Technical Supplement 14K

Streambank Armor Protection with Stone Structures

Issued August 2007

Cover photo: Interlocking stone structures may be needed to provide a stable streambank.

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

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Contents

Tables

Figures

Technical Supplement 14K — Streambank Armor Protection with Stone Structures

Purpose

Structural measures for streambank protection, particularly rock riprap, have been used extensively in support of stream restoration designs. Stone continues to be an important component of many stream restoration and stabilization projects, where stone or rock provides the needed weight or erosion protection, as well as providing a needed foundation for other design elements. This technical supplement is intended to provide field staffs with an understanding of some of the basic principles, design considerations, and techniques used to treat streambank erosion with rock. Design considerations that are applicable to any structure involving the use of stone are addressed. The use of stone as part of soil bioengineering and to complement instream habitat is also addressed.

Introduction

Stone has long been used to provide immediate and permanent stream and river protection. It continues to be a major component in many of the newer and more ecologically friendly projects, as well. The use of stone in a stream restoration design is a function of the engineering and ecological requirements of the final design. While the term stone can also be used to refer to a unique size of material (between cobbles and boulders), it is used interchangeably in this technical supplement with the term rock. Herein, these terms refer to large, engineered, geologic material used as an integral part of the restoration design.

This technical supplement describes some of the typical applications of both integrated streambank stabilization systems and stand-alone riprap treatments. It is recognized that stone and rock are also used to create desired habitat elements, but this technical supplement focuses primarily on the design of stone treatments for streambank stabilization and protection. Basic principles, stone requirements, design considerations, and techniques used to treat streambank erosion with rock are all described. While much of the guidance described herein was developed for application of stone riprap revetments, it is also applicable for other designs involving rock.

Benefits of using stone

Structural measures are designed to withstand high streamflows and provide adequate protection as soon as installation is complete. Rock may be readily available to most sites, but where it is not, alternative structural measures are designed based on the local cost of available materials (concrete, steel, manufactured materials, wood). Established techniques exist for rock design and construction. Rock riprap measures have a great attraction as a material of choice for emergency programs where quick response and immediate effectiveness are critical.

Rock riprap is needed for many streambank stabilization designs, especially where requirements for slope stability are restrictive, such as in urban areas. It is one of the most effective protection measures at the toe of an eroding or unstable slope. The toe area generally is the most critical concern in any bank protection measure. The primary advantages of stone over vegetative approaches are the immediate effectiveness of the measure with little to no establishment period. The use of stone may offer protection against stream velocities that exceed performance criteria for vegetative measures.

Stone considerations

Not all rocks are created equal. A variety of important stone design characteristics and requirements exist that must be accounted for to successfully use rock in the stream.

Stone size

The stone used in a project, whether it is part of a combined structure or used as a traditional riprap revetment, must be large enough to resist the forces of the streamflow during the design storm. A stone-sizing technique appropriate for the intended use must also be selected. Many established and tested techniques are available for sizing stone. Most techniques use an estimate of the stream's energy that the rock will need to resist, so some hydraulic analysis is generally required. Guidance for stone sizing techniques is provided in NEH654 TS14C.

Stone shape

Some methods use different dimensions to characterize stone size. The critical dimension is the minimum sieve size through which the stone will pass. Some techniques assume that riprap is the shape of a sphere, cube, or even a football shape (prolate spheroid). To avoid the use of thin, platy rock, neither the breadth nor the thickness of individual stones is less than a third of its length. The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) riprap specifications allow riprap to be a spheroid three times as long as it is thick (L/B = 3). Note that the shape of most riprap can be represented as the average between a sphere and a cube. An equation for an equivalent diameter of riprap shaped between a cube and a sphere is:

$$D = \left[\frac{2 \times W}{\gamma_s \times \left(1 + \frac{\pi}{6}\right)} \right] \quad \text{(eq. TS14K–1)}$$

where:
W = weight of the stone, lb
γ_s = density of the stone, lb/ft^3
D = equivalent diameter, ft

This relationship may be helpful if a conversion between size and weight is necessary for angular riprap with this shape.

Riprap should be angular to subangular in shape. Field experience has shown that both angular (crushed limestone) and rounded rock (river stones) can be used for riprap protection with equal success, but shape differences do require design adjustments. Rounded rock does not interlock as well as angular rock. Generally, rounded rock must be 25 to 40 percent larger or more in diameter than angular rock to be stable at the same discharge.

Stone gradation

Stone gradation influences resistance to erosion. The gradation is often, but not always, considered by the technique used to determine the stone size. In general, specifications typically include two limiting gradation curves. The design becomes more conservative as the coarser upper gradation limit is used. A question that should be answered as part of the design is whether a standard gradation, which could be considerably bigger than a special gradation, would be cheaper to build. U.S. Army Corps of Engineers (USACE) EM 1110–2–1601 (USACE 1991b) contains standardized gradations for riprap placement in the dry, low-turbulence zones. One set of standard gradations are those used by the USACE. This method assumes the specific gravity of a stone, G_s = 2.65 and a stone shaped as a sphere. Another approach is to specify American Society for Testing and Materials International (ASTM) D6092 for standard gradation requirements.

For most applications, the stone should be reasonably well graded (sizes are well distributed) from the minimum size to the maximum size. Onsite rock material may be used for rock riprap when it has the desired size, gradation, and quality. A well-graded distribution will have a wider range of rock sizes to fill the void spaces in the rock matrix. The stone gradation influences the design and even the need for a filter layer or geotextile. Further information on the design, use, and application of geotextiles is provided later in this technical supplement, as well as in NEH654 TS14D.

There are exceptions to this well-graded requirement. For instance, a steep slope rock chute will have a higher stable discharge if the rock is poorly graded (all rock is the same size). However, once this poorly graded material starts to fail, it will fail more rapidly than a well-graded material.

Stone quality

Rock quality or durability is important for the long-term success of any streambank protection project that uses riprap. In most applications, the rock must last for the life of the project. The stone should be sound and dense, free from cracks, seams, and other defects that would tend to increase deterioration. Poor quality rock can break down or deteriorate into smaller pieces, thereby reducing the effective diameter. This breakdown can be due to physical, chemical, and mechanical factors. Physical factors include freeze-thaw cycles or, in some cases, capillary action. An example is shown in figure TS14K–1. A chemical reaction with the runoff water can also cause the stone to break down. Rough handling during delivery and placement can mechanically fracture rock into smaller pieces. Interbedded layers of weaker material can also cause accelerated rock break down.

