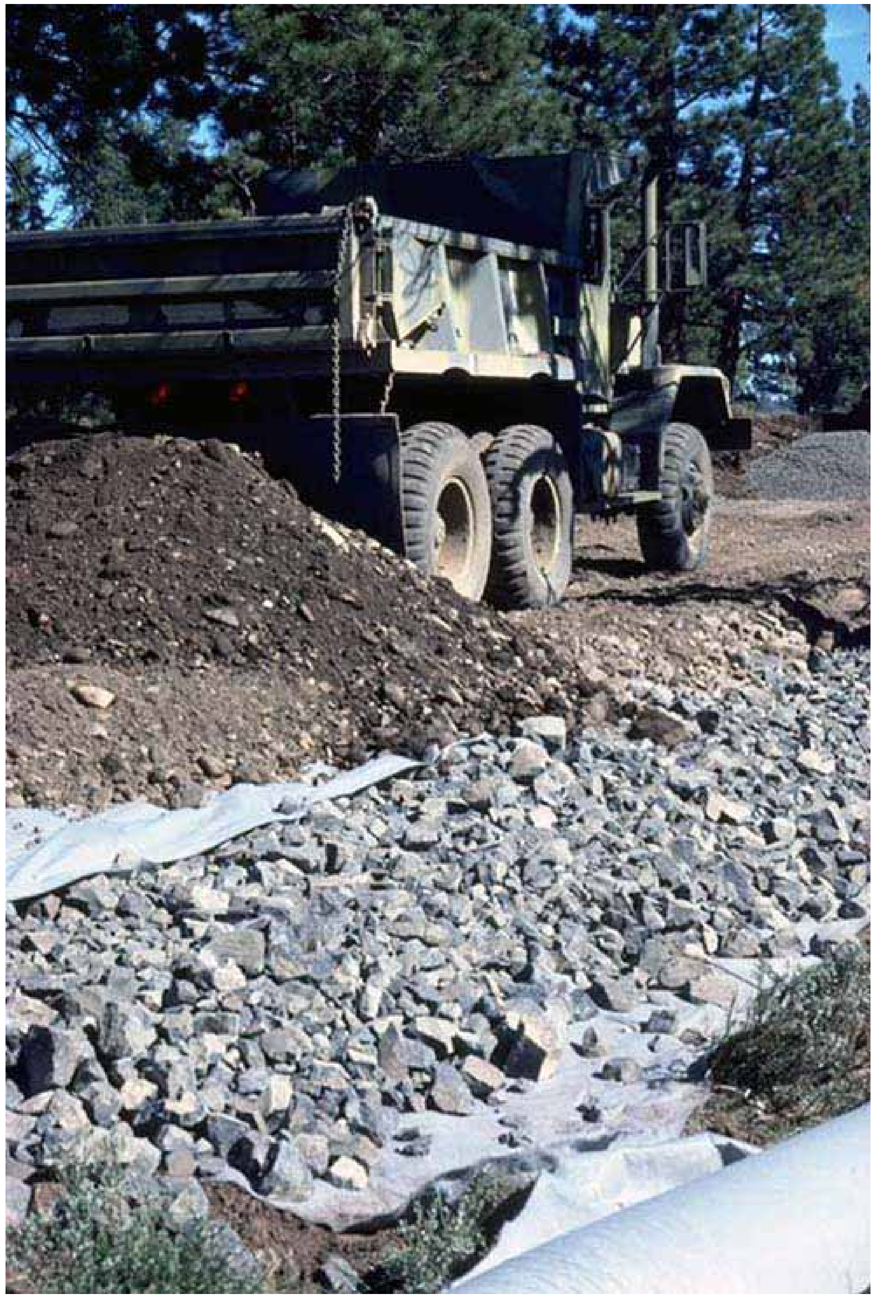


Figure 3-110—A blanket drain constructed over a wet spring area in the road.

3.5. STREAM AND WET AREA CROSSINGS SOLUTIONS

Natural drainage crossings require hydrologic and hydraulic design to determine the proper type and size of structure. These include bridges, culverts, and fords or low-water crossings. Because drainage crossings are at areas of running water, they can be costly to reconstruct and they can have major negative impacts on water quality. Impacts from improper design, repair, or installation of structures can include degraded water quality, bank erosion, channel scour, traffic delays, and costly repairs if a structure fails. Repairs often include improved streambank stabilization measures. Also structures can greatly impact fish at all stages of life as well as other aquatic organism species. Failures are costly in many ways. If a structure has failed it is important to analyze and determine the cause of failure, improve the design, and prevent a failure from happening again!

Reconstruction or improvements to natural stream channel crossings should be consistent with the natural form of the drainage. Maintain the channel without large steps, steep gradients, or waterfalls. Install and maintain structures big enough or wide enough, considering the natural channel bankfull width, to minimize channel disturbance, channel constrictions, and changes in water profile and velocity. To avoid flow constriction or concentration, relatively wide structures, bridges, or multiple pipes or multiple box structures may be needed in broad channels. Structures also should conform to the grade of the natural channel bottom as much as possible. Protect culvert outlets to prevent scour holes from forming, which could lower the channel and impact adjacent riparian areas.

To minimize impacts on water quality, armor or stabilize the actual stream crossing structures (fords or culverts), add surfacing to the roadbed for a couple hundred feet on both sides of the crossing, and drain water off the road surface and ditches before reaching the crossing (figure 3-111). Install stream channel armoring as needed or place a culvert at the elevation of the natural stream channel bottom.

To minimize site and channel disturbance, the road approach and structure should be nearly perpendicular to the direction of the stream channel (figure 3-112). A skew angle is sometimes necessary, but it typically involves higher construction costs and more site disturbance and impacts.

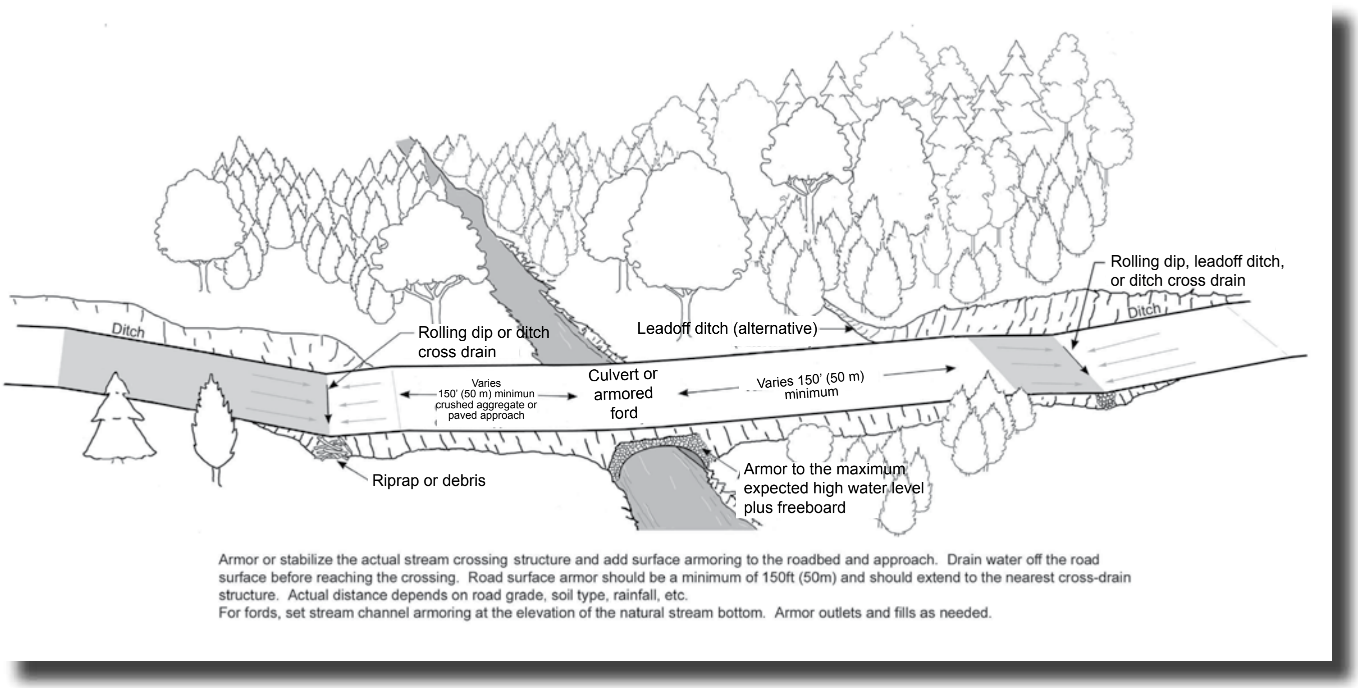
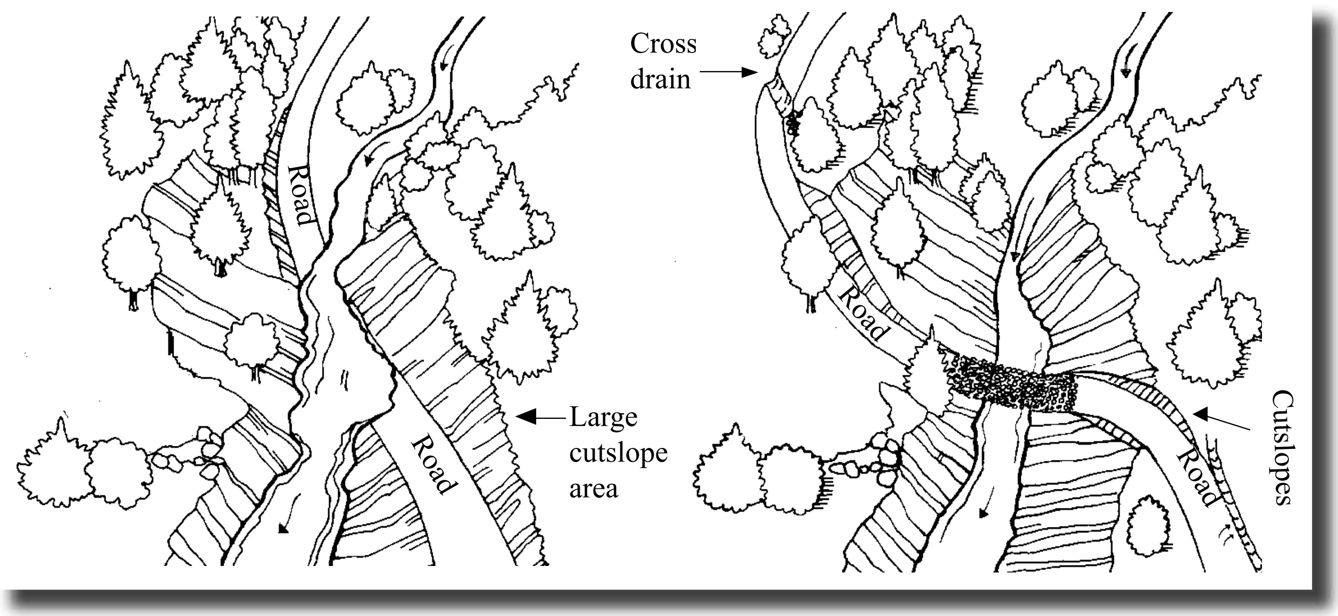


Figure 3-111—Measures to keep sediment out of streams at road-stream crossings.



Poor Stream Crossing **Better Stream Crossing**

Figure 3-112—Poor and good natural drainage crossing alignment.

Roads that cross meadows or other wet areas present a special set of problems and solutions. It is a poor place to have a road, but many improvements have been made to existing roads by reconstructing the road with rockfill and adding multiple pipes (section 3.5.5). These measures prevent the concentration of water and keep it spread out across the meadow, and maintain a naturally high water table. Since these measures are expensive, various techniques have been developed for crossing wet areas with temporary road stabilization measures.

3.5.1. Culvert Solutions for Aquatic Organism Passage, Capacity, or Repairs

Culvert replacement is very important in the design of roads because culverts are critical to the function of the road by passing intermittent or perennial stream flows under the road or removing surface ditch water off the road; a large amount of money is invested in culverts on almost any road; and culvert failures can have high environmental impacts by putting large quantities of sediment into watercourses, damaging water quality and aquatic species habitat, as well as causing road delays and expensive repairs.

If fish are present, use a structure that provides for fish passage, such as open bottom culverts, culverts with a buried bottom, or a bridge. Maintain a natural stream channel bottom wherever possible, without large steps or waterfalls, which could prevent passage for fish and other aquatic organisms. Small, long, or steep gradient pipes all discourage fish passage and should not be used in fisheries streams. Construct culvert pipes with baffles for fish passage, but baffles work best when used as an existing culvert retrofit. They can be ineffective and difficult to maintain. Stream simulation measures are ideal. The additional cost to accommodate fish passage is often minor compared to the total cost of the drainage crossing structure.

The selection of structure and care used during construction partially depends on fisheries considerations in the stream. Consult local fisheries biologists or personnel to determine the need for fisheries-compliant design habitat. For more details on aquatic organism passage, consult the publication “Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings” (Forest Service Stream Simulation Working Group 2008).

Since culverts are a basic part of road infrastructure and a significant cost in road repairs and reconstruction, this section discusses the factors involved in good culvert predesign, design, installation, and maintenance. Culverts also can be problematic because of a lack of specific flow capacity, their ability to plug with debris, increased velocity at the inlet and outlet that can lead to channel erosion, their ability to restrict or be a barrier to fish and other aquatic organism passage, and damage to the road and environment if they fail. Thus, the correct structure, size, and installation of culverts are very important. Site evaluation also is critical to ensure compatibility between the site and the chosen structure and to prevent damage to the stream's function and its aquatic resources.

There is a wide range of culvert drainage structure types, shapes, and materials available, including round pipes, squash pipes, arches, bottomless arches, structural plate pipe arches, low-profile arches, box culverts, and many other shapes. Materials include CMP, aluminum pipe, concrete, and plastic (polyethylene) pipes, as well as masonry and wood. Box culverts commonly are made of concrete or masonry, and some corrugated metal options exist. Single or multiple pipes of each type may be used. In a forest environment, native materials have been used, including stacked parallel logs, cross-stacked poles (Humboldt culverts), simple short-span log box culverts, hollow logs, and timber boxes made from cut planks. However the wood culverts have a relatively short design life and many designs have a very limited flow capacity so their use is typically not recommended. Thus they are used only for temporary or seasonal roads, and should be removed before the rainy season.

The material used depends on cost and availability. CMP and concrete pipe are commonly used and are more durable than plastic pipe. However plastic pipe has gained popularity because of its light weight and ease of construction. Plastic pipe requires good compaction quality control, and can burn if exposed to fire. The culvert's shape, such as a round pipe, pipe arch, structural arch, or box, depends on the site, needed span, allowable fill height, loading, and soil-cover thickness. Examples of pipe types and shapes are shown in figure 3-113. Key factors for culvert selection in any road repair or rehabilitation project are:

- ❑ Flow capacity is adequate for water, sediment, and debris.
- ❑ Culvert fits the site and need.
- ❑ Culvert is properly aligned and installed.
- ❑ Aquatic organism passage issues are addressed properly.
- ❑ Installation is cost effective.

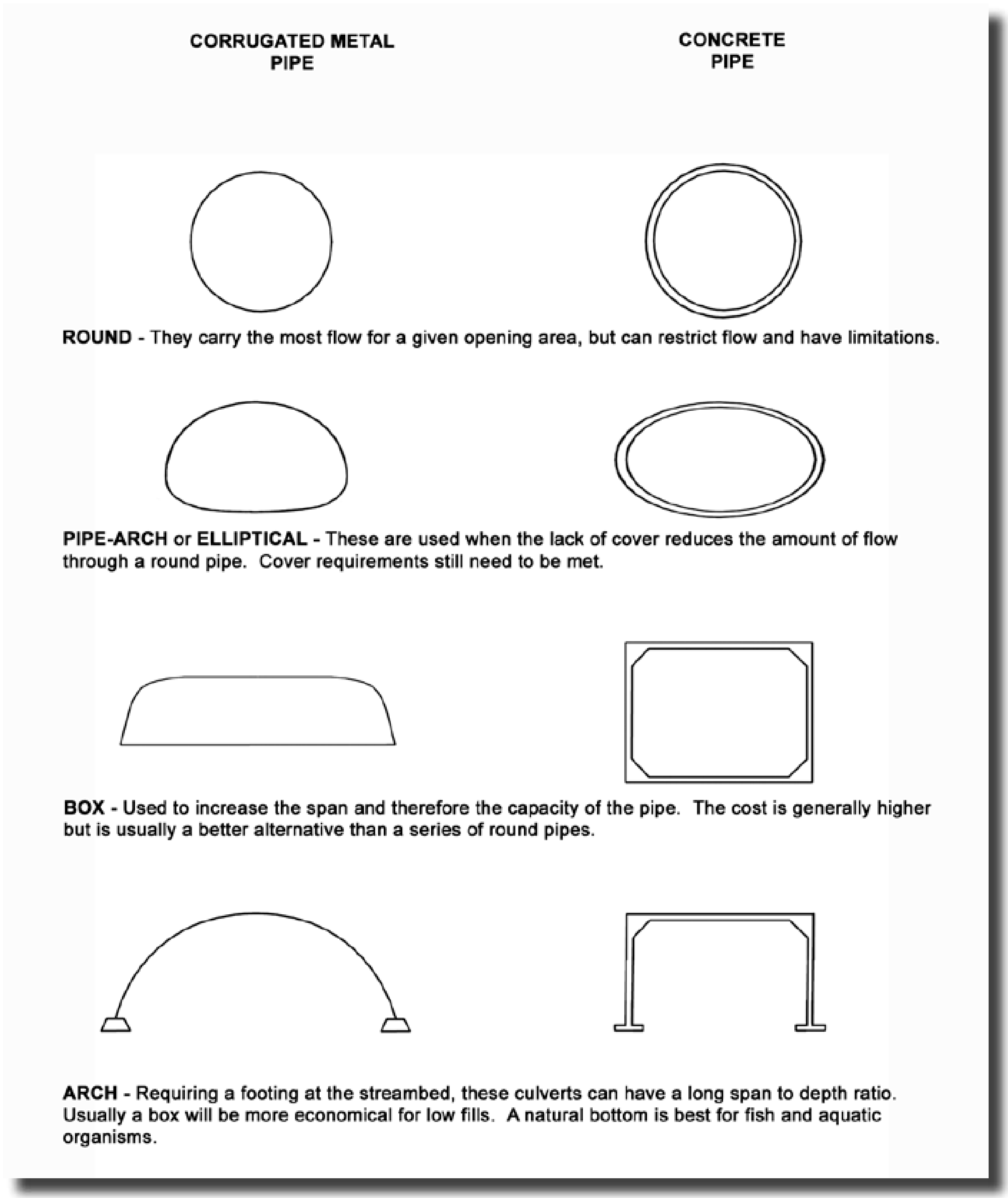


Figure 3-113—Examples of some typical culvert pipe types and shapes.