Stone density

The unit weight of stone (γ_s) typically ranges from 150 to 175 pounds per cubic foot, and different quarries will usually provide material with different unit weights. Designs should be based on realistic unit weights for the project area. If $G_s = \gamma_s / \gamma_w = 2.65$, then $\gamma_s = 2.65 \times 62.4$ pounds per cubic foot (density of water) = 165.36 pounds per cubic foot (a normal design assumption for rock density). NRCS specifications for riprap allow a minimum $G_s = 2.50$. Note that specific gravity is also shown as ρ in some specifications.

A rule of thumb is that for a 5-percent decrease in the unit weight of riprap ($G_s = 2.65 \rightarrow 2.50$), the design diameter would need to be about 10 percent larger than that originally designed, to resist the same forces.

Stone inspection

Rock used for riprap should come from approved sources. Sufficient testing should be performed to ensure that durability requirements are met for the expected service conditions and for the life of the project. In lieu of adequate test records on rock quality, a record of successful performance of the identical material for at least 5 years, and with similar site conditions, may be used as documentation of appropriate quality for some applications. Specific rock quality requirements are provided in NRCS Material Specification #23.

Mechanisms should be in place to ensure that a characteristic size or weight used in the design is actually delivered and placed at the project. When the project is constructed, the stone must be checked to ensure that the delivered stone size and material properties meet design requirements. Visual examinations can be misleading, so physical sampling should be conducted if the project involves a significant investment or is of high risk. A rock sample should be large enough to ensure a representative gradation and to provide test results to the desired level of accuracy (ASTM D5519).

Figure TS14K–1 Capillary breakdown of stone

Design considerations

Stabilizing channel banks is a complex problem and does not always lend itself to precise design. The success of a given installation depends on the judgment, experience, and skill of the planners, designers, technicians, and installers. Several important issues that must be considered for the successful design of projects that depend on the rock performance are briefly described.

Filter layer

Where stone is placed against a bank that is composed of fine-grained or loose alluvium, a filter layer or bedding is often used. This filter layer prevents the smaller grained particles from being lost through the interstitial spaces of the riprap material, while allowing seepage from the banks to pass. This filter layer needs to be appropriately designed to protect the in-place bank material and remain beneath the designed stone or riprap. Therefore, the gradation is based in part of the gradation of the riprap layer and the bank material. The filter layer typically consists of a geosynthetic layer or an 8-inch-thick layer of sand, gravel, or quarry spalls. For design of appropriate filters under rock riprap, refer to NEH633.26.

Banks with fine-grained silts or sands may require a geotextile to provide separation and filtration under riprap. Geosynthetics are covered in more detail in NEH654 TS14D, as well as in Design Note #1 and Material Specification 595 for the design and material considerations for geotextiles. A useful reference for geotextile design considerations is the American Association of State Highway and Transportation Officials (AASHTO) M28.

Some soil bioengineering techniques do not function well under geotextiles, and placing holes through the geotextile for plantings may provide a seepage path that would weaken the structure. This may require a trade-off analysis to balance the advantages of incorporating soil bioengineering against the advantages of an intact geotextile filter. Finally, there will also be cases where the banks may have sufficient gravel or cobbles, so that neither bedding nor geotextiles are needed.

Bank slope

Many stone sizing techniques also require information about the bank slope. In addition, a geotechnical embankment analysis may impose a limit on the bank slope. The recommended maximum slope for most riprap placement is 2H:1V. Short sections of slopes at 1.5H:1V are sometimes unavoidable, but are not desirable. Most rock cannot be stacked on a bank steeper than 1.5H:1V and remain there permanently. For riprap placement of 1.5H:1V and steeper, grouting of the rock to keep it in place must be strongly considered. Alternative measures, such as gabion baskets, are well suited to steep banks. Also, flatter slopes increase the opportunity for vegetation establishment.

Height

Stone should extend up the bank to a point where the existing vegetation or other proposed treatment can resist the forces of the water during the design event. In a soil bioengineering project, a stone revetment typically does not exceed the elevation of the level of the channel-forming flow event. However, there are exceptions where it is advisable to extend the riprap to the top of the bank.

Thickness

Different stone-sizing techniques may have different assumptions concerning the blanket thickness. The thickness of the placed rock should equal or exceed the diameter of the largest rock size in the gradation. In practice, this thickness will be one and a half to three times the median rock diameter (D_{50}). A typical minimum thickness is the greater of 0.75 times the D_{100} or one and a half times the D_{50}. The ability to use vegetative methods within a riprap revetment is diminished by additional riprap depth. While posts have been installed in revetments up to 4 feet thick, live cuttings or joint planting within a riprap thickness larger than 24 inches has had limited success.

Length

The revetment should significantly overlap the eroding area. The starting point needs to be well protected, properly keyed into the bank, and located sufficiently upstream of the major point of streamflow attack. Starting the treatment upstream helps prevent the streamflow from getting behind the structure and progressively eroding and undermining the protection. Likewise, if the bank protection does not extend sufficiently past the critical area of attack to a point where the streamflow is safely guided back into the primary channel, severe erosion can occur and start progressive failure in an upstream direction.

Where it is not possible to begin and end a structural revetment at a stable area, it is recommended that a stone revetment be extended a minimum distance of one channel width upstream and one and a half channel widths downstream of the eroded area. However, this limited treatment area has a higher risk of failure.

Tiebacks

Tiebacks or key-ins are used to reduce the likelihood of high flows concentrating behind stone slope protection. Tiebacks are used on both the upstream and downstream ends of a stone revetment. A typical rule of thumb for the depth to key into the bank is the bank height plus the anticipated scour depth. On long stone revetments, intermediate tiebacks are often used to ensure the reach integrity. Also, it is suggested that key-ins not be positioned at 90 degrees to the flow, but rather at an angle (30 to 45 degrees to the direction of flow) into the bank. Keying at an angle reduces sudden transitions of flow at the beginning and end of the revetment, and if the stream migrates, the key-in will act as a deflector.