Regardless of the culvert type used, one must check the high flow capacity of the culvert. This ensures the survival of the culvert and road fill during extreme storm flow events. Road fill stability, road overtopping, allowable headwater depth, the likelihood of debris plugging the culvert, backwater effects, or a combination of these factors may determine the culvert high flow capacity. In some forested environments culverts fail more often due to debris plugging than lack of flow capacity.

There are several ways to minimize the likelihood of a culvert failure. A properly sized culvert is consistent with the width of the natural stream channel, aligned with the upstream channel, and has an efficient inlet to prevent debris plugging. Risk might also be managed with appropriate flood and debris capacity and culvert height, a spillway for overtopping, concrete headwalls, or additional flood capacity through other structures in a floodway. Also flow velocity typically accelerates in a culvert pipe, so the pipe outlet area is commonly subject to scour and may need armoring or scour protection. Armoring, such as riprap is common, cutoff walls may be used, or a stable energy dissipation pool can be designed at the pipe outlet.

One large pipe is almost always better than multiple small pipes. Not only is a larger pipe more hydraulically efficient, a single relatively large pipe is much less susceptible to plugging compared to multiple smaller pipes. The fill area between multiple pipes acts as an excellent trash rack to catch debris and promote plugging of the pipes. However, multiple pipes often are used to minimize the structure’s height (for vertical alignment considerations), and because small pipes are often readily available. Avoid multiple pipes if aquatic organism passage is an issue because they create a barrier for passage.

The footings of arch pipes also are subject to scouring and undermining. Set the footings of arch pipes at an elevation below the depth of possible scour or set on a scour-resistant material, such as bedrock. A stream thalweg profile through the site may be necessary to determine the desired elevation of the bottom of the footings.

3.5.1.1. General Culvert Repair Issues

Culvert Maintenance

Culvert maintenance and periodic cleaning is critical to the proper function of a pipe. Lack of maintenance has contributed to many culvert failures. Ideally crews maintain the pipes before any major storm. Maintenance only can be guaranteed if it is part of the crew's normal routine and it was accomplished after the last major storm. Maintenance items include the following:

- ❑ Keeping the inlet clear of sediment buildup, rocks, and vegetation.
- ❑ Ensuring that headwalls are in good condition.
- ❑ Relining worn culvert barrels or replacing the pipe.
- ❑ Replacing damaged or missing splash aprons or riprap.
- ❑ Bending back damaged metal blocking the entrance.

Old and damaged pipes can be repaired or their life extended by grouting the damaged areas, placing a local concrete or epoxy lining in worn out sections of the pipe, such as the bottom that receives the most constant flow plus abrasion from sediment, installing a new slip lining of plastic or rubber inside an old pipe, and so forth (section 3.5.1.3).

Culvert Capacity

Repair or replace damaged culvert inlets, or add an end section to the pipe to maintain its hydraulic capacity as well as to minimize plugging potential. Figure 3-114 shows the percent reduction in culvert capacity caused by some reduction in the pipe inlet cross-sectional area. The decrease in pipe capacity is significant from a relatively small reduction in inlet area.

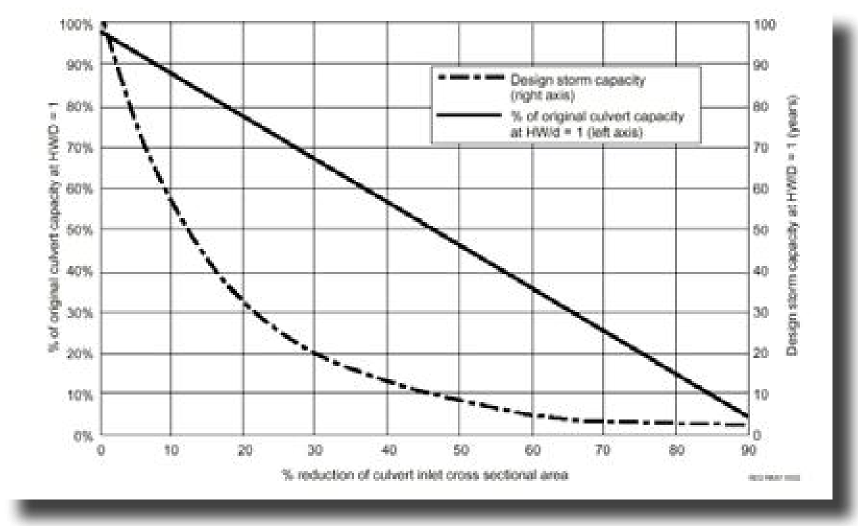


Figure 3-114—Culvert capacity versus reduction in inlet area.

Information regarding culverts, design, installation, problems and solutions, and so forth is found in "Hydraulic Design of Highway Culverts" (Norman et al. 2005). This is a comprehensive culvert design publication available from FHWA at <http://www.fhwa.dot.gov/engineering/hydraulics/culverthyd/index.cfm>.

3.5.1.2. Common Culvert Rehabilitation Techniques

Overflow Protection and Diversion Prevention

The physical consequences of exceeding the capacity of a stream crossing usually depend on the degree of exceedance, crossing fill volume, fill characteristics, soil characteristics, and the flowpath of overflowing stream discharge. Stream crossings frequently have the potential to divert streams from their channel if the capacity of the crossing pipe is exceeded. Road-stream crossings with diversion potential typically pose much greater overall risks than those without diversion potential. Repairing roads to avoid diversion potential is straightforward, and remediating existing crossings to correct diversion potential is usually inexpensive and very desirable.

A stream crossing has diversion potential if, when stream crossing pipe capacity is exceeded or if the culvert pipe plugs, the stream would back up behind the fill and flow down the road rather than flow directly over the road fill and back into the natural channel (Weaver and Hagans 1994), as shown in figure 3-115. Diversion potential exists on roads that have a continuous climbing grade across the stream crossing or where the road slopes downward away from a stream crossing in at least one direction. A crossing without diversion potential may breach the crossing fill if it overtops, but the stream does not leave the natural channel (figure 3-116). In almost all cases, diversion creates more damage than streamflows that breach the fill but remain in the channel. Stream diversion also can be caused by accumulations of snow and ice on the road that will direct overflow out of the channel. Snow removal operations need to consider this potential effect and configure removed snow such that stream diversion does not occur (Furniss et al. 1997).

In drainages with uncertain flow values, large quantities of debris in the channel, or sites with existing undersized pipes, there is a high risk of diversion potential or that a fill overtops and washes out. In such areas, particularly in sensitive watersheds, a ford or armored overflow protection is desirable (figure 3-117). If a ford is not installed, build a low point into the fill and an armored overflow spillway to protect the fill. This keeps the flow in the same drainage, thus reducing diversion potential, and usually prevents a total fill failure. The cost of an overflow dip is relatively small compared to the cost of replacing the entire fill, and therefore can be cheap insurance.

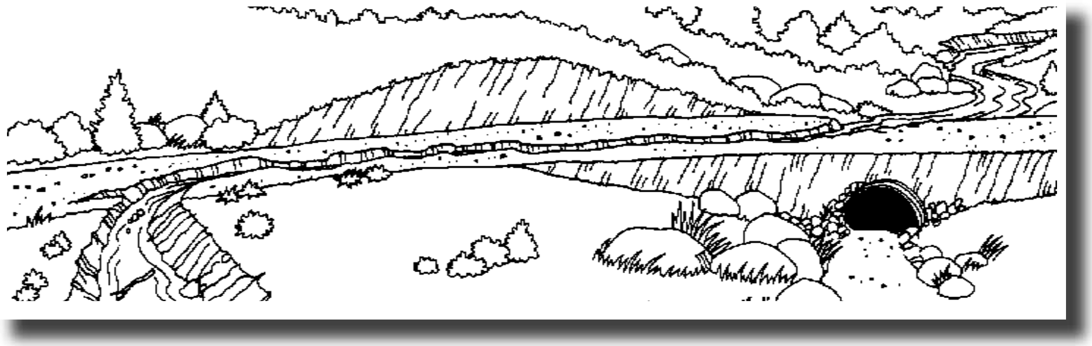


Figure 3-115—A stream diversion where plugged culvert crossing sends water down the road rather than staying in its natural channel.

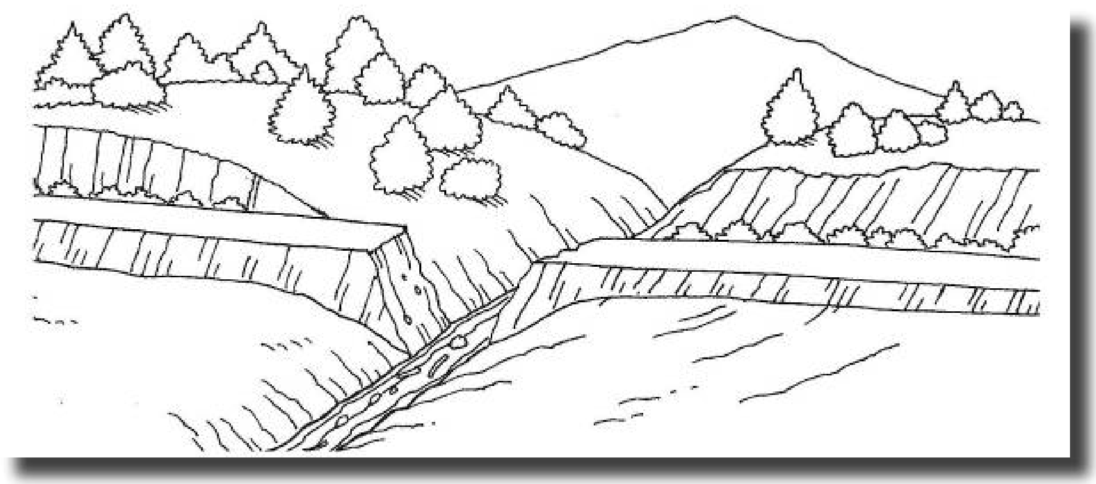


Figure 3-116—Overtopping and washout caused by a plugged culvert, but where the flow stays in its natural channel.

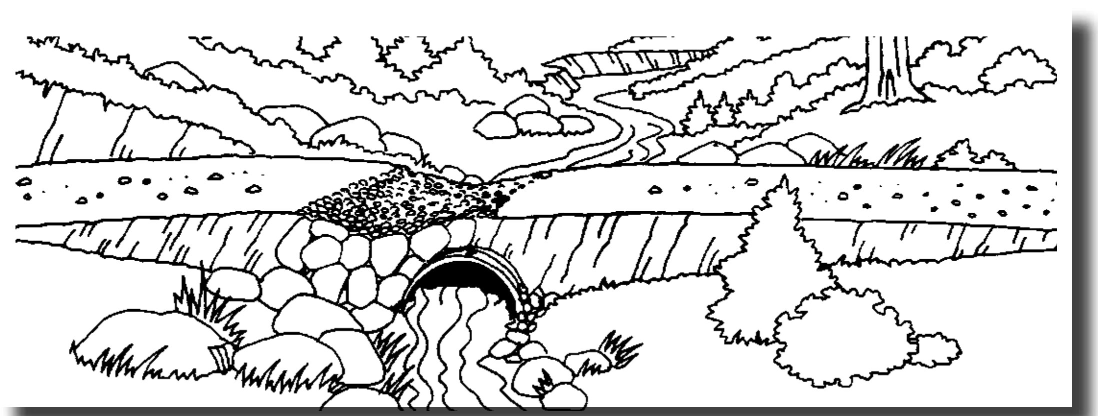


Figure 3-117—Existing undersized culvert fitted with an armored overflow dip to pass water without stream diversion or washing out the fill (adapted from Furniss et al.1997).

For technical information on diversion potential consult Furniss et al. (1997). The publication discusses the physical effects of diversion potential, and provides design considerations for remediation of existing crossings that have diversion potential. Link to the document <http://www.fs.fed.us/eng/pubs/pdf/w-r/97771814.pdf>.

3.5.1.3. Trenchless Technology

Culvert repairs or replacement in high fills in sensitive areas or on heavily used roads can be very problematic and quite expensive. Today, an emerging field, trenchless technology, exists with solutions for pipe repairs, lining existing pipes (figure 3-118), replacing pipes in place, and installing new pipes without conventional trench excavation. Trenchless technology uses the methods, materials, and equipment for replacing, rehabilitating, or installing pipes with little or no excavation of the ground above. Closely associated with this technology are various techniques for investigating, locating, inspecting, and assessing culverts and the surrounding earth materials.

Figure 3-118– New high density polyethylene pipe that has been pulled inside the old CMP pipe with a badly corroded invert (photo courtesy of Clakamis County, Oregon).

Pipe bursting and pipe splitting are trenchless methods used to replace a culvert at its exact location and alignment. In both cases, the contractor uses tools to break or cut the old pipe and force the fragments out into the surrounding soils. Simultaneously, the tools draw the new pipe into the resulting void. Pipe bursting is used to break brittle pipe, such as concrete, through a mechanically applied force from within the pipe. A new pipe, of the same or larger diameter, is installed behind the bursting tool as shown in figure 3-119. The force may be a steady, statically applied pushing or pulling force (Piehl 2005).

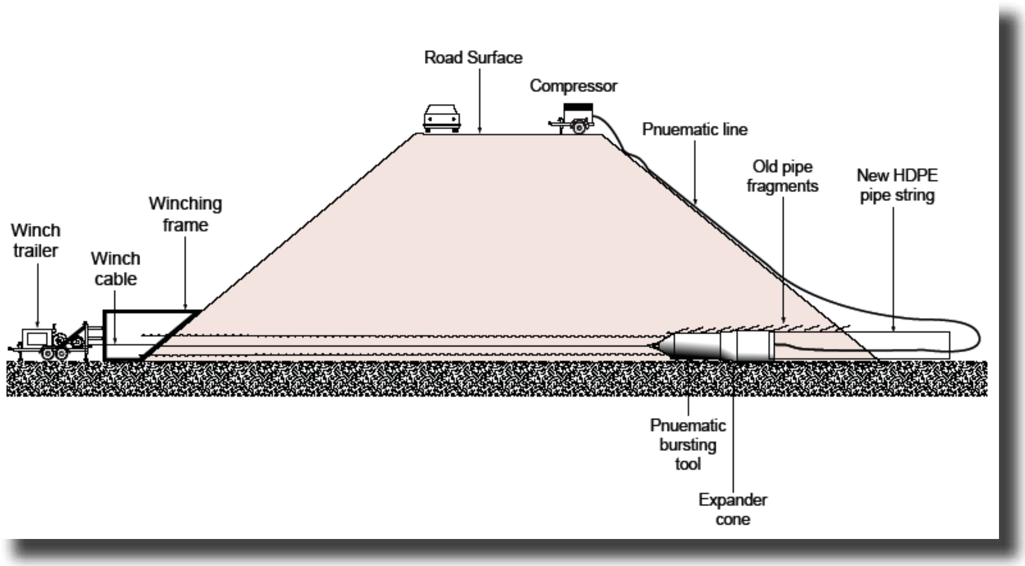


Figure 3-119—Sketch of pipe bursting, with a new pipe being pulled through an old pipe, thus avoiding trench excavation and traffic delays.

Engineers need to assess the advantages and disadvantages of trenchless versus open-cut methods when planning culvert rehabilitation or replacement. Trenchless technology has the following advantages:

- ❑ Cost: Substantial cost savings are possible. However, even when trenchless methods are very expensive, such technology may be the best alternative because of other considerations discussed below.
- ❑ Environmental effects: Less soil is disturbed so impacts on adjacent organisms and water bodies can be reduced significantly.
- ❑ Disruption: Traffic delays are reduced or eliminated, as is heavy truck traffic associated with culvert excavation deep below the roadway.
- ❑ Speed of installation: Construction often takes less time, regardless of the road fill depth.

- Safety: Many safety concerns associated with steep-excavation slopes, work inside trench boxes, and worker exposure to traffic may be eliminated or reduced.
- Less engineering: Less surveying, fewer design calculations, and fewer drawings and specifications may be required.
- Possible fewer unknowns: Minimal ground disturbance results in fewer contingencies associated with subsurface conditions with pipe lining options.

Trenchless technology has the following disadvantages:

- Cost: Where placement is shallow and traffic is not a major constraint, excavation is usually more cost effective.
- Level of engineering difficulty: Specialized expertise in related technologies and the impact on subsurface site conditions is required.
- Decreased flow capacity: Practices, such as lining pipes with thick structural sections, reduce pipe openings, decreasing the pipe's flow capacity.
- Grade or alignment corrections: Effecting necessary changes to the existing grade and alignment are not always possible.
- Shorter design life: Rehabilitation techniques, such as spot repair or grouting, have a shorter design life than new pipe installation.
- Susceptible to fire damage: Engineers found that culverts lined with plastic or replaced with corrugated polyethylene pipe may be damaged severely when subjected to wildfires. Fire can cause the plastic to burn or melt.

Consult "Summary of Trenchless Technology for Use with USDA Forest Service Culverts" (Piehl 2005) for additional technical information about trenchless technology. The report, which summarizes the trenchless technologies most appropriate for Forest Service roadway culvert applications, can help engineers best determine where and when to use this rapidly evolving technology. Techniques for replacing or rehabilitating CMP culverts, 18 inches or greater in diameter, are emphasized because they are commonly used for culverts. Link to the document <http://www.fs.fed.us/eng/pubs/pdf/05771201.pdf>.

3.5.1.4. Aquatic Organism Passage/Fish Passage Design and Retrofits

Restoring aquatic organism passage through a road-stream crossing has become one of the more frequently occurring restoration activities on National Forest System roads. The preferred design is stream simulation, which is achieved with bridges (optimum), bottomless culverts of various materials and shapes, and embedded culverts in conjunction with simulation of the slope, streambed material and character, and width of the natural stream channel through the structure. Figure 3-120 shows culverts that have been constructed to create or maintain a natural stream channel bottom.

Full-span bridge crossings typically have less risk and impact than culverts, and generally minimize site disturbance and stream impacts. While bridges are considered to be the most expensive road-steam crossing, it is not always the case and they should be evaluated along with other designs for a proposed project. Bridges are discussed in section 3.5.3.

Passage of fish and aquatic organisms at road-stream crossings is a complex issue. There are technical issues that should be considered by a range of expertise (biological, engineering, geomorphology, geotechnical, structural, hydrologic, and others), and designs should be done with interdisciplinary teams. Many of the concepts used today were originally developed by Washington Department of Fish and Wildlife and have been expanded by the Forest Service and others.

Whenever a culvert on a fish-bearing stream needs to be replaced or the road undergoes major reconstruction, the need for fish passage should be evaluated. Other benefits, in addition to providing fish passage with a stream-simulation structure, are lower maintenance costs, lower potential for plugging, greater movement of sediment and woody debris, aquatic organism passage (not just certain fish), hydrologic connectivity, and often passage for terrestrial animals. Long-term benefits typically outweigh the increased initial cost of a larger structure.

Figure 3-120—(a) and (b) Small and large embedded fish-friendly culverts with a natural stream bottom for aquatic organism passage.

If working with stream simulation design methodology, read the Forest Service Stream Simulation Working Group publications (2008) and Bates et al. (2003). These publications are written by experts experienced in fish passage and stream simulation design procedures.

While stream simulation is the preferred design, there are other design methods that also can be used under certain circumstances:

- Low-slope design – The low-slope design is a low-tech design for new culvert installations in low-risk sites with a low-gradient channel and a short culvert.
- Hydraulic design – Hydraulic design focuses on passage of target species of fish during specific flows. It was often applied to new culverts in many areas and is now used primarily for retrofits of existing culverts. It may be necessary where other options cannot physically be applied. It can be applied to low to moderate channel slopes. Figure 3-121 shows a comparison of a traditional culvert installation that would require a hydraulic design versus a stream simulation arch or embedded pipe-arch culvert.

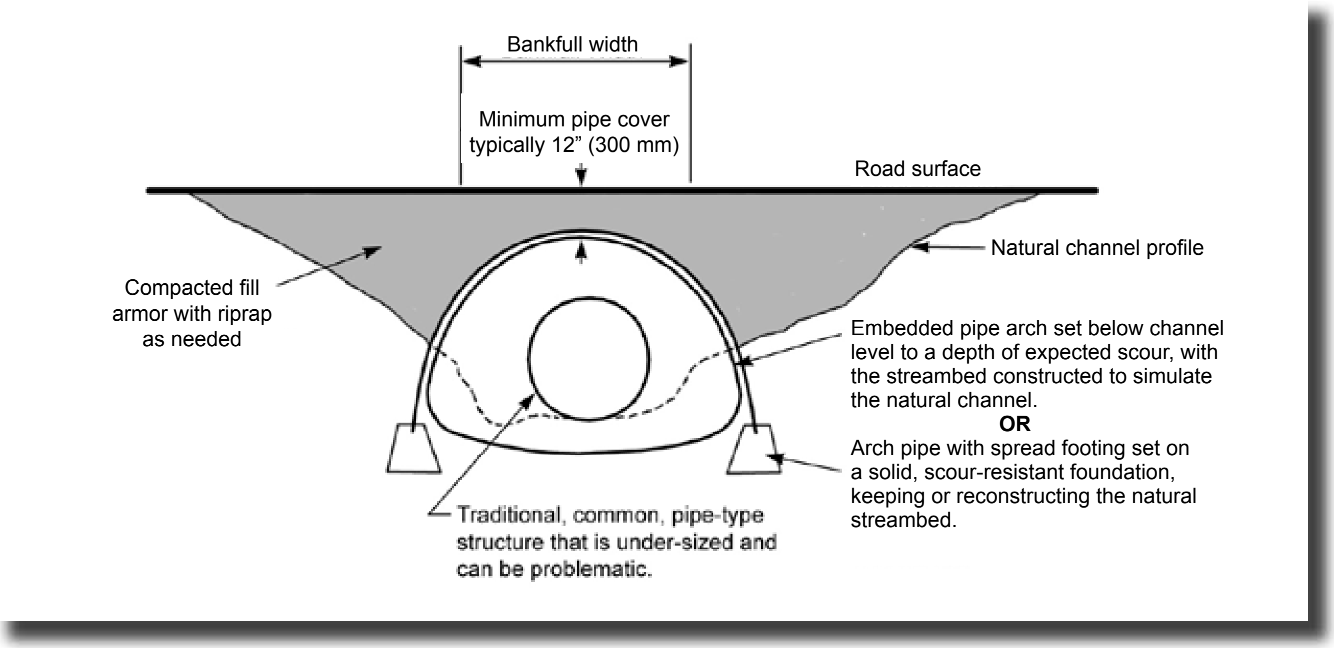


Figure 3-121- Traditional culvert installation versus stream simulation structures.

Hydraulic modeling software, such as FishXing, is helpful for hydraulic culvert design calculations to accommodate fish passage. A team headed by the Forest Service and FHWA developed FishXing, which is available at <www.stream.fs.fed.us/fishxing/index.html>.

Baffles, weirs, and fish ladders are hydraulically designed structures that can be used to retrofit existing culverts under special circumstances, such as very deep fills (expensive construction) or as an interim solution. They are seldom used in new construction.

Baffles are constructed inside culverts to disrupt flow so that fish can find low-velocity areas to rest in between short, high-velocity zones. They are fish and flow specific and may not pass juvenile fish. Baffles decrease the hydraulic capacity of the culvert, increase maintenance needs (woody debris tends to catch on the baffles), may increase turbulence sufficiently to cause a passage barrier, and are prone to damage by bedload and debris.

Weirs typically are constructed downstream of a perched culvert in order to raise the water level and improve passage by backing water through the pipe (figure 3-122). This has been used successfully, the one caveat being that care must be taken that the weir itself does not become a passage barrier. Weirs also can be used inside culverts to hold streambed material in place. When using them for this purpose, the height of the weir should be less than the elevation of the streambed or, through scour, they can become a jump barrier.

Figure 3-122—An old shotgun or perched pipe with water flooded back through the pipe for fish passage with use of a downstream elevated rock weir.

Fish ladders are a common means for passage of fish over a dam. They also have been used at culverts that have perched outlets and where replacement is not feasible in the near future. Fish ladder designs are complicated and problematic, so they need to be evaluated carefully and designed by experienced personnel.

For technical information about aquatic organism passage consult Forest Service Stream Simulation Working Group (2008). The guide to stream simulation—a method for designing and building road-stream crossings intended to permit free and unrestricted movements of any aquatic species—is intended to help national forests achieve their goal of maintaining the physical and biological integrity of the stream systems they manage, including existing populations of fish and other wildlife species. Habitat fragmentation is an important factor contributing to population declines of fish, and crossing structures that are barriers are a large part of the problem. Stream simulation provides continuity through crossing structures, allowing all aquatic species present to move freely through them to access habitats, avoid adverse conditions, and seek food and mates. Stream simulation applies to crossing structures on any transportation network, including roads, trails, and railroads. For brevity, the guide refers to all of these types of transportation infrastructure as roads. This state-of-the-art guide is available at <http://www.fs.fed.us/eng/pubs/pdf/StreamSimulation/index.shtml>.

The Federal Highway Administration publication HEC-26 has also produced a summary of fish passage options in their publication "Culvert Design for Aquatic Organism Passage" (Kilgore et al. 2010) Their emphasis is on conventional alternatives rather than a stream simulation approach. It is available at <http://www.fhwa.dot.gov/engineering/hydraulics/pubs/11008/hif11008.pdf>.

3.5.2. Low-Water Crossing Repairs

Low-water crossings, fords, or drifts, as they are occasionally called, can offer a desirable alternative to culverts and bridges for stream-crossing repairs or replacements on low-volume roads where road use and stream flow conditions are appropriate. Like other hydraulic structures for stream crossings, their construction or repair requires specific site considerations and specific hydrologic, hydraulic, and biotic analyses.

Ideally, locate low-water crossings at a relatively narrow, shallow stream location and in bedrock or coarse soil for good foundation conditions. A armored ford can be narrow or broad, but should not be used in deeply incised drainages that require a high fill or excessively steep road approaches. An armored ford is a desirable structure on some very low traffic roads to minimize turbidity and potential pollution problems. However, some State agencies discourage fords because of negative impacts to the stream and fish when driving through the water, and for traffic safety concerns. Design a ford to not create a low-flow depth barrier to fish passage.

This can happen if a ford is wider than the natural channel. Ensure that neither scouring nor perching develops along the downstream edge of the ford, which may turn into a fish passage barrier.

Low-water crossings may have a simple rock reinforced (armored) driving surface or an improved surface, such as gabions or a concrete slab. Vented fords combine culvert pipes or box culverts to pass low flows and a reinforced driving surface over the culverts to support traffic and keep traffic out of the water most of the time. The reinforced driving surface over the pipes also resists erosion during overtopping at high water flows. The entire wetted perimeter of the structure should be protected to a level above the anticipated high water elevation. Low-water bridges are elevated bridge structures that are located in areas that periodically overtop the structure during extreme events. Thus, they must be designed to withstand overtopping by water and debris. Because basic designs require tailoring to individual site requirements and locally available materials, many variations of each of the basic types of low-water crossing structures have been developed over time (figure 3-123).

Key factors to consider for the design and location or repair of a ford include the following: low- and high-water levels; foundation conditions; scour potential; allowable traffic delays; channel cross-section shape and confinement; protection of the downstream edge of the structure against local scour; stream channel and bank stability; locally available construction materials; and grade control for fish passage.

For fish or aquatic species passage, maintain a natural or rough stream channel bottom through the ford, and do not accelerate water velocities, similar to requirements through a culvert. Ideal structures are vented fords with large box culverts and a natural stream bottom or simple on-grade fords with a reinforced, rough driving surface. Low-water bridge structures are ideal for fish passage.

Vented fords have a driving surface elevated some distance above the streambed with culverts (vents) that enable low flows to pass beneath the roadbed. The vents can be one or more pipes, box culverts, or open-bottom arches. In streams carrying large amounts of debris, the driving surface over the vent may be removable, such as a cattle guard, permitting debris to be cleared after a large flow event.

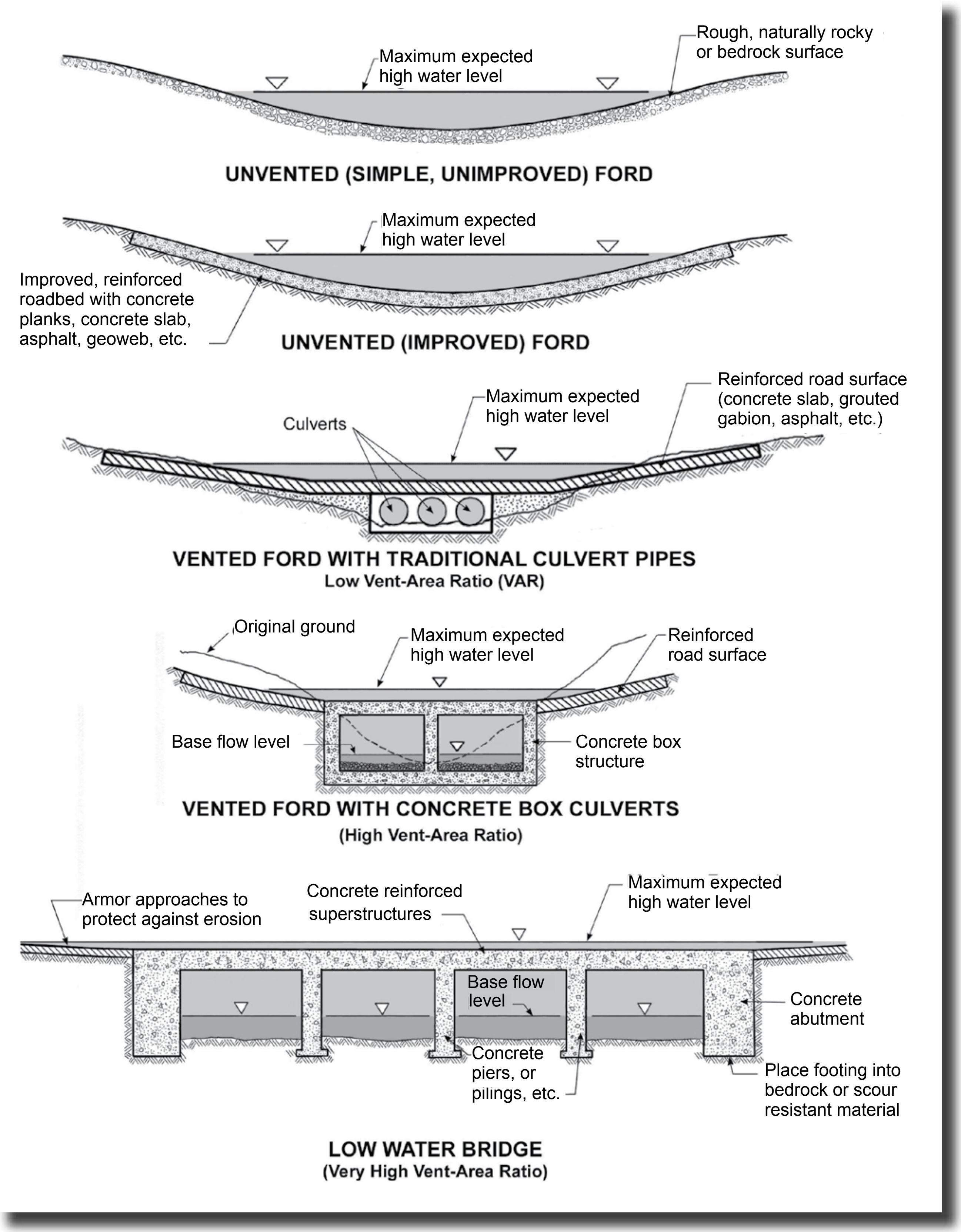


Figure 3-123—Low-water crossing types.

Vented fords fall into two categories—low vent-area ratio (VAR) and high VAR—each of which affects stream channels differently (figure 3-124). Vented fords with culverts that are small relative to the bankfull channel area have a low VAR. A vent opening that approximates or exceeds the size of the bankfull channel has a high VAR. Low VAR structures plug with debris easily; act as a dam and cause deposition of sediment upstream of the structure; and may accelerate flows downstream, creating a barrier to fish passage through the pipe, as well as channel scour. A high VAR structure is much better for aquatic organism passage and to maintain the natural function of the stream.