Scour

Toe scour is the most frequent cause of failure in streambank armor protection projects. Scour can be long term, general, and local. More information on scour is provided in NEH654 TS14B.

The greatest scour depths generally occur on the outside and lower portion of curves. Scour depths may increase immediately below and adjacent to structural protection due to the higher velocity section of a stream adjacent to the relatively smooth structure surface. This may undermine the structure and result in failure.

Common methods for providing toe protection are:

- placing the stone to the maximum expected scour depth

- placing sufficient stone along the toe of the revetment to launch or fall in, and fill any expected scour
- providing a sheet-pile toe to a depth below the anticipated depth of scour or to a hard point
- paving the bed

The most commonly employed method is to extend (or key-in) the bank protection measures down to a point below the probable maximum depth of the anticipated bed scour. Where the project involves a significant investment for the protection of valuable property, potential scour can be calculated using the procedures described in NEH654 TS14B. Where there is less of an investment, approximations can be employed. A typical rule of thumb for a minimum key-in depth is one and a half times the riprap thickness or a minimum of 2 feet below the existing streambed. This practical solution generally gives good protection against undermining. Designers can review reliable data on local scour in the area, regional data, or use local experience in determining this minimum depth.

Ice and debris

River ice can have a major impact on riprap protection. Ice and debris increase the stresses on riprap by impact and flow concentration. Ice attached to stone may also dislodge stone and decrease blanket stability. Ice rafting, lifting or plucking, raft impact damage, ice raft push, and velocity increase below ice jams can all cause problems. Detailed discussions of these issues are available (Vaughan, Albert, and Carlson 2002; USACE EM 1110–2–1612, 1999).

A general rule of thumb for riprap subject to attack by large floating debris is that thickness should be increased by 6 to 12 inches, accompanied by an appropriate increase in stone size. Riprap damage from debris impacts is usually more extensive on banks with steep slopes. Therefore, streams with heavy debris loads should be not have armored slopes steeper than 1V:2.5 H (USACE EM 1110–2–1601, 1994f).

Vandalism

Many rock treatments are composed of a relatively thin layer of stone, and unauthorized removal of selected stones from the rock matrix can cause serious problems. Stone is often removed from projects for landscaping and other personal uses. Monitoring and maintenance activities should be in place to protect the project, minimize vandalism, and provide timely repair. Where vandalism is expected, it may be advisable to use larger stone than that required for stability to reduce the likelihood of removal by hand.

Placement of rock

Rock should be placed from the lowest to the highest elevation to allow gravitational forces to minimize void spaces and help lock the rock matrix together. It is important that riprap be placed at full-course thickness in one operation. Final finished grade of the slope should be achieved as the material is placed. Care should be taken not to segregate or group material sizes together during placement. Allowing the stone to be pushed or rolled downslope will cause stone size segregation. See ASTM D6825 on placement of riprap revetments.

An advantage of using riprap structures is that materials are generally readily available, and contractors with appropriate equipment and experience can be found. However, careful consideration should be given early in the design process to the stone installation method. Two commonly employed installation methods are described below.

Dumped rock riprap

This method of protection may be necessary where access to the streambed is limited or for emergency situations. Streambank work using dumped rock requires a source of low-cost rock. Access roads must be available near the stream channel, so that rock can be hauled to the streambank and either dumped over the bank or along the edge. If the job requires large quantities of rock, the operation must be set up to accommodate regular deliveries to the job site. In some cases, the banks may be too weak to support a loaded truck, thereby preventing dumping of rock directly over the streambank. In such cases, the rock may be dumped as close to the edge as possible and pushed over the edge with a bulldozer or front-end loader. Larger rock should be placed at the bottom of the revetment work to provide a stable toe section. The use of a front-end loader may be useful to select rock by size and push it over the bank.

This type of placement usually results in a poor gradation of material due to material segregation, requiring more volume to make up for the lack of gradation. While this type of bank protection requires more stone per square yard of bank protection than machine-placed riprap, it generally requires less labor and equipment operating hours.

Machine-placed riprap

This type of riprap is placed using a track-mounted backhoe or a power crane with a clam shell or orange peel bucket. The riprap is placed on a prepared slope of the streambank to a minimum design thickness of 12 to 18 inches. The larger stones are placed in a toe trench at the base of the slope. This method requires an experienced equipment operator to achieve uniform and proper placement. The toe or scour trench can be dug with the backhoe or clam shell as the machine moves along the slope. The machine can do the backfilling with rock in the same manner.

The bank sloping or grading generally is accomplished with a backhoe or sometimes a Gradall®. If a power crane is used, a dragline bucket must be used with the crane for slope grading. A perforated dragline bucket works best because it allows excess water to drain from the bucket.

Appropriate bedding and/or geotextile can be installed after the grading and slope preparation are completed. The primary function of these materials is for filtration—to prevent movement of soil base materials through the rock riprap. Bedding is normally placed by dump truck and spread to the desired thickness with a backhoe bucket, a front-end loader, or a small dozer. Geotextile must be placed by hand, secured in place as recommended by the manufacturer, consistent with site specifications. It is important that the geotextile be placed in intimate contact with the base to preclude voids beneath the geotextile. Under larger stone, a coarse bedding may be placed on the geotextile to assure that the geotextile stays in contact with the subbase. In some locations, geotextiles may also be used as a reinforcement in very soft foundation conditions. As previously noted, there will also be situations where the banks may have sufficient gravel content, so that neither bedding nor geotextiles are needed.