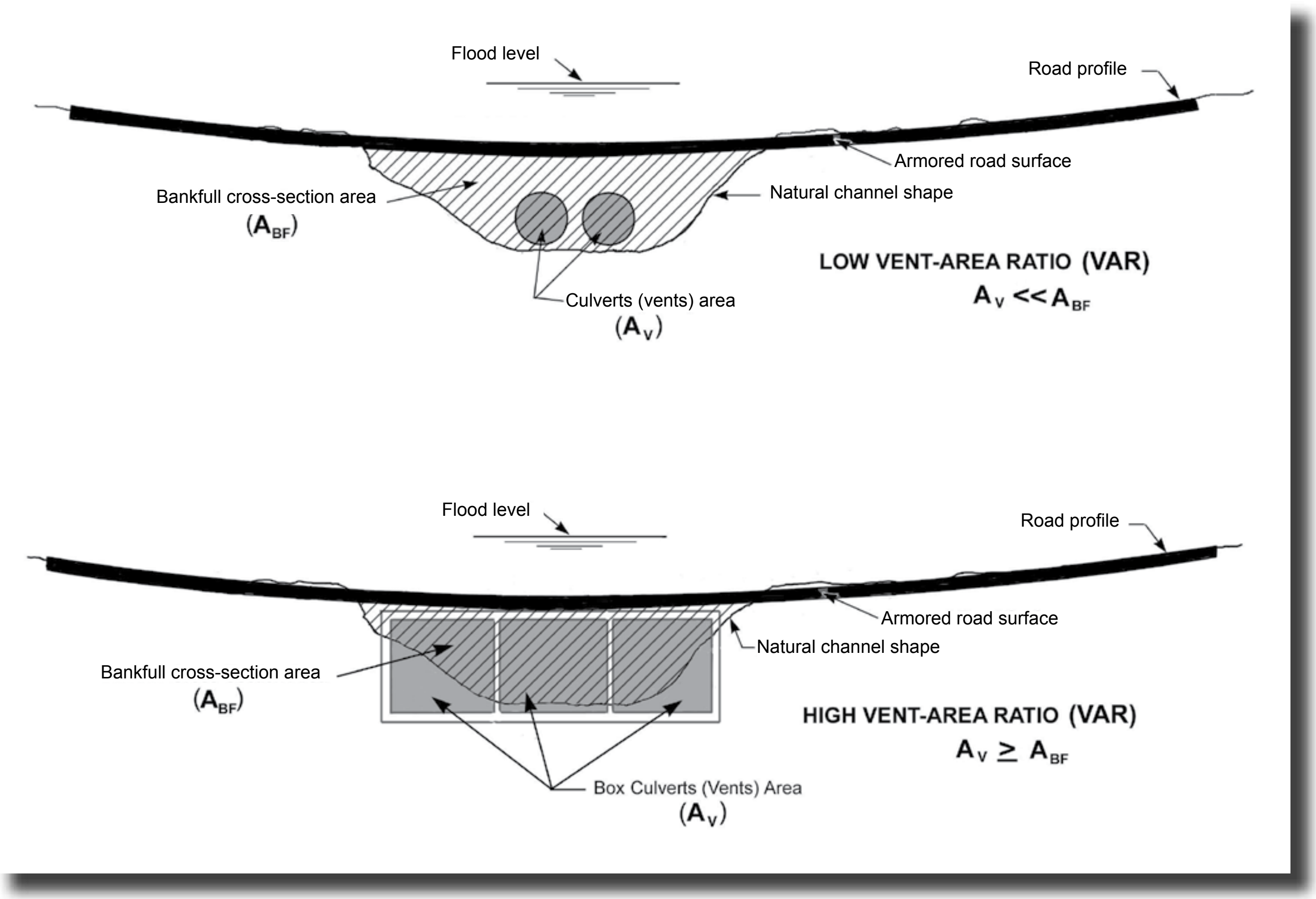


Figure 3-124—Ford vent-area ratio.

Numerous factors must be taken into consideration when fitting a structure to a specific site. To be compatible with its site, a structure should preserve channel function as well as provide for safe traffic use. The structure should match the shape of the natural channel and conform to the site as much as possible (figure 3-125). Broad, shallow (slightly entrenched) channels are the ideal shape for unvented fords. Slightly to moderately entrenched channels can be well suited for crossings with vented fords. Deep, entrenched channels are least suited for fords, but in special circumstances rock-fill fords and vented fords are appropriate crossings even in these channels, particularly if the channel is prone to debris torrents.

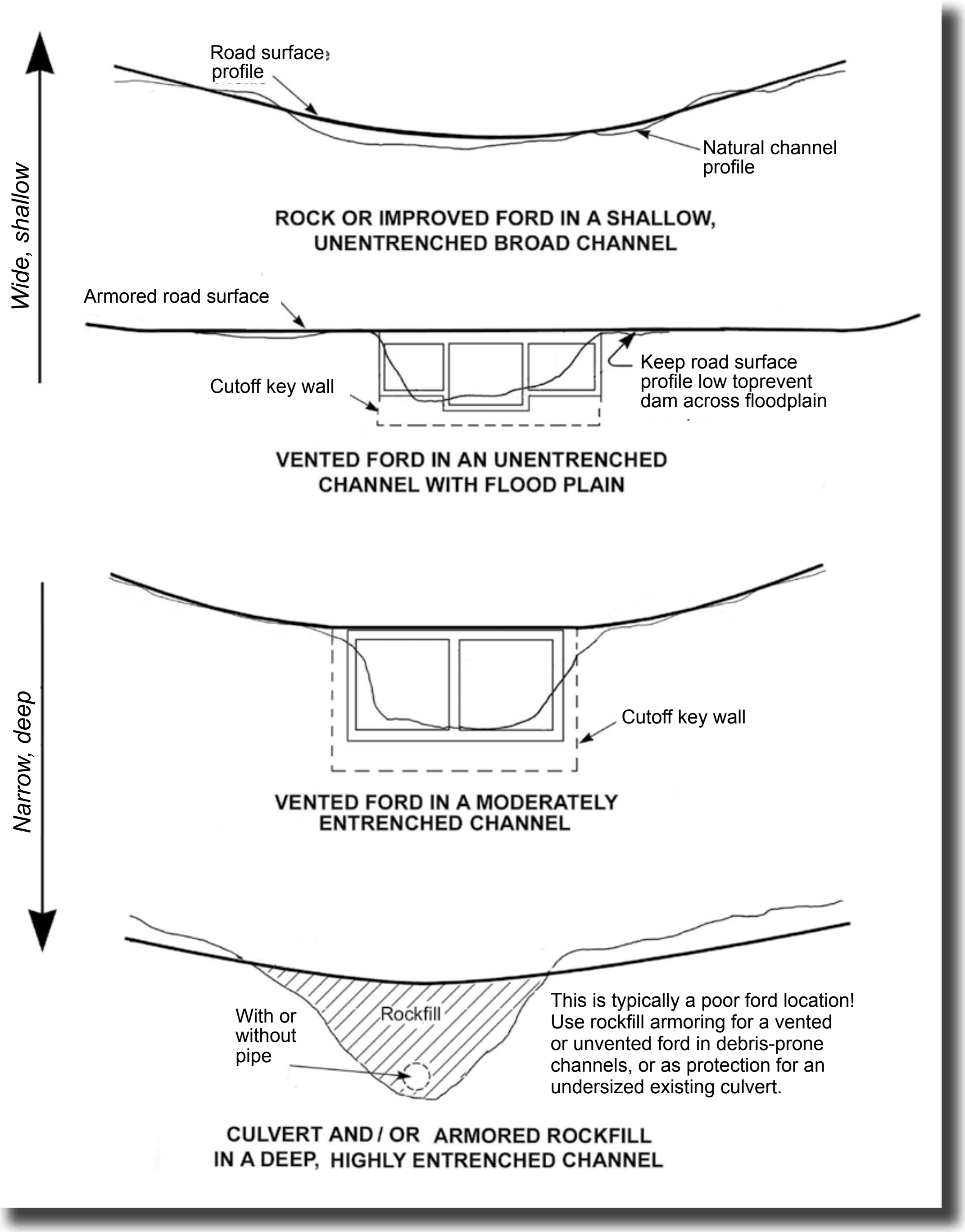


Figure 3-125—Matching channel shape and low-water crossing type.

Figure 3-126 summarizes many of the key design issues necessary to make a ford or low-water crossing function properly and avoid damage. Many existing fords found throughout the United States and used by the Forest Service have been damaged at some time during a flood and have required repairs or have been replaced. To avoid damage to the structures as well as environmental damage, consider the following key design issues:

- ❑ Provide an armored surface clear through the high-water wetted perimeter of the structure, plus some freeboard.
- ❑ Keep the driving surface as low and as close to the natural stream channel elevation as possible.
- ❑ Provide scour protection below the downstream edge of the structure.
- ❑ Maintain a natural stream channel bottom through vented fords.
- ❑ Stabilize and properly drain the road surface on both approaches to the crossing.
- ❑ Use appropriate vertical and horizontal alignment through the crossing for traffic safety and use.
- ❑ Use delineators, signs, and depth markers as needed to make the crossing safe.

For low-water bridges, the FSM 7720 (Transportation System Development) requires that all structures receive specific hydrologic, hydraulic, structural, and foundation design in accordance with AASHTO (2007). A qualified engineer must design and review the structure.

Figure 3-127 shows a simple concrete slab ford (left) and a vented ford (right), both on low-volume roads. The concrete structures are durable, well designed , and have a good road alignment. With the vented ford, delays due to overtopping are minimal since the vents handle the flow most of the time, it has a high VAR, and the natural stream channel bottom through the structure is good for fish passage, as well as sediment and debris movement. This type of vented low-water crossing is ideal but relatively expensive, yet less expensive compared to any bridge alternative at this site.

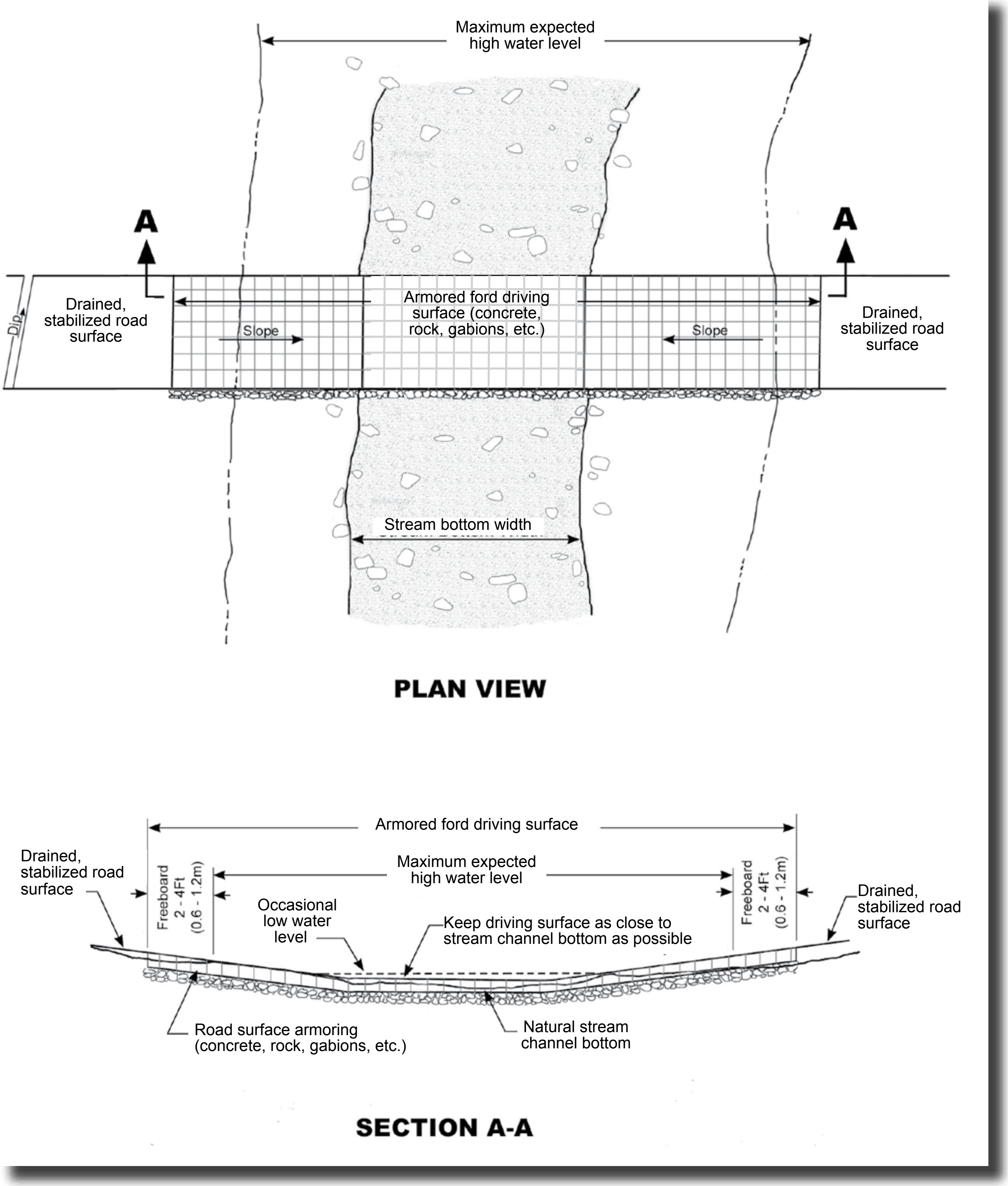


Figure 3-126—Key design components for an unvented, improved low-water ford crossing.

Figure 3-127—A simple concrete ford (left) and a vented ford (right), ideal for fish passage, both on low-volume roads.

For additional technical information about the fords and low-water crossings, consult “Low-Water Crossings: Geomorphic, Biological, and Engineering Design Considerations” (Clarkin et al. 2006). It is particularly useful, for example, where streamflow is highly variable and large amounts of woody debris pose a risk to crossing structures. The publication reviews the advantages and disadvantages of different low-water crossing structures in various stream environments and illustrates situations in which low-water crossings may be the optimal choice of crossing structure. The publication provides multidisciplinary teams planning and designing road-stream crossing structures with answers to questions about where and how to best use overtoppable crossing structures. Link to the Web site <http://www.fs.fed.us/eng/pubs/pdf/LowWaterCrossings/index.shtml>.

3.5.3. Bridge Repairs

Bridge repair projects are necessary to correct structural or functional deficiencies, vehicular collision damage, concrete or steel deterioration, scour problems, etc. Most bridge damage occurs either because of inadequate hydraulic capacity (too small) or because of scour and undermining. Many bridge failures occur due to foundations placed on fine materials that are susceptible to scour. Also bridges are expensive! Thus any bridge repair or replacement requires good site evaluation, analysis, design, and construction oversight. Bridge repairs should be designed or reviewed by a bridge or structural engineer to ensure that they provide adequate structural capacity to support the heaviest anticipated vehicle or load limit, as well as hydraulic and geotechnical engineers to determine hydraulic capacity and an adequate foundation.

Sometimes a bridge has deteriorated beyond repair or has been destroyed by high flows or scour, so bridge replacement is required. The new bridge location and length should ideally be determined by an engineer, a hydrologist, and a fisheries biologist working together as a team. If possible, a bridge should be constructed or moved to a narrow channel location and should be in an area of bedrock or coarse soil and rock for good foundation conditions. The publication "Locating Your Trail Bridge for Longevity" (Groenier and Gubernick 2009) was written for trail bridges but in fact is very applicable for most low-volume road bridge locations. It discusses many of the geologic, geomorphic, and physical requirements for good bridge location.

A single-span bridge with its opening (span) wide enough to minimize constriction of the natural channel is preferable to minimize impact on the stream and scour potential for the bridge. A spill-through abutment with sloping banks (often a 2:1 or 3:1 slope), similar to a natural stream channel shape, minimizes problems with scour and debris plugging. Also remember that natural channels have a tendency to shift laterally and vertically over time, forming meanders in low-gradient settings, and may change flow direction during major flow events, damaging bridge sites (figure 3-128). Thus a bridge site needs to be assessed for lateral and vertical stability. The structure may need wingwalls and streambank armor to protect it and keep the flow directed through the structure.

Figure 3-128—Scour due to lateral migration of the channel (left), and the repair (right) with streambank armor using a concrete wing wall and riprap. Scour is one of the most common causes of bridge failure.

Simple span bridges may be made of logs, timbers, glue-laminated wood beams, steel girders, cast-in-place concrete slabs, prefabricated precast concrete voided slabs, “T” or “I” beams, or modular bridges such as Hamilton EZ or Bailey Bridges. Figure 3-129 shows concrete and timber glue-laminated bridges with spill-through abutments. Many structures and materials are used and are appropriate, so long as they are structurally designed, have a suitable foundation, an adequate span, and have protection against scour.

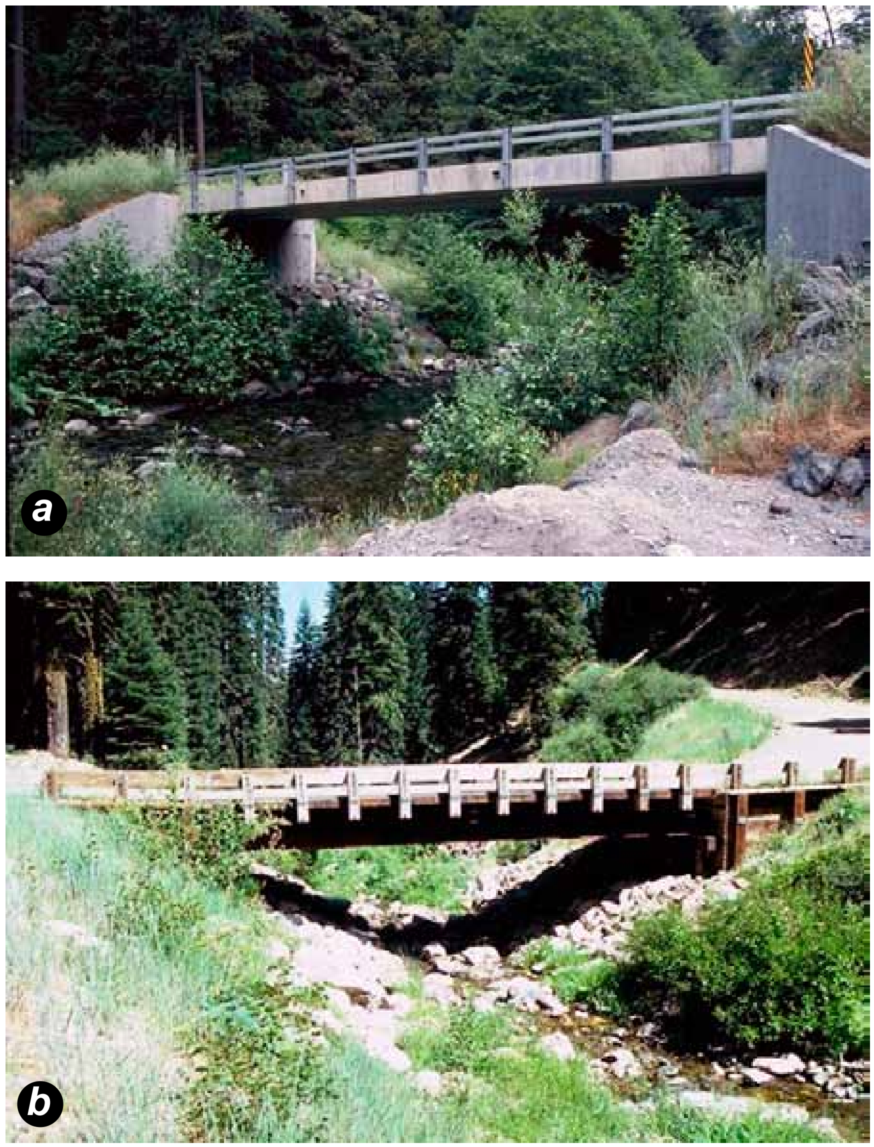


Figure 3-129—Typical (a) concrete and (b) timber glue-laminated bridges with spill-through abutments.