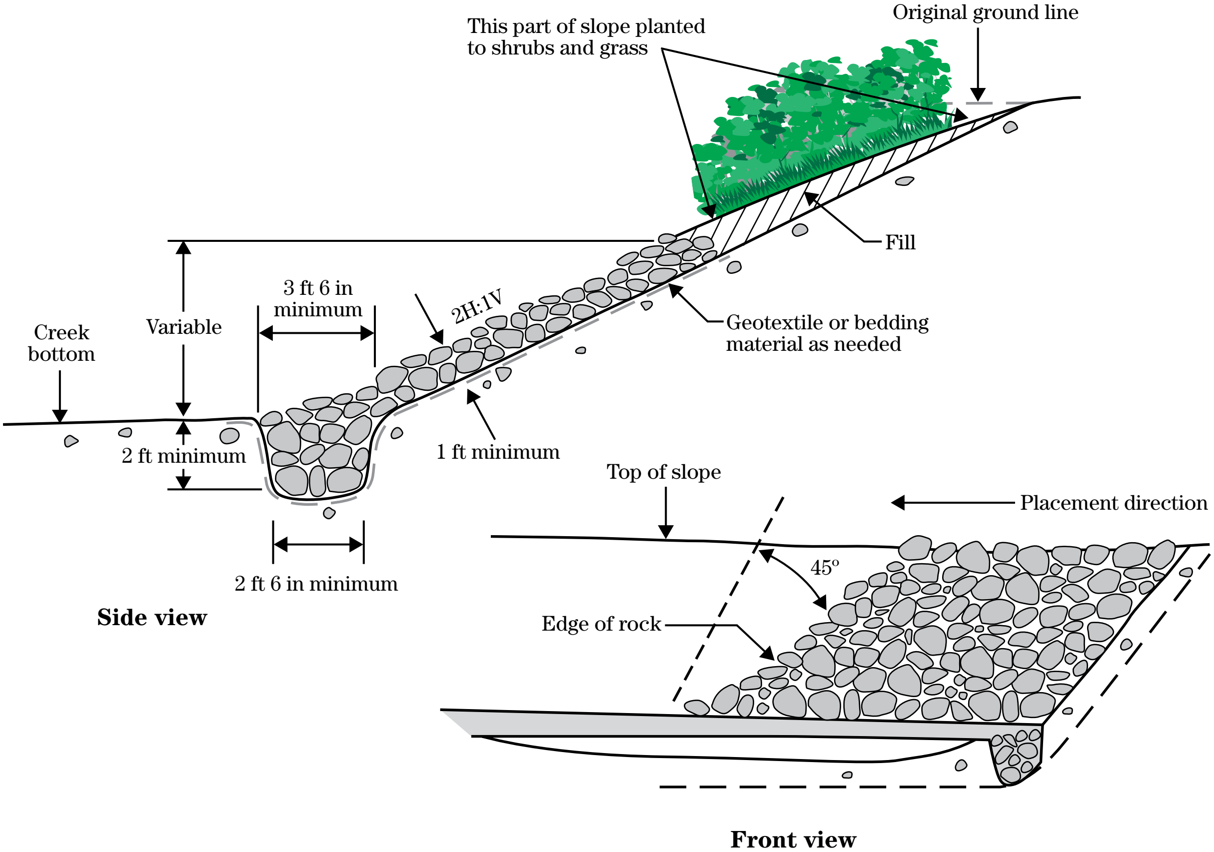
Riprap should be placed to provide a reasonably well-graded and dense mass of rock with a minimum of voids and with the final surface meeting the specified lines and grades. The larger stones should be placed in the toe trench or well distributed in the revetment. The finished stone protection should be consolidated by the backhoe bucket or other acceptable means so that the surface is free from holes, noticeable projections, and clusters or pockets of only small or only large stones.

Riprap placement should begin at the toe trench and progress up the slope maintaining the desired rock placement thickness as the work proceeds. After the toe trench has been filled to the original stream bottom level, the operator should build a wall or leading edge with the riprap, which is the full layer thickness. That thickness should be maintained throughout the placement of the riprap. The wall should be maintained at about a 45-degree angle from a transverse line down the slope, as the placement progresses from the initial starting point at the streambed and progresses up and across the slope (fig. TS14K–2).

Riprap rock should be handled and placed to the full layer thickness in one operation so that segregation is minimized and bedding or geotextile materials used under the riprap are not disturbed after the initial rock placement. Adding rock to the slope or removing it after the initial placement is not practical and generally produces unsatisfactory results. Dumping stone from the top and rolling it into place should also be avoided. This type of operation causes segregation and defeats the purpose of a rock gradation. Running on the riprap slope with track equipment, such as a bulldozer or rubber tire mounted front end loader, should also be avoided. It can damage the rock mass already in place. This operation can also tear the geotextile or damage the bedding by displacing material throughout the rock course. Tamping of the rock with the backhoe bucket can sometimes be used effectively to even up the surface appearance of riprap placement and further consolidate the rock course.

It is advisable to have a test section when riprap is being placed over geotextile to check for geotextile puncturing. After the riprap is placed, it is removed, and the geotextile is evaluated.

Figure TS14K–2 Typical riprap section



Treatment of high banks

The application of rock riprap protection on streambanks that are too high to be practically sloped can be accomplished using the following two methods:

- embankment bench
- excavated bench

Embankment bench method

The embankment bench method provides a reasonable approach to stabilize steep banks with little or no disturbance at the top of the slope and minimal disturbance to the streambed. The method also lends itself to an appropriate blend of structural, soil bioengineering, and vegetative stabilization treatments. This method, or some variation of it, is the most practical and preferred method of treating high, eroding streambanks.

The embankment bench method involves the placement of a gravel bench along the base of the eroding bank (fig. TS14K–3). The elevation of the bench should be set no lower than the height of the opposite bank and, where practicable, 1 to 2 feet higher. This gravel bench provides drainage and protection at the base of the bank and a stable fill to support the structural toe protection. It also provides a working space for the equipment to place the toe protection, which is most often rock riprap or a combination of riprap and soil bioengineering practice.

The embankment bench method requires that the convex side (low bank) of the channel be shaped by excavation of channel bed materials, normally bar removal, to compensate for the reduction in area taken by the bench projection. Offsite materials could be used for the bench in lieu of channel bed materials, but costs would be higher, and the resultant channel restriction could endanger the project. The high bank is generally left in its natural state and appropriately vegetated to assist stability. Some sloughing of the bank onto the prepared bench may occur before a good vegetative cover is established. Willows and other soil bioengineering materials can be established on the bench to help stabilize the toe of the bank and provide vegetative cover. By joint planting in the rock or by sediment accumulation and volunteer vegetation, the bench often can become a self-sustaining solution.

Excavated bench method

The excavated bench method (fig. TS14K–4) is used in situations similar to the embankment bench. The excavated bench method does not require the gravel fill material or enlarging of the channel to compensate for the encroachment of the bench area. Instead, it involves shaping the upper half or more of the high bank to allow the formation of a bench to stabilize the toe of the slope. This is accomplished in a manner which leaves the upper part of the excavated slope at least in no worse shape than it was before the excavation. This solution is rarely practical, but may be necessary in cases where stream access is restricted or not allowed. It may also be a solution on lower banks where the excavation quantity is relatively small.

Surface flow protection

The damage to high banks is often exacerbated by surface runoff. If this is not treated, any protection at the toe may be damaged. High banks subject to damage by surface water flow can be protected by using diversion ditches constructed above the top slope of the bank. Water from active seepage in the high banks should be collected by interceptor drainage and conveyed to a safe outlet. Trees or other vegetative materials in a buffer strip along the top of the bank can be used to help control the active seepage by plant uptake and transpiration. Some soil bioengineering designs can also include ancillary drainage as a function.

Treatment of bedrock controlled streams

Channels with exposed bedrock or ledgerock along the invert or streambank toe inverts require special methods to assure that the toe of the riprap can be anchored and will remain in place. The use of steel dowels and precast toe blocks are two methods that have been successfully implemented in such conditions.

Figure TS14K–3 Embankment bench method

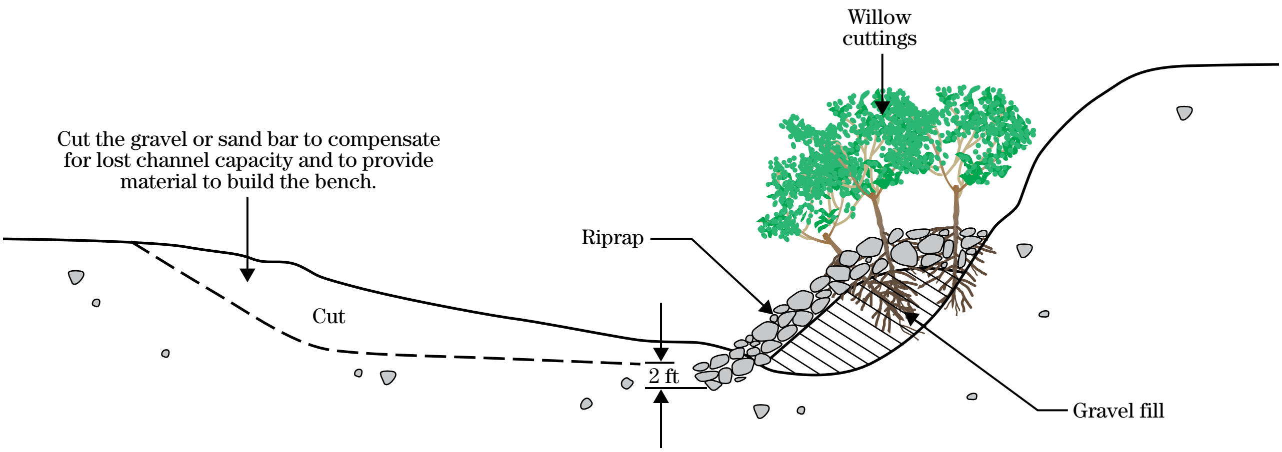
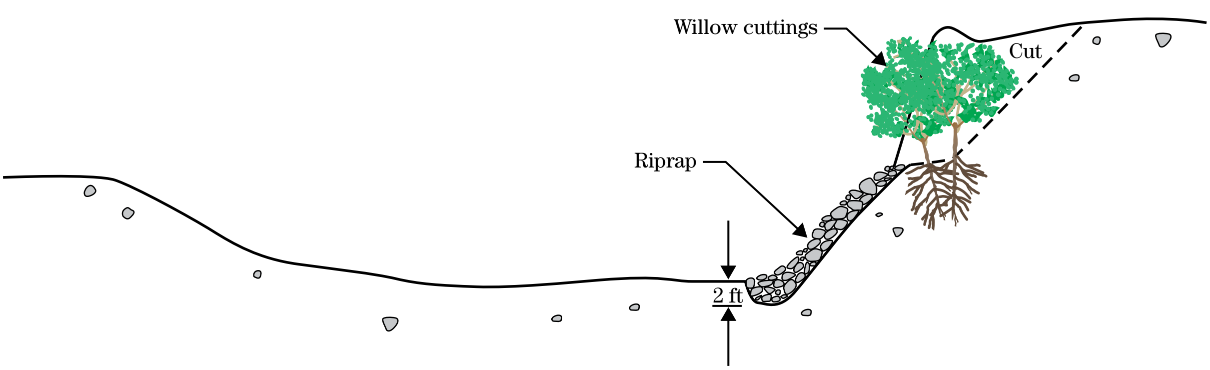


Figure TS14K–4 Excavated bench method



Steel dowel method

This method uses No. 8 or No. 6 steel reinforcing rods, depending on the size of the rock riprap. These rods are typically about 3 feet long and are grouted in place in holes that have been drilled into the bedrock (fig. TS14K–5). This method requires the larger rock be placed along the outer edge of the toe. The steel dowels are placed in position downslope against the large rocks that act as key stones in the toe to support the remainder of the rock riprap on the slope above. A modification of this approach is to drill holes into the toe rock and fit the stones over the steel dowels.

Precast toe blocks method

This method uses precast concrete blocks (fig. TS14K–6) to anchor the bottom row of riprap. The precast blocks should be 12 inches square and 5 feet long. Reinforcing rods extend 12 inches from each end of the blocks to form loops. These steel loops are placed so that they encircle steel bars which are drilled into the bedrock and grouted in place. The steel bars should be a minimum of 3 feet long and 1 inch in diameter (No. 8 bars). Where a 3-foot bar is used, a minimum of 2 feet should be grouted into the rock streambed. Because the blocks are of uniform length, bars are grouted in place on 6.5-foot centers. A template should be used when drilling holes to ensure proper spacing of the steel bars. The precast blocks are easily placed using a power crane. Wood planks should be used to protect the concrete blocks during the placement of the stone to avoid damaging the blocks by dropping stones on them. In channel sections where the bed is uneven, the steel loops may be bent so that they anchor to the steel bars properly.