AASHTO (2007) and the most recent AASHTO “Load and Resistance Factor Design” (2007) are the definitive references on the design of highway bridges. They are available at the AASHTO bookstore <https://bookstore.transportation.org/category_item.aspx?id=BR>.

Concrete structures are one of the most common bridges built today for moderate free spans (around 100 feet (30 m)) and are desirable because they can be relatively simple and inexpensive, require minimal maintenance, and have a relatively long design life (100+ years) in most environments. They are also the most adaptable to many configurations and for multiple-span applications (figure 3-130). Historically, log bridges have been used because of locally available materials, particularly in remote areas, but are now often replaced with other types of structures. Keep in mind that logs have relatively short spans and a relatively short design life (15 to 30 years). Treated timber bridges and glue-laminated bridges are used and have a design life of around 50 years if properly treated. Care must be exercised when using treated timber near water courses, and only certain types of wood preservatives are EPA approved for use around water.

Figure 3-130—A concrete bridge that is durable and uses multiple spans to cross a broad flood plain.

Foundations for small, temporary bridges may be simple log sills, gabions, masonry retaining walls or cribwalls, or concrete stem walls with footings. Most permanent road bridges use either spread footings set on scour resistant materials (shallow foundations) or drilled piers or driven piles (deep foundations). Since many bridge failures occur because of scour with a foundation placed upon fine soils, foundation considerations are critical.

Geosynthetic reinforced bridge abutment structures (GRS) offer a desirable alternative to conventional bridge abutments in many applications and can be substantially less expensive. With a GRS abutment, the bridge superstructure sits on top of the geosynthetic reinforced abutment fill. Abutment construction can typically be made using common construction equipment and, with the superstructure and abutment on the same material, differential settlement is minimized. Information on the design and use of GRS bridge abutments can be found in NCHRP Report 556 (Wu et al. 2006). Keller and Devin (2003) discuss the advantages and disadvantages of GRS bridge abutments for rural road applications, as well as general considerations for their use. It is available at <http://trb.metapress.com/content/w474561011x576g0/>.

The "Geosynthetic Reinforced Soil Integrated Bridge System Synthesis Report" (Adams et al. 2011) provides a summary of GRS bridge advantages, building and use experiences, and current design methodologies. It is available at <http://www.fhwa.dot.gov/publications/research/infrastructure/structures/11026/11026.pdf>.

Periodic bridge inspection (typically every 2 years) and maintenance are needed to ensure that the structure continues to be safe to pass the anticipated vehicles, that the stream channel is clear, and to maximize the design life of the structure. Bridge maintenance includes cleaning the deck and seats of the girders, clearing vegetation and debris from the stream channel, replacing object markers and signs, repairing streambank protection measures, treating dry and checking wood, replacing missing nuts and bolts, and repainting the structure.

Water quality protection measures and BMPs should always be incorporated into any bridge improvements or repairs. This includes measures such as site dewatering, working in a cofferdam, containing toxic materials such as lead paint or creosote, and preventing road sediment from getting into the waterway. Measures to prevent sediment movement in the vicinity of structures include building rolling dips into the road or adding leadoff ditches to divert ditch and roadway water before getting to the drainage, and armoring the road surface in the vicinity of the bridge. Figure 3-131 shows a forest bridge with paved road approaches.

Figure 3-131—A bridge with paved bridge approaches to prevent sediment movement into the drainage.

Common Scour Countermeasures

To minimize future bridge flood damage and ensure public safety requires developing and implementing improved procedures for designing bridges and inspecting them for scour. “Every bridge over water should be assessed as to its vulnerability to scour in order to determine the prudent measures to be taken for that bridge and the entire inventory” (Richardson and Davis, 2001).

The Federal Highway Administration has identified common scour countermeasures and has provided guidelines for their use. They recently published a two volume document, “Bridge Scour and Stream Instability Countermeasures” (HEC-23) (Lagasse et al. 2009a) and (Lagasse et al. 2009b). HEC-23 provides guidance for scour countermeasure applicability, design, installation, and maintenance, highlighted by a countermeasure matrix. Many of the countermeasures applicable to low-volume road bridges are included. The most common forms of scour at bridge sites are contraction scour, general channel scour, and local scour around piers and abutments (figure 3-132).

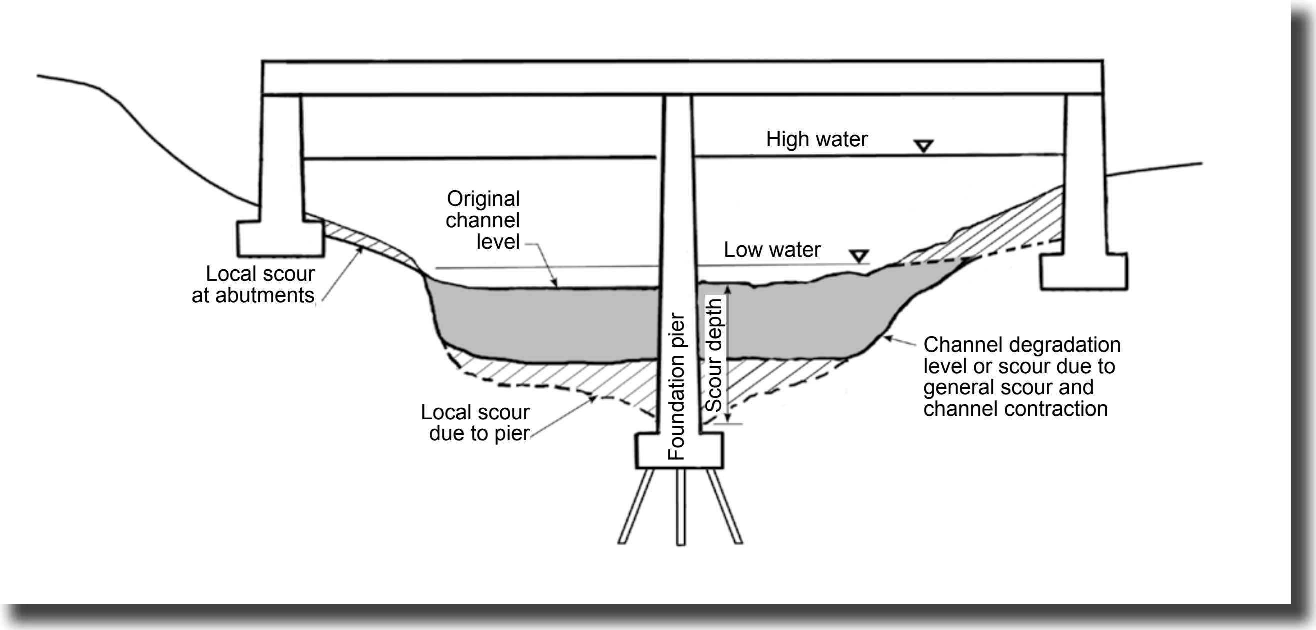


Figure 3-132—Common scour susceptible areas. (Adapted and reproduced with the express written authority of the Transportation Association of Canada, from Neill 1973.)

Key areas needing scour protection are:

- ❑ Along banks, on the outside of a river bend, where flows are directed against the streambank.
- ❑ Along the downstream edge of an in-channel structure, where accelerated velocities or water dropping off a structure produces a waterfall with plenty of erosive energy.
- ❑ Around or beneath midchannel piers, posts, or box walls that create turbulence or accelerated flows.
- ❑ Along the edges and beneath abutments and footings, where locally accelerated flows and scour occur.
- ❑ Around the approaches to structures (outflanking), where high water level may exceed the elevation of armoring or road surface reinforcement.

Common mitigation measures used for protecting structures against scour include:

- ❑ Moving a structure to a location where the local materials are not scour susceptible, such as areas of coarse rock and bedrock.
- ❑ Widening a structure to avoid constricting the flow channel, thus avoiding flow acceleration.
- ❑ Armoring the entire channel with materials (grouted gabions, riprap, concrete, etc.) to resist scour.
- ❑ Protecting the channel, streambanks, and waterfall areas locally against scour, using vegetation, rootwads and logs, riprap, sack concrete, articulated concrete blocks, vegetated turf reinforcing mats, gabions, and so forth.
- ❑ Redirecting stream channel flow with barbs, spur dikes, weirs, cross vanes, and so forth.
- ❑ Installing deep foundations, placed below the anticipated scour level, such as relatively deep spread footings, or drilled or driven piles.
- ❑ Adding shallow scour cutoff walls, gabion or concrete splash aprons, plunge pools, or a riprap layer along the downstream edge of an in-channel structure.
- ❑ Installing deep cutoff walls or deep sheet piles installed to a depth below the depth of scour, or to scour-resistant material, such as bedrock.

Debris and Scour

Channel debris may cause scour problems for bridges. However, debris problems and the associated scour are difficult to anticipate and remedy on existing bridges. New bridge designs can account for potential debris problems by sizing spans to accommodate debris, providing additional freeboard, and minimizing or eliminating piers in the channel. Typical countermeasures for an existing bridge with debris problems include:

- ❑ Monitoring debris buildup for prompt removal.
- ❑ Clearing upstream debris.
- ❑ Installing debris catchers/deflectors.

Trash racks are sometimes used on culverts, but typically are not used on major streams with bridges. A debris catcher/deflector on mountainous streams requires maintenance, and its use must be carefully considered with respect to stream mechanics. A catcher/deflector could cause the stream channel to shift, resulting in other scour problems, debris accumulation, fish passage blockage, and so forth. Deflectors or veins/spurs are occasionally used in channels upstream of a bridge to direct the flow through the middle of the bridge.

For additional technical information about scour, consult "Evaluating Scour at Bridges" (HEC 18) (Richardson and Davis 2001) and Lagasse et al. (2009a) and (2009b). These manuals are part of a set of Hydraulic Engineering Circulars (HECs) issued by FHWA to provide guidance for bridge scour and stream stability analyses. The manuals present the state of knowledge and practice for the design, evaluation, and inspection of bridges for scour. Links to the manuals: HEC-18 (Richardson and Davis 2001) <http://isddc.dot.gov/OLPFiles/FHWA/010590.pdf> and HEC-23 (Lagasse et al. 2009a and Lagasse et al. 2009b) <http://www.fhwa.dot.gov/engineering/hydraulics/pubs/09111/index.cfm>.

Riprap

Riprap is, and probably remains, one of the primary scour countermeasures to resist local scour forces at abutments for small bridges. Riprap is generally abundant, inexpensive, and requires no special equipment. However, proper design and placement is essential. Within HEC-18, riprap is included under local scour armoring. HEC-18 and HEC-23 provide guidelines for proper sizing and placement. Also "Design of Riprap Revetments" (HEC-11) (Brown and Clyde 1989) provides specific design criteria for use of riprap. When designing riprap countermeasures, maintaining an adequate hydraulic opening through the bridge must be considered. Improperly placed riprap can reduce the hydraulic opening significantly and create contraction scour problems. Riprap to protect intermediate piers is now considered only a temporary solution. Again, if placed improperly, riprap can increase local scour forces. Additional riprap information is found in section 3.5.4.2

Spur Dikes, Barbs, Groins, Vanes

Spur dikes, barbs, groins, and vanes are considered river training structures that alter stream hydraulics to mitigate undesirable erosional and/or depositional conditions. They commonly are used on unstable stream channels to redirect stream flows to a more desirable approach or location through the bridge, and minimize streambank erosion.

Foundation Strengthening

On typical low-volume road bridges, foundation strengthening may include:

- Extending the footing deeper to offset long-term stream channel degradation.

- ❑ Providing additional tiebacks on a vertical wall abutment if scour has caused loss of support and the abutments have begun to settle.
- ❑ Installing a new abutment with deeper footings or piles.
- ❑ Providing local armor around piers or abutments.

A geotechnical engineer should be involved in bridge foundation repairs.

For additional technical information about bridge scour, consult “Bridge Scour Evaluation: Screening, Analysis, and Countermeasures” (Kattell and Eriksson 1998). Scour, defined as “the erosion or removal of streambed or bank material from bridge foundations due to flowing water” is the most common cause of road bridge damage or failure in the United States. To minimize future bridge flood damage and ensure public safety requires developing and implementing improved procedures for designing bridges and inspecting them for scour. The FHWA issued a Technical Advisory in 1988 revising the National Bridge Inspection Standards to require evaluation of all bridges for susceptibility to damage resulting from scour. Link to Kattell and Eriksson (1998) <http://www.fs.fed.us/eng/pubs/pdf/98771207.pdf>.

3.5.4. Solutions for Streambank Instability

Streambank protection consists of restoring and protecting banks of streams, lakes, estuaries, and excavated channels against scour and erosion by using vegetative plantings, soil bioengineering, and structural systems. The solutions for streambank instability often involve a combination of physical and soil bioengineering techniques. Streambank stabilization measures often are needed at road-stream crossings where a road fill may encroach on the stream, a culvert fill is placed across the stream, or where a flow constriction accelerates the natural stream channel velocity leading to local scour.

Many remedies are available to minimize the susceptibility of structures or streambanks to disturbance-caused erosive processes. They range from vegetation-oriented remedies, such as conventional plantings, to a combination of ecological and engineering elements, such as soil bioengineering, to engineered grade stabilization structures. Historically, many organizations involved in water resource management have given preference to engineered structures; they remain viable options. However, in a growing effort to restore sustainability and ensure diversity, preference should be given to those methods that restore the ecological functions and values of stream systems as well as protect the structure. The value of vegetation in civil engineering and the role woody vegetation plays in streambank stabilization have gained considerable recognition in recent years.

Once a stream crossing structure is placed in a channel, the dynamics of the site may be changed or the structure itself may need protection. The structure may need armoring, the stream channel may need protection or bank stabilization, or it may be desirable to control the flow in the channel with some river training measures to protect the structure and/or the banks.

The two basic categories of protection measures for structures and streambanks are:

- ❑ Those that increase the local resistance to erosion.
- ❑ Those that reduce the force of water against the structure or streambank.

Examples of ways to increase local resistance to erosion include:

- ❑ Conventional vegetation.
- ❑ Soil bioengineering measures, such as live stakes, joint planting, brushmattress, live fascines.
- ❑ Conventional engineering measures, such as rock riprap, gabions, concrete.
- ❑ Structural biotechnical measures, such as erosion control blankets, turf reinforcement mats, rootwads and boulder revetments, articulated concrete blocks, and so forth.

Examples of ways to reduce the force of water include many river training structures, such as spur dikes, groins, jetties, barbs, weirs, drop structures, in-channel logs (large woody debris) and boulders, increased channel sinuosity, vegetated floodways, and so forth. A combination of methods often is used. Some considerations on which stabilization method to use include:

- ❑ Selecting self-sustaining, permanent solutions that (in the case of soil bioengineering measures) have the ability to grow stronger with age and require minimum future maintenance.

- ❑ Protecting or restoring the natural functions and values of the stream as much as possible.
- ❑ Using native, natural living plants and locally available inert materials.
- ❑ Protecting or improving water quality by reducing water temperatures and sedimentation problems.
- ❑ Selecting measures that are strong or durable enough to resist the erosive forces of the stream during a major storm event.

One of the key references on this topic is the U.S. Department of Agriculture, Natural Resources Conservation Service, Engineering Field Handbook, Chapter 16 "Streambank and Shoreline Protection" (NRCS 1996). This classic reference describes traditional physical streambank stabilization methods, uses of vegetation, and soil bioengineering methods. Link to document <http://directives.sc.egov.usda.gov/OpenNonWebContent.aspx?content=17553.wba>.

Another key reference is NCHRP Report 544, "Environmentally Sensitive Channel and Bank Protection Measures" (McCullah and Gray 2005). This publication presents an excellent and comprehensive summary of the many channel and bank stabilization options. Link to the document <http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_544.pdf>.

3.5.4.1. Soil Bioengineering for Streambank Instability

Soil bioengineering uses sound engineering practices in conjunction with integrated ecological principles. It takes advantage of the benefits of vegetation systems, arranged in specific ways, to prevent or repair damage caused by erosion and stream scour. The role of soil bioengineering for streambank stability is instrumental in road rehabilitation and stabilization for use along the road, adjacent to an eroding streambank, or at structures such as a bridge. Adapted types of woody vegetation (shrubs and trees) are installed initially in specified configurations that offer immediate soil protection and reinforcement.

Additionally, soil bioengineering systems create resistance to sliding or shear displacement in a streambank as plantings develop roots or fibrous inclusions. Environmental benefits derived from woody vegetation include diverse and productive riparian habitats, shade, organic additions to the stream, cover for fish, temperature reduction, and improvements in aesthetic value and water quality. Table 3-27 presents a summary of soil bioengineering measures used in streambank protection.