Figure TS14K–5 Steel dowel method

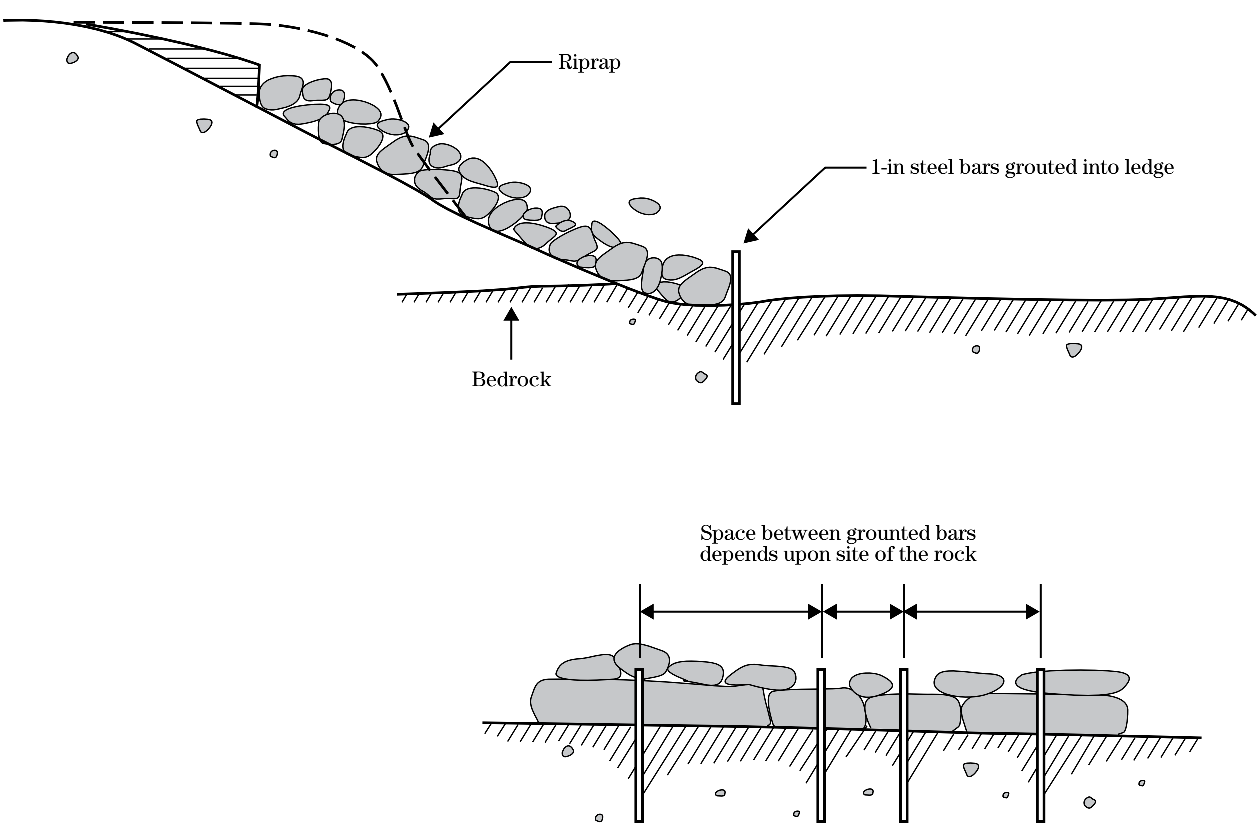
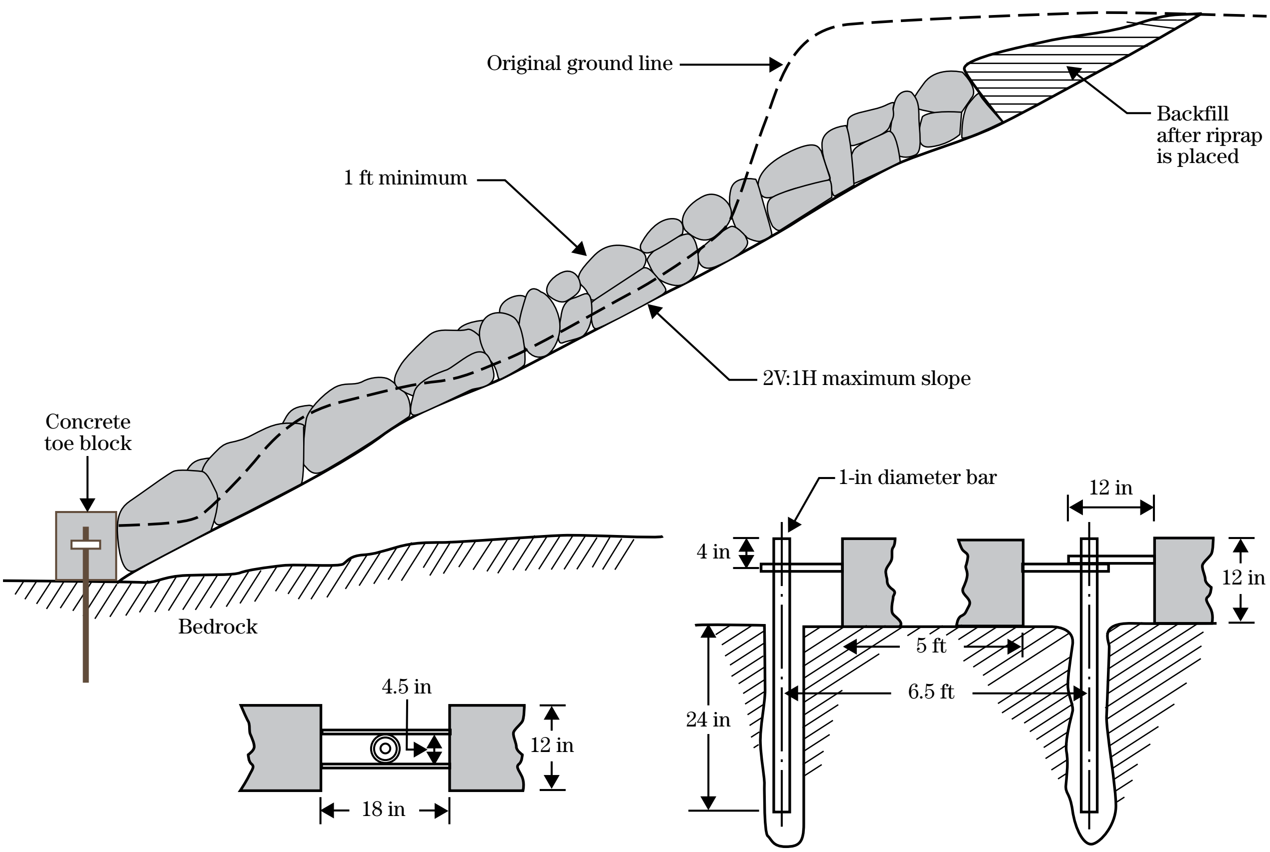


Figure TS14K–6 Precast toe block method



Plan view
Installation details of concrete toe blocks

Section
Installation details of concrete toe blocks

Other structural treatments

There are many structural streambank treatment techniques which involve the use of riprap. Several are briefly described, and others are described elsewhere in NEH654.14.

Stone with soil bioengineering

Combining rock with soil bioengineering treatments can achieve benefits from both techniques. Soil bioengineering is covered in more detail in NEH654 TS14J. The inert rock material often provides immediate toe protection, while the living plant materials protect, reinforce, and stabilize the banks.

Figure TS14K–7 shows a stone toe and live poles. The stone is keyed into the bed below an anticipated scour depth. Live poles can be installed with the aid of a waterjet stinger.

Figure TS14K–8 shows a brush layer being installed over a stone toe. Since the stone is not keyed into the bed, additional stone is placed in the toe. As the bed is scoured adjacent to the bank protection, this additional stone is available to fall into the scour hole.

Figure TS14K–9 shows a vertical bundle being installed under a stone toe. The bundles are placed in trenches which are then filled with soil. This minimizes potential damage to the live material during stone placement, as well as maximizes soil-to-stem contact.

Longitudinal peak stone toe

Longitudinal peak stone toe (LPST) involves the placement of a windrow of stone in a peak ridge along the toe of an eroding bank. The top of the stone is typically one-third to two-thirds of the bank height (Biedenharn, Elliott, and Watson 1997). LPST is particularly applicable where the upper bank is fairly stable, and the erosion is due to mass wasting from the toe of the bank. This technique protects the toe, while allowing the upper bank to stabilize on its own.

The main advantage of this technique is cost savings. An LPST is designed by specifying a weight or volume of rock to be placed along the length of the project reach, rather than finished elevations or dimensions.

Figure TS14K–7 Stone toe and live poles

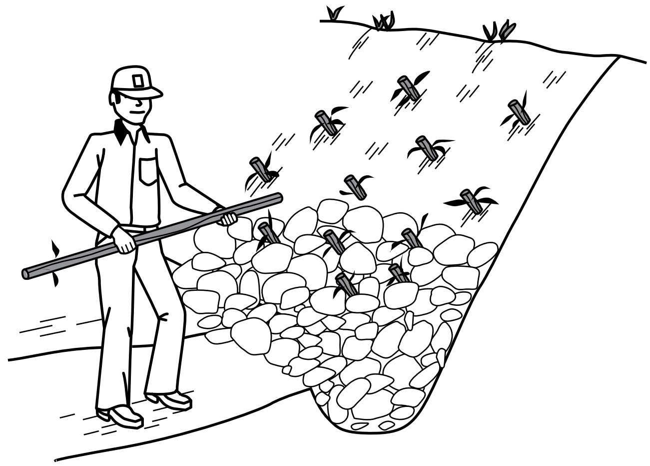


Figure TS14K–8 Brush layer over stone toe

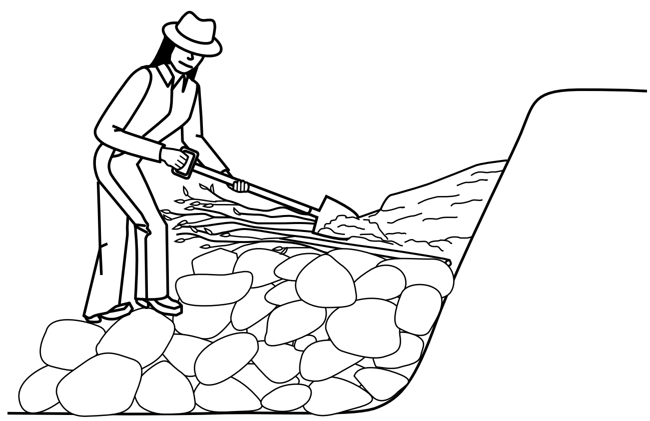
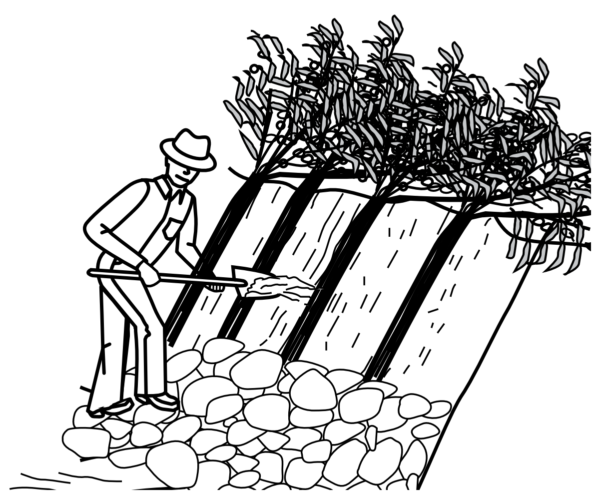


Figure TS14K–9 Vertical bundle and stone toe



On moderate-sized tributaries along the Mississippi River, typical applications can be 1 to 2 tons per linear foot, resulting in a triangular peak between 3 and 5 feet above the streambed (Biedenharn, Elliott, and Watson 1997). Usually, this simple technique is constructed by dumping stone from the bank. Since neither a filter layer nor geotextile fabric is used, a self-filtering, well-graded quarry run stone is specified. This technique depends on the rapid establishment of vegetation landward from the stone. Therefore, it is important to minimize disturbance of natural vegetation during installation, and it may be advisable to consider the addition of soil bioengineering practices.