Under certain conditions, soil bioengineering installations work well in conjunction with structures to provide more permanent protection and health function, enhance aesthetics, and create a more environmentally acceptable product. Soil bioengineering systems normally use plant parts, such as live cut branches and/or rooted plants. For streambanks, live stakes, live fascines, joint planting through rock (vegetated riprap), vegetated geogrids and gabions, live cribwalls, branch packing, and live brushmattresses are all used in various configurations as appropriate for specific location and show a joint planting system with live stakes tamped through riprap, both initially after installation and after several years. Figure 3-133 and figure 3-134 show a joint planting system with live stakes tamped through riprap after installation and after several years. Figure 3-135 shows a style of streambank stabilization using logs, rootwads, and boulders.

Rooted seedlings and rooted cuttings are excellent additions to soil bioengineering projects. They should be installed for species diversification and to provide habitat cover and food for fish and wildlife. Optimum establishment is achieved within the first few years, with an initial flush the following spring.

Table 3-27—Summary of soil bioengineering measures for streambank protection (courtesy of Robbin B. Sotir & Associates, Inc.).

SUMMARY SOIL BIOENGINEERING STREAMBANK PROTECTION MEASURES ADAPTED FOR LOW-VOLUME FOREST ROADS			
Method Type	**Instream Work (below bed elevation)**	**Useful for Specific Conditions**	**Comments and Restrictions**
Live Stake	No	Small bank scour, overbank runoff after regrading	Suitable for small, simple erosion problems where velocities are low and best used in conjunction with other soil bioengineering measures and with erosion control fabrics.
Live Fascine	No (Trench excavation)	General bank scour; overbank runoff after regrading.	Useful for moderate to severe erosion; should not be used on bank faces longer than 25 feet (8 m). May be installed on contour or on incline (to control internal seepage and reduce flow velocities). In outside meanders these are best installed on angle (low ends oriented downstream) to prevent linear erosion along installed live fascines. Best to include live stakes as part of the measure and in between the installed live fascines. May be combined with brushlayers to increase roughness. Erosion control fabrics can also be useful when installed under each live fascine.
Live Siltation Construction	Yes/No (trench construction) May be below bed in high-flow channels.	Moderate toe erosion or lower bank scour.	Useful to reduce velocities near the toe, offer dense overhanging cover, and provide immediate toe reinforcement. Rock may be added behind/overtop of this measure to increase protection. May be installed in several rows along the bank, creating habitat for waterfowl. It is installed parallel to the streamflow.

Table 3-27—Summary of soil bioengineering measures for streambank protection (courtesy of Robbin B. Sotir & Associates, Inc.) continued.

Method Type	Instream Work (below bed elevation)	Useful for Specific Conditions	Comments and Restrictions
Vegetated Reinforced Soil Slope	Yes (Foundation below scour elevation and bank excavation.)	Large local bank scour; toe erosion, bank failure.	Useful up to 1.5H to 1V steep slopes by 15 feet (5 m) long, where space is limited, velocities high. A large hole requires immediate repair, possibly in a critical area such as near a bridge, and soil reinforcement (geogrid) is required. Foundation is required. May be constructed with live branch cuttings and/or rooted plant materials in the summer growing season (expanding the construction time and providing diverse species for riverine (habitat value). Detailed and expensive measure requiring extensive excavation and fill. Requires major engineering.
Brushmattress	No (After the bank has been regraded.)	Local and general bank scour; debris gouging.	Generally used on 2-3H:1V graded banks. Restricted to sites up to 50 feet (15 m) long. Excellent in straight reaches. May be installed in several layers to cover the bank from the bottom to the top. Is typically installed with a live fascine along the bottom to secure live branches placed against the bank and live stakes in the mattress itself to secure the branches to the ground. Measure has several details but is well known. It may be constructed using live cut branches or rooted plants. Rooted plants provides for summer installation and species diversity.
Joint Planting	No	Toe erosion or shallow bank failure.	Gentle to moderate banks 2-4H:1V. Requires engineering for the riprap rock.

Note: All soil bioengineering streambank measures provide riverine (riparian and aquatic life) benefits. Overhanging vegetation does the following:

- ❑ Provides cover near the water's edge.
- ❑ Provides food for shredders.
- ❑ Provides insect food for fish.
- ❑ Modifies water temperatures.
- ❑ Reduces near-bank velocities.
- ❑ Provides resting, feeding, nesting, drinking places for riverine life.

Figure 3-133—An installed joint planting system (courtesy of Robbin B. Sotir & Associates, Inc.).

Figure 3-134—Biotechnical riprap streambank stabilization after several years.

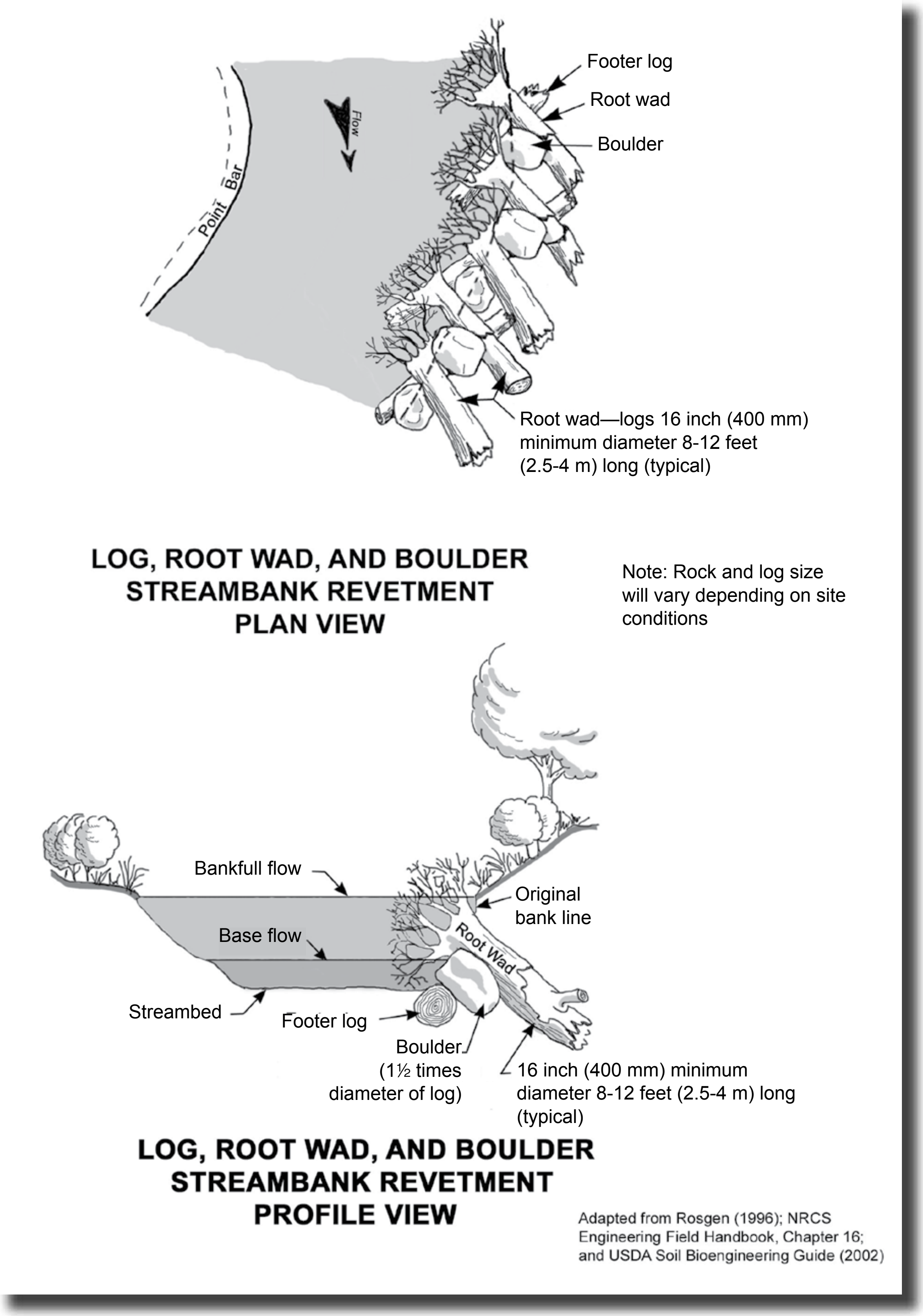


Figure 3-135—Log, rootwad, and boulder streambank stabilization measures.

The planning stage of any stream or river project is the most critical. In-channel streambank stabilization or protection work, with or without biotechnology, can be very complicated and difficult to assess and implement. Use an interdisciplinary approach including engineering, hydrology, fisheries biology, and other disciplines. Find experts who have experience working with these types of projects. The results can be the best of several worlds. A stable stream channel can be achieved with long-lasting results. The combination of conventional structures and soil bioengineering can provide strong functions, including ecological habitat values for the riverine environment, aesthetic benefits, and mechanical strength.

"A Soil Bioengineering Guide for Streambank and Lakeshore Stabilization" (Eubanks and Meadows 2002) addresses the many environmentally friendly alternatives for bank stabilization. The guide provides information on how to successfully plan and implement soil bioengineering techniques. It is designed for recreation staff personnel and forestry technicians who are engaged in the day-to-day construction and maintenance of water-related recreation facilities, including dispersed areas, forest roads, and trails. Link to the document <http://www.fs.fed.us/publications/soil-bio-guide/>.

For more information on streambank protection, consult Cramer et al. (2003). Link to the Web site <http://wdfw.wa.gov/hab/ahg/ispgdoc.htm>.

3.5.4.2. Traditional Streambank Stabilization Measures

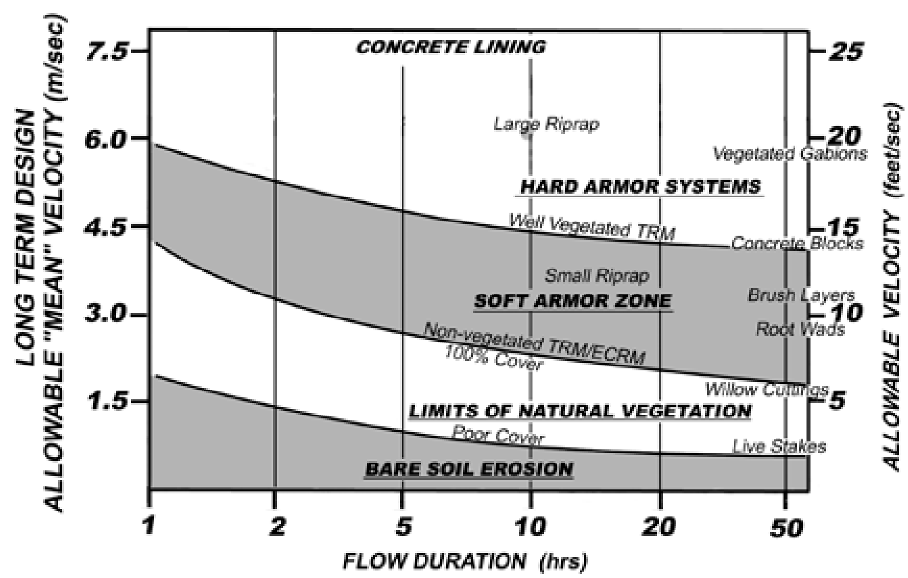
If local or average velocities exceed the permissible velocities of the materials for movement, erosion and scour result. Therefore, either take measures to reduce the velocities, redirect the flow, dissipate the energy of the flow, provide stability below the likely depth of scour, or armor the areas with materials that can resist the flow's forces.

Many treatments have traditionally been used to stabilize a streambank or protect the entrance and outlet to a structure, both as a repair measure and as a preventative treatment. Measures include the use of revetments, such as rock riprap, gabions, concrete slabs, cable concrete, and rootwads. Lighter treatments, such as turf reinforcing mats in some circumstances, help promote vegetation growth.

Different structures types have different scour risks. Some structures accelerate flows through pipes or vents, some confine channel flow, some accelerate flow across the driving surface, and some create a water drop off the downstream edge. These areas commonly need protection. Depending on the velocity of flow and erosion potential, the following treatments provide scour protection and/or bank stabilization:

- ❑ Vegetation, erosion control mats, or small riprap for low velocities.
- ❑ Soft armor systems, such as biotechnical treatments, vegetated turf reinforcing mats, rootwads, logs, and boulders for moderate velocities.
- ❑ Hard armor systems, such as articulated concrete blocks, gabions, large riprap, grouted riprap, or concrete for high channel velocities or high shear stress areas where flows are turbulent or impinging upon the streambank.

Figure 3-136 (adapted from Fischenich (2001)) provides general guidelines for selecting channel and bank stabilization measures as a function of mean channel velocity and the duration of flow (i.e., how long the area is subject to inundation). McCullah and Gray (2005) present an excellent summary of the channel and bank stabilization options available today.



NOTES:
1. **Hard Armor** - *includes Concrete, Riprap, Gabions, Concrete Blocks, etc.*
2. **Soft Armor** - *includes Turf Reinforcement Mats (**TRM**), Erosion Control Revegetation Mats (**ECRM**), Vegetated Geocells, and many Biotechnical Treatments.*
3. *Available data shows considerable variability in limit velocities.*

Figure 3-136—Allowable velocities and flow duration for various erosion and bank protection measures (adapted from Fischenich 2001, Theisen 1992, and McCullah and Gray 2005).

Rock Riprap

A rock riprap revetment, as discussed earlier, is one of the most commonly used erosion and scour protection measures because of its resistance to high stream velocities, relatively low cost, durability, adaptability to many sites, revegetation opportunities, and some self-healing aspects of loose rock. Because riprap is a loose rock structure, to some degree it can move, deform, and conform to scour areas and still offer erosion or scour protection. It can effectively armor an entire channel cross section (above water and under water), armor streambanks to the expected high water level, and armor a plunge pool or stilling basin. Riprap can be placed at a pipe's outlet, along a structure's downstream edge, in a scour hole, or around and along a channel protrusion, such as a pier.

Riprap-sizing criteria have been developed by many agencies. The most rigorous criteria are based upon shear stresses or tractive forces exerted by flowing water along the rock surface. The FHWA publication HEC-11 (Brown and Clyde 1989) provides a comprehensive design process for riprap sizing, using permissible tractive forces and velocity, along with design examples. HEC-23 (Lagasse et al. 2009a) and (Lagasse et al. 2009b) also discusses riprap design. Size criteria based upon permissible velocity are often used because velocity information may be available from Manning's Equation, direct measurements, or other sources (figure 3-137). Install rock large enough that it is not displaced by the forces of flowing water.

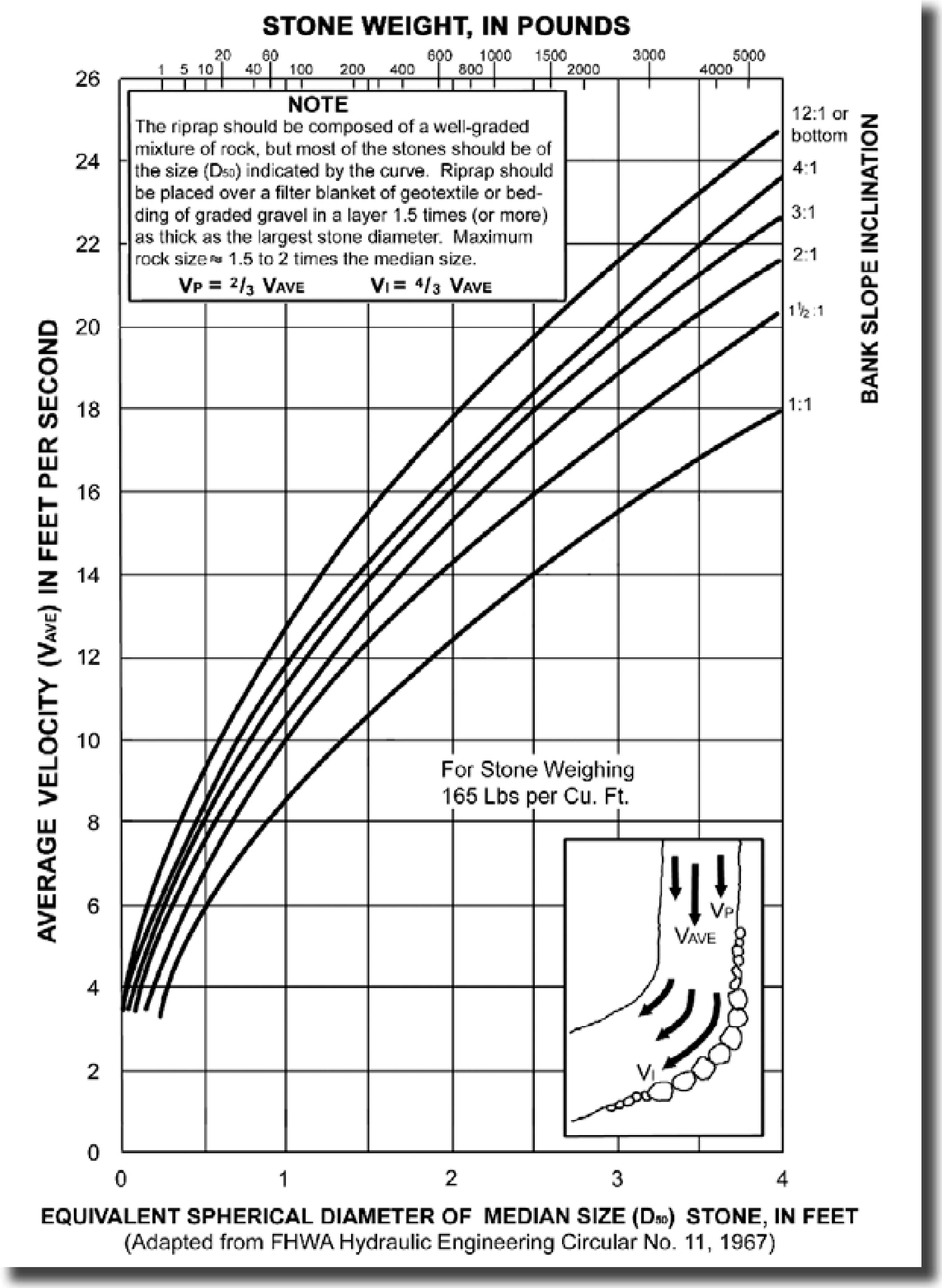


Figure 3-137—Sizing criteria for riprap that will resist displacement versus flow velocities (note that 1 foot/second = 0.305 meters/second and 1 pound = 0.454 kilograms)

Several design and installation details are important when using riprap (figure 3-138):

- ❑ Use well-graded riprap to provide a dense armoring layer. The riprap layer should be at least as thick as the maximum rock size, and preferably 1.5 times the maximum.
- ❑ Use hard, durable, and angular rock.
- ❑ Place riprap upon a filter layer of either gravel or geotextile. The filter allows water to drain from the soil while preventing soil particle movement behind the riprap. In critical applications, a multiple filter layer may be desirable. A sand cushion over a geotextile prevents damage to the geotextile.
- ❑ Key in riprap around the layer's perimeter, particularly along the toe of an armored slope and at the upstream and downstream ends of the rock layer. Extend the protection through a curve or beyond the area of where fast or turbulent flow is expected. Excavate the toe key to the depth of expected scour, or to at least several feet deep.
- ❑ Place riprap with an excavator or by hand. Dumped riprap can result in an uneven layer thickness.

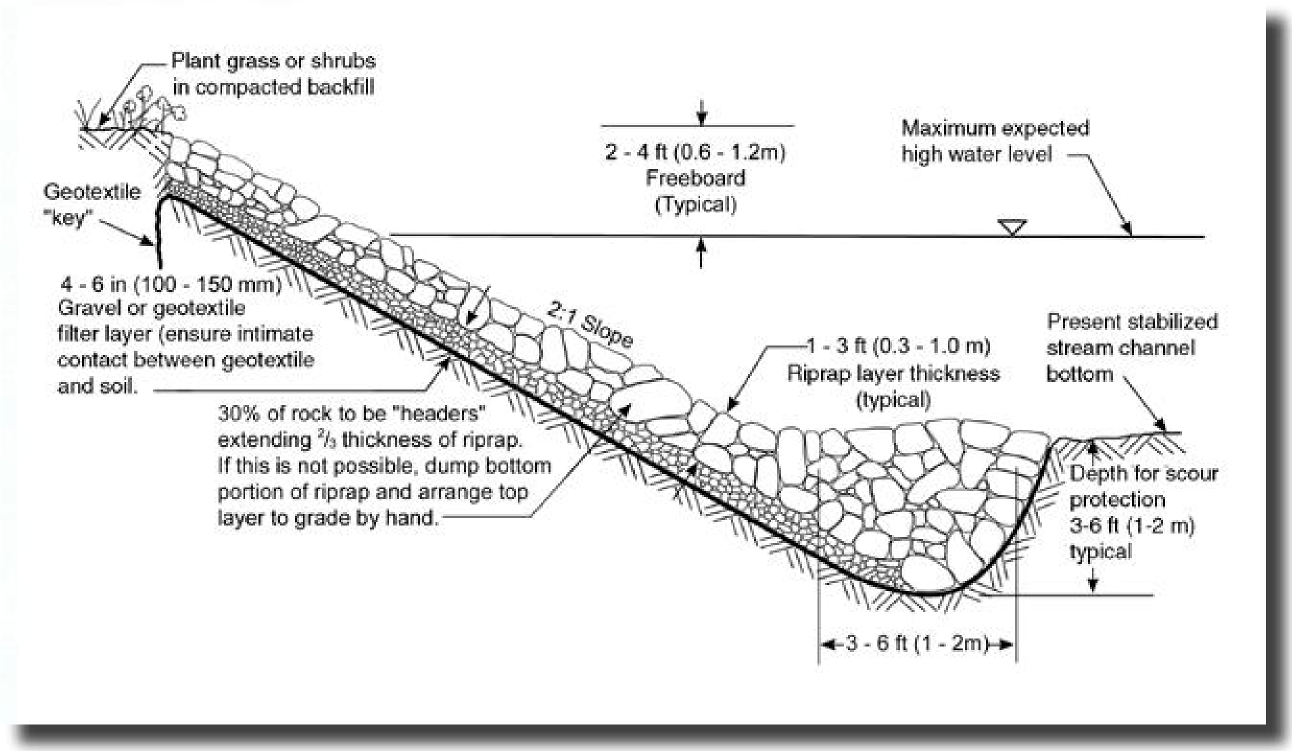


Figure 3-138—Riprap installation details for streambank protection.

The maximum rock size used in remote areas is often dictated by what's available. If large rock is not available, then grout a smaller rock with concrete or use gabions. Otherwise, risk of failure becomes higher. Relatively large riprap is needed around a bend in a stream where the streambanks are subject to the force of impinging flows. Smaller riprap can be used in areas of parallel flow. Figure 3-139 shows the use of riprap at a bridge site on a bend in the creek.

Figure 3-139—Large riprap armoring used for streambank protection through a bridge that is located near a bend in the creek.

Gabions

Gabions offer an alternative to rock riprap in areas where larger rock is not available. Gabions are formed by filling 1- to 4-cubic-yard (meter) baskets with relatively small 4- to 8-inch (100 to 200 mm) size cobbles (section 3.2.2.1.1.1). This effectively creates large rock baskets with small rocks. Generally, loose rock riprap is preferable because it is less expensive than gabions and can deform better in cases of local scour or undermining of the structure. Furthermore, gabion baskets can eventually fail by abrasion, corrosion, snagging on floating debris, or rusting out, requiring costly repairs or replacement.

The useful life of gabions may only be 15 to 30 years, or less in aggressive environments and if the wire is not coated. Longevity also depends on location of the baskets, local corrosion conditions, corrosion protection (such as galvanizing or a plastic coating on the wire), and amount of abrasion from bed load movement. When using gabions, place a filter layer (usually a geotextile) behind the baskets to protect them against scour. Using gabions in conjunction with vegetation can improve their effectiveness by reinforcing the soil mantle behind the baskets over time, especially if sediment becomes deposited between the rocks in the wire basket. Also vegetation adds frontal roughness, protecting the gabions from abrasive bedload movement. Figure 3-140 shows the use of gabions (and concrete) to protect the entrance to a bridge.

Figure 3-140—Gabions and concrete wall streambank protection at a bridge.

Vegetation

Vegetation is the most desirable method of streambank protection (as well as some channel protection where vegetation can grow) because of low cost, aesthetics, compatibility with the natural environment, and overall mechanical and ecological functions. Vegetation alone, however, is suitable only for streambank protection with velocities in the range of 1 to 5 feet per second (0.3 to 1.5 m/s). It is not adequate for protecting areas of turbulent flow, areas of fast or impinging flows, midchannel piers, or areas that are underwater. Vegetative-stabilization performance can be improved significantly by using it in conjunction with rootwads and boulders, soil bioengineering treatments, and reinforcement mats, as discussed in section 3.5.4.1.

Use soil bioengineering treatments with live stakes or brush mats to resist velocities up to 4 to 6 feet per second (1 to 2 m/s). Well-installed soft armor, such as biotechnical streambank protection measures using vegetation along with rootwads, tree trunks, or boulders, are suitable for velocities of at least 6 to 12 feet per second (2 to 4 m/s) (Gray and Sotir, 1996). For faster velocities, hard armor systems are commonly used (see figure 3-136). Ideally, vegetation should be native, deep rooted, and adapted to local site conditions. A variety of pioneer species, including willow, is commonly used.

In-channel scour protection treatments differ from streambank treatments. In-channel stabilization measures mostly are rock, gabions, or concrete whereas streambank stabilization measures, especially above bankfull levels, are vegetation, either alone or in conjunction with the more rigid measures.

3.5.4.3. Road Realignment Into the Cutslope

Road realignment or narrowing a section of the road may be ways to deal with slope instability and also with erosion at the toe of a slope, especially if that slope toe ends up in a stream. Shifting and widening into the cutbank gains space in a narrow canyon or steep area, often caused by a stream channel eroding and over-steepening the roadway fill. This situation is demonstrated in figure 3-141 and figure 3-142 where a roadway fill toe is originally in the stream. After reconstruction, the road level is raised and the template shifted into the cutbank, away from the creek. Also the toe of the fill is armored with riprap along the creek.

Figure 3-141—Steep and scoured fillslope extending into the river before reconstruction (courtesy of Mike Balen).

Figure 3-142—Road centerline is shifted away from the river after reconstruction with a flatter, stable fillslope and riprap armor along the river (courtesy of Mike Balen).

In this situation the road is likely poorly located too close to a stream channel. However, construction in narrow, confined canyons may be necessary and often results in this situation. To correct this situation, construct a retaining wall, with a foundation set below the stream scour level, or place rock riprap to armor the roadway fill against stream scour. However, minor road realignment or road relocation may be more cost effective, particularly for a long-term solution. Raising the road grade also may be desirable to ensure that the roadway surface elevation is above the high-water level of the stream.

Realignment of a roadway into a cutslope can be simple if the cutslope is low, if vegetation is sparse or small, and if little or no ground water exists. Otherwise, realignment can develop into a major project with significant impacts and costs.

3.5.5. Solution for Meadow and Wet Area Crossings

First, do not locate roads in or cross meadows or wet areas! Wet areas are ecologically valuable, important for wildlife and the environment, and are difficult for road building, logging, or other operations. Soils in these areas are often weak and saturated, requiring considerable subgrade reinforcement. Drainage measures are expensive and may have limited effectiveness. Thus crossing meadows and wet areas, such as swamps, high ground water areas, and spring sources are problematic, expensive, and technically challenging.

If a meadow must be crossed, it is important to achieve a stable road surface, prevent damage to the meadow, and prevent alteration of ground water flow patterns. Meadows typically have dispersed, low velocity surface and subsurface flow regimes. Improperly located and constructed culverts and fills may cause significant damage by concentrating the flow, creating new channels or gullies, damming the flows, and increasing velocities through drainage structures.

Avoid placement of drainage structures below the natural grade of the meadow. This often results in the gully formation at both ends of the pipe. The concentrated flow and increased velocities lead to additional down cutting and gully expansion. Eventually, this results in lowering of the water table and drying of at least part of the meadow.

However, wet and meadow areas can be crossed, or damaged roads and meadows can be reconstructed to achieve a stable road platform while minimizing damage to the meadow. If wet areas must be crossed and cannot be avoided, it is important to achieve a stable, dry road surface, prevent damage to the meadow or wet area, and prevent alteration of ground water flow patterns and ground water elevation in these areas.

The most significant factors in wet area crossings are:

- ❑ Ideally, select an alternative route that does not cross the meadow. If the meadow must be crossed, look for the narrowest crossing point and cross perpendicular to the direction of flow.
- ❑ Determine the depth of the water table, zone of water flow, and type and strength of soils to ensure proper design and construction.

- ❑ Ensure free water flow through the roadbed, such as with a coarse rock fill. Maintain cross drainage at the elevation of the natural ground surface or channel bottom. Protect the inlet and outlet of cross drains to prevent local scour.
- ❑ Keep the natural flow patterns in the meadow, typically with a dispersed flow using multiple culvert pipes.
- ❑ Use adequate subgrade and surface reinforcement to achieve a solid, nonsettling road surface. Coarse rock often is used to add structural stability and provide free-draining material.
- ❑ Keep the coarse rock free draining by separating it between filter layers of geotextile.

Keeping these factors in mind, the natural flow regime can most effectively be preserved by passing any surface flow through a series of small-diameter, low-profile culverts set at the meadow elevation rather than concentrating the flow into one large culvert. Also set the pipes into a coarse rock fill enveloped in geotextile to promote the flow of ground water and shallow surface flow. Protect the pipe inlet areas with low rock berms to prevent headcutting and armor the outlets with small riprap to protect against erosion. Figure 3-143 shows a proper crossing design, built with multiple culverts, and set at meadow elevation and grade to keep the water dispersed and prevent down cutting. This process requires paying attention to detail to ensure that the pipes are installed properly. The additional cost can be significant, but it is an investment in the environment to prevent damage to a sensitive area, as well as to construct a stable road. Figure 3-144 shows multiple drainage pipes to keep water flow dispersed across a meadow.

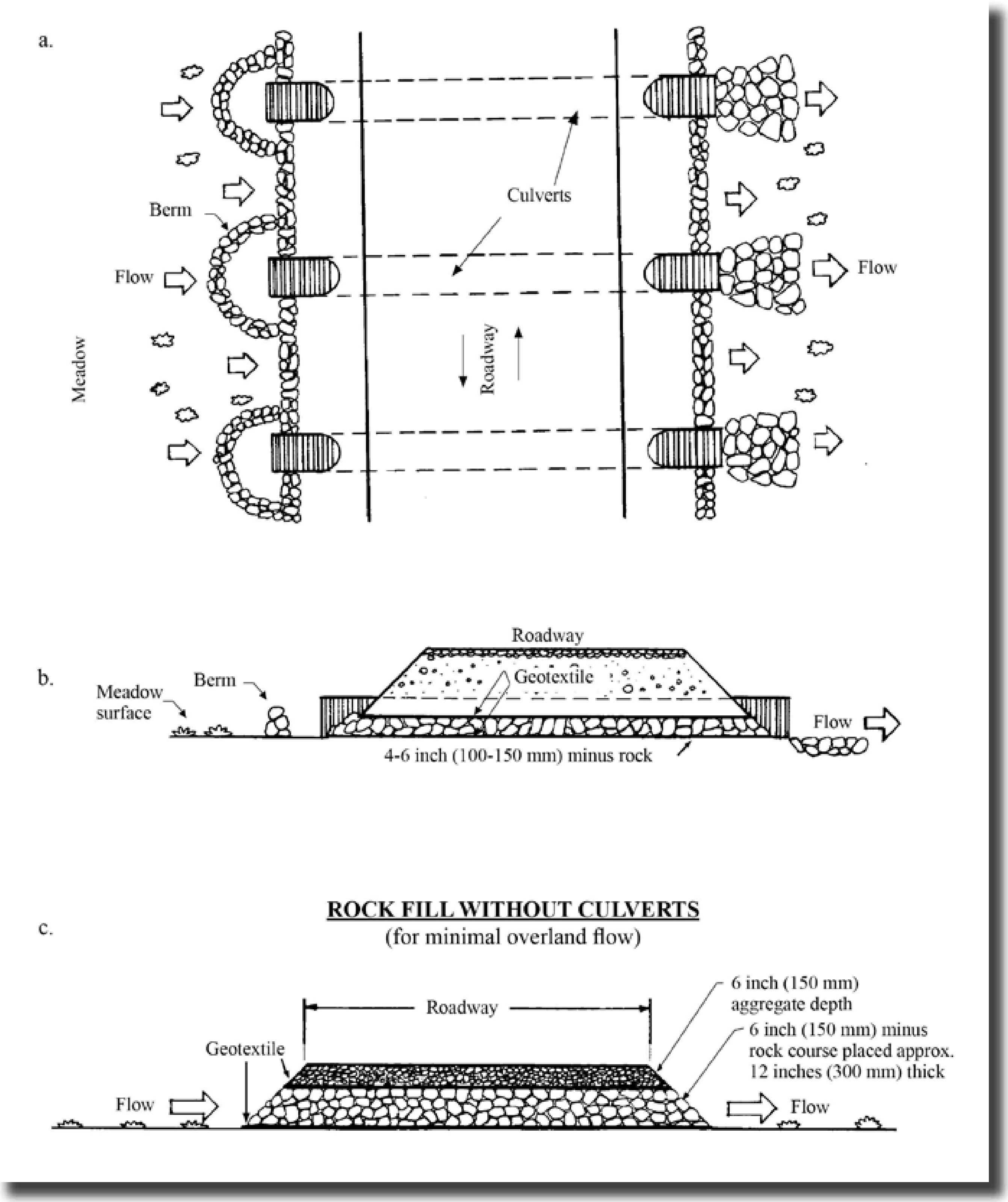


Figure 3-143—A wet meadow crossing design with multiple culverts and rockfill. (Adapted from Zeedyk 1996.)

Figure 3-144—Multiple pipes and rock fill a wet-meadow crossing.

For additional technical information about the meadow crossing techniques and meadow restoration, consult “Mangaging Roads for Wet Meadow Ecosystem Recovery” (Zeedyk 1996).

3.5.6. Temporary Wet Area Crossings Solutions

The best way to protect streams and wetlands is to avoid crossing them. If this is not feasible, then minimize and mitigate impacts while using the crossing. For any type of crossing, selecting a crossing option that is cost effective, that adequately addresses environmental concerns, and that satisfies the wide range of regulatory constraints is difficult but important. Temporary crossing structures may be the best alternative to minimize long-term damage to a site.

Temporary wetland crossing options include a variety of materials, such as rock or aggregate, wood chips, corduroy logs or poles, wood mats and panels, expanded metal grating, polyvinyl chloride (PVC) and high definition polyethylene (HDPE) pipe mats, tire mats, and low ground pressure equipment. Low ground pressure equipment includes machines with wide tires, duals, tire tracks, bogies, tracks, lightweight, and/or central tire inflation. Temporary bridges also can be used. Also, frozen ground may be a viable crossing option in many parts of the country with winter activities (Blinn et al. 1998).

Any materials placed in a wetland for temporary crossing should be placed on a geosynthetic so that all foreign materials can be removed when the crossing or road is no longer needed. With a layer of geosynthetic on the ground, any other material is kept separated from the soil. This facilitates easy removal of any fill material, with less damage to the site. However, if much weight is placed on the geotextile, reinforced strong, durable geosynthetic must be used.

For additional technical information about wetland crossings, consult "Temporary Stream and Wetland Crossing Options for Forest Management" (Blinn et al. 1998). The publication provides detailed information about a broad range of reusable temporary stream crossing and wetland crossing options. Link to the document <http://www.ncrs.fs.fed.us/epubs/gtr202/>.

Corduroy or Log Corduroy

Corduroy is a crossing made from coarse brush, small logs cut from low-value and noncommercial trees onsite, split logs, or mill slabs that are usually laid perpendicular to the direction of travel, as shown in figure 3-145 and figure 3-146. Logs occasionally are placed parallel to the direction of travel, but this blocks any ground water flow. The effect of corduroy is to spread the load over the whole length of the log or slab, effectively increasing the load-bearing area. Flotation increases with increasing surface area (especially length) of the individual pieces of corduroy. Multiple layers of corduroy may be required in some crossings, where the top layer is placed perpendicular to the bottom layer. Brush corduroy provides less floatation than small logs or mill slabs. Logs begin to deteriorate after several years, so corduroy is clearly a temporary road crossing measure. Submerged logs may decay very slowly.

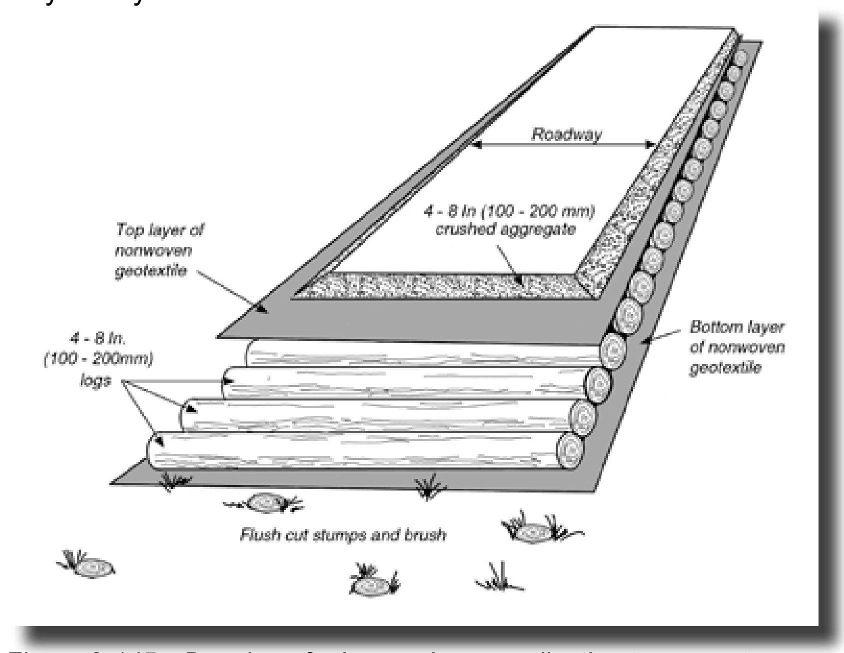


Figure 3-145—Drawing of a log corduroy application to support a temporary road across a wet area.

Figure 3-146—Log corduroy for temporary crossing of a wet area.

Wood Mats, Panels, and Pallets

Wood Mats

Wood mats are individual cants or logs cabled together to make a single-layer crossing. A 10-foot (3 m) long, 4-inch by 4-inch (100 by 100 mm) cant or log is the recommended minimum size. Longer cants or logs may be needed to distribute the weight better on very weak soils or under heavy loads. The smaller mats cost less and are lighter weight, which facilitates onsite installation.

To construct wood mats, drill holes through each cant or log and thread galvanized steel cables through these holes to form the mat. Connect individual mats to one another onsite to form the complete crossing. Limiting the mat length to about 10 feet (3 m) reduces weight and facilitates installation. Use shorter lengths if the mats are wider than about 12 feet (4 m). During installation, it is important to tuck the ends of all cable loops under the mats to avoid their being caught by a passing vehicle. If the surface of the crossing becomes slick during use, add expanded metal grating as a running surface to provide traction (Blinn et al.1998).

Wood Panels

Construct two-layer wood panels by nailing parallel wood planks to several perpendicular wood planks where the vehicles' tires pass. The actual running surface may be on either side of the panel, unless the nails have gone all the way through it. The individual panels can be preconstructed or constructed onsite.

Interconnecting adjacent panels in a crossing helps minimize the rocking that occurs when vehicles drive over the panels and improves the overall flotation provided by the crossing. However, using interconnecting panels increases the time required for installation and removal of the crossing. Adjacent panels can be interconnected using eye hooks screwed into the end of each panel with quick links or other heavy duty connectors through the hooks.

Wood Pallets

Wood pallets for crossings are sturdy, three-layered pallets similar to those used for shipping and storage but designed specifically to support traffic. They are a commercially available product generally made from dense hardwood planks that are nailed together. They are designed to interconnect and be reversible; broken planks can be replaced easily, and nail points do not surface. Some pallets are designed so that the top and bottom pieces are already interconnected similar to a traditional pallet, while others are designed so that the top and bottom pieces are separate and interlock during installation to prevent longitudinal movement.

Hislop and Moll (1996) indicate that the width of some commercial wood pallets is a disadvantage.

Interconnection along the 8-foot (2.4 m) edge is too narrow for haul roads. It may be necessary to cut commercial pallets in half to make two 4-foot (1.2 m) wide by 14-foot (4.3 m) long pallets. Pallets can be custom made so that the interconnection is along the 12-foot (3.7 m) or 14-foot-(4.3 m) wide edge (Blinn et al. 1998). Figure 3-147 shows wooden pallets for a temporary road.

Most commercial pallets are designed to be moved with a forklift, which is not a common piece of equipment in the woods. So, run a thin choker cable between the planks and hook them to lifting chains. This helps when using a front-end loader or backhoe (Hislop and Moll, 1996). Before installation, the ground surface should be fairly level to reduce breakage.

Figure 3-147—Wood pallets used for a temporary road.

PVC and HDPE Pipe Mats

A portable, reusable, lightweight corduroy-type crossing can be created with PVC or HDPE pipe mats (figure 3-148). An important advantage of using pipe is it provides a conduit for water to move through the crossing without further wetting or damming the area. A pipe mat is constructed using 4-inch (100 mm) diameter Schedule 40 pipe. Pipes are tightly connected using galvanized steel cables to form panels.

Because standard PVC pipe is light sensitive and loses strength when exposed to sunlight for extended periods, avoid using PVC pipe that has been exposed to the sun. Maintain the strength of the crossing by covering or painting the PVC pipe or use an ultraviolet-resistant pipe, such as HDPE (Blinn et al. 1998).

Figure 3-148—HDPE pipe bundles.

Tire Mats

Create a mat or panel of tires by interconnecting tire sidewalls and/or treads with corrosion-resistant fasteners or rebar (figure 3-149). Develop mats of varying lengths and widths. The amount of weight that can be handled by onsite equipment during installation and removal is important when deciding on mat length and width. Designs include a double layer of sidewalls or a layer of treads topped by sidewalls. The mats conform to the areas after placement.

Anchoring may be needed to prevent lateral movement during use, especially in areas with a grade over about 5 percent. The mats can be dragged into place with a skidder or installed using a loader. Tire mats can be placed on top of geotextile or corduroy to provide additional flotation. No running surface is needed over the mat, although gravel can be added to improve traction (Blinn et al. 1998).

Figure 3-149—Tire mats.

4.1. USE OF GEOSYNTHETICS

The use of geosynthetics for engineering applications is not a new concept; people have been trying to reinforce soils for centuries. The first attempts were done to stabilize boggy soils using tree trunks, bamboo, stones, straw, and small bushes. This type of soil stabilization was followed by the development of more systematic techniques. The use of logs or tree limbs to form a corduroy to stabilize roads can be found before Christ.

Geosynthetic materials include geotextiles (construction fabrics), geonets, geogrids, geocells, geofoam, and geocomposites, such as sheet drains. Geosynthetics also include plastic pipe, plastic fencing, and impermeable membranes and liners. Most of these materials become a permanent part of the road, so they must be covered with soil or rock to prevent damage by ultraviolet light. Geosynthetic erosion control materials also have important uses for slope and bank protection.

Geosynthetics are materials (usually made from synthetic polymers-plastics) used with soil or rock during construction. Their use in road construction has grown significantly in the last 40 years, and in the last 15 years for trail construction. In road applications, geosynthetics have four basic functions:

- ❑ Reinforcement.
- ❑ Separation.
- ❑ Drainage.
- ❑ Filtration.

The concept of reinforcing soils with low load-carrying capacity is constantly evolving. The first textiles were used in road construction in the United States in 1926. Woven geotextiles were used during the 1960s to control erosion. Woven and nonwoven geotextiles began being used in retaining walls and reinforced soil applications in the 1970s. Prefabricated underdrains wrapped in filter cloth were first used in the 1970s.

Today a variety of geosynthetic materials can be used in many engineering projects, such as roads, railroads, dams, retaining walls, tunnels, landfills, recreation areas, etc. They accomplish tasks such as subsurface drainage, soil reinforcement, repaving, erosion control, or subgrade stabilization (figure 4-1). Geosynthetics extend the service life of roads, increase their load-carrying capacity, keep drainage measures functioning, trap erosion, and reduce the incidence of ruts. Any one project

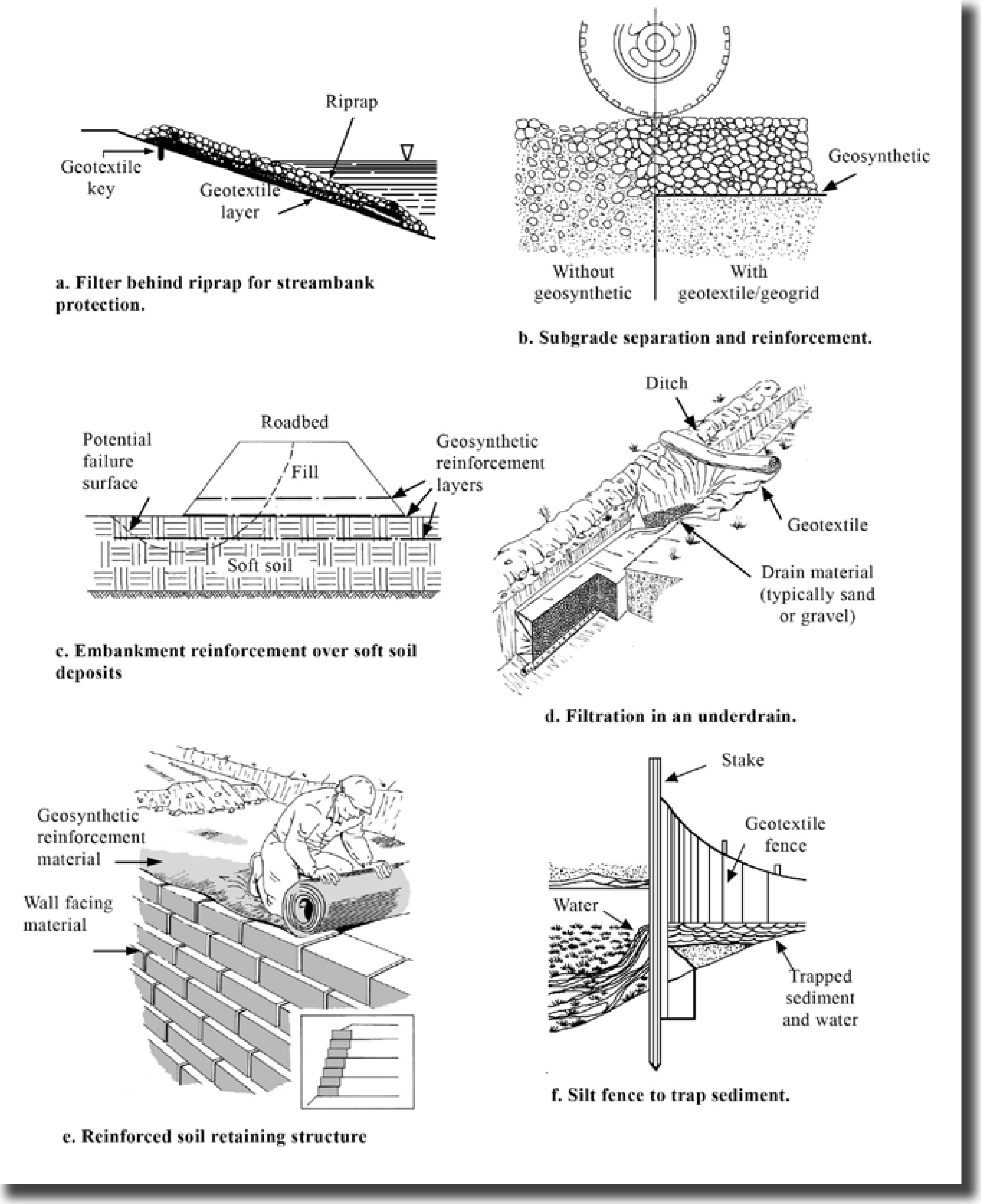


Figure 4-1—Use of geosynthetics in road applications (adapted with permission from AMOCO Fibers Corporation).

may use more than one type of geosynthetic material, such as geotextiles for underdrain filters and a geogrid for subgrade reinforcement. Also many geosynthetics serve multiple functions. A geotextile around an underdrain functions for **drainage** and as a **filter**, allowing water in but keeping the soil in place. Geosynthetics placed over soft soils function for soil **reinforcement** as well as **separation**, keeping fine soil from pumping up into the aggregate.

A number of organizations and conferences, as well as considerable research, have helped to accelerate the use of geosynthetics in engineering. The Industrial Fabrics Association International and its trade magazine Geosynthetics have information on the manufacture, use, design, and testing of these materials as well as case histories of applications. Link to the Web site <http://www.ifai.com>.

The basic functions of geosynthetics are outlined below.

Reinforcement

The geosynthetic acts as a reinforcing element in a soil mass or in combination with the soil to produce a composite structure that has improved strength and deformation properties. For example, geotextiles and geogrids are used to add tensile strength and confinement to a soil mass as reinforcing layers in a geotextile reinforced soil wall or a reinforced soil slope (figure 4-2).

Figure 4-2—Geogrid reinforcement in a timber-faced retaining wall.

Separation

The geosynthetic acts to separate two layers of soil that have different particle size distributions. For example, geotextiles are used to prevent road base materials from penetrating into soft underlying subgrade soils, maintaining design thickness and roadway integrity. Separators also help to prevent fine-grained subgrade soils from being pumped into permeable granular road base material (figure 4-3).

Figure 4-3—Geotextile used to separate aggregate from a weak subgrade.

Drainage

The geosynthetic acts as a drain to carry fluid flows through less permeable soils or into and out of an underdrain. For example, geotextiles are used to dissipate pore water pressure at the base of roadway embankments, or in a geocomposite drain to move water in an underdrain (figure 4-4).

Figure 4-4—A geotextile wrapped underdrain for subsurface drainage.

Filtration

The geosynthetic acts like a filter by allowing water to move through the soil while retaining the soil particles. For example, geotextiles are used to prevent soils from migrating into drainage aggregate or pipes while maintaining flow through the system. Geotextiles are also used behind riprap and other armor materials in coastal and riverbank protection systems to filter and prevent soil movement (figure 4-5).

Figure 4-5—A geotextile used as a filter layer behind riprap.

Containment

The geosynthetic acts as a relatively impermeable barrier to fluids or gases. For example, high density polyethylene geomembranes, thin film geotextile composites, geosynthetic clay liners, and field-coated geotextiles are used as fluid barriers to impede the flow of liquids or gases in landfills or as pond liners.

Confinement

Geosynthetics act as a confining member when used as layers in reinforced soil applications. Confinement of aggregate with a geogrid adds to the stability of a roadway structural section for reinforcement. Also geocells are used with sand and gravel and keep it confined, adding to its strength (figure 4-6).

Figure 4-6—Geocells used to confine gravel over a soft road subgrade.

Erosion Control

The geosynthetic acts to reduce soil erosion caused by rainfall impact and surface water runoff. For example, temporary geosynthetic blankets and permanent lightweight geosynthetic mats are placed over the otherwise exposed soil surface on slopes. Geotextile silt fences are used to remove suspended particles from sediment-laden runoff (figure 4-7). Some erosion control mats are manufactured using biodegradable wood fibers wrapped in light geosynthetic netting.

Figure 4-7—Geosynthetic silt fencing used to trap sediments and control erosion.

Other Functions

Today geosynthetics are used in various other road functions such as plastic tubing and fencing. Advanced drainage system pipe is used because of its lightweight and easy to install. Fences are used in a variety of barricade applications (figure 4-8).

Figure 4-8—Geosynthetic fencing used for temporary protection of a sensitive site during construction.

For additional technical information about the use and design with geosynthetics, consult the comprehensive FHWA document "Geosynthetic Design and Construction Guidelines—Reference Manual" (Holtz et al. 2008).

The AASHTO (American Association of State Highway and Transportation Officials) Standard Specification M-288 (2006) is a useful reference when working with geosynthetics. It summarizes the design property requirements necessary for each geosynthetic use by specific function, as well as having some installation guidelines.

A comprehensive commercially available and widely referenced textbook on uses and design with geosynthetics is Koerner (2006).

For additional technical information about the use of geosynthetics in trail applications, consult Groenier et al. (2008). The report describes several types of geosynthetics; explains basic geosynthetic design concept for trail construction in wet areas; and provides information about geosynthetic products.

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