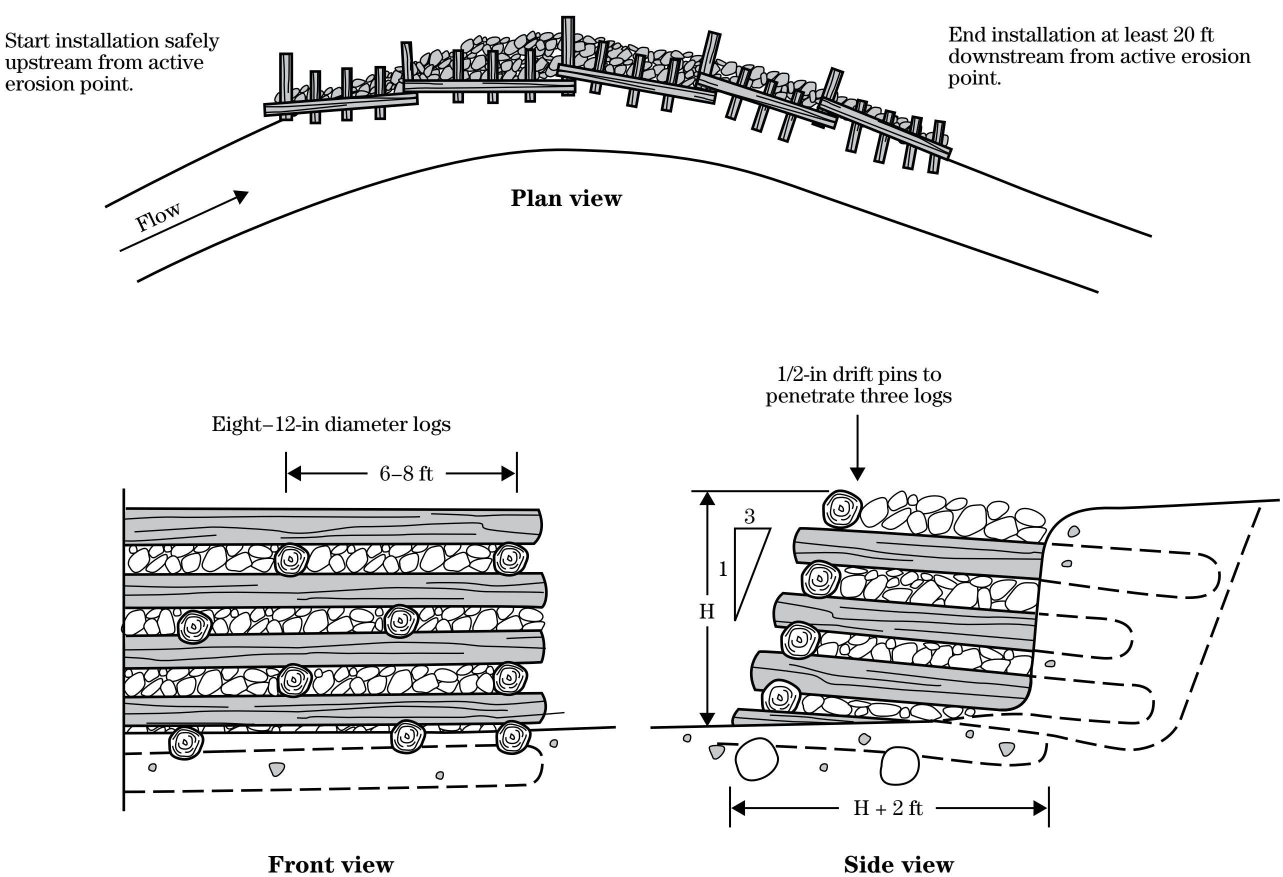
An LPST is often enhanced with the inclusion of woody debris and stone spurs along the length. These encourage deposition along the toe, create edge habitat, and move the higher velocity flow away from the bank.

Timber and rock cribbing

Timber cribbing backfilled with rock and coarse gravel is a traditional bank protection technique. This type of protection was popular many years ago when hand labor was more readily used in streambank protection. It has held up reasonably well, but becomes difficult to repair and maintain with age. Figure TS14K–10 illustrates a method of timber and rock cribbing.

The construction of a timber and rock crib requires considerable hand labor, and its useful life depends on the length of time the logs will hold the rock in place before rotting. As with gabions, the cribbing allows for the protection of unstable banks with stones that would be too small if used in a riprap revetment. While not exactly duplicating a riprap revetment, similar design characteristics are required for its design, such as scour, filtration, drainage, and length.

Figure TS14K–10 Timber and rock cribbing



Wire mesh gabions

Gabions offer important advantages for bank protection. They can provide vertical protection in high-energy environments where construction area is restricted. Gabions can also be a more affordable alternative, especially where rock of the needed size for riprap is unavailable. Gabion wire mesh baskets can be used to stabilize streambank toes and entire slopes. Gabions can also be compatible with many soil bioengineering practices. Gabions come in two basic types: woven wire mesh and welded wire mesh.

Woven wire mesh is a double-twisted, hexagonal mesh consisting of two wires twisted together in two 180-degree turns. Welded wire mesh has a uniform square or rectangular pattern and a resistance weld at each intersection. Within these two types there are two styles of gabions: gabion baskets and gabion mattresses. Baskets are 12 inches or more in height, while mattresses typically range from 5 to 12 inches in height.

Gabion baskets can be particularly effective for toe stabilization on problem slopes. They provide the size and weight to stay in place, with the further advantage of being tied together as a unit. Baskets can be installed in multiple rows to increase stability and provide a foundation for other measures above them. Gabion mattresses are best suited for revetment type installations, channel linings, and waterways. They may also be used for basket foundations and scour aprons.

Table TS14K–1 Specified rock sizes for gabions (from CS#64)

Gabion	Predominant rock size (in)	Minimum rock dimension (in)	Maximum rock dimension (in)
12-, 18-, or 36-in basket	4 to 8	4	9
6-, 9-, or 12-in mattress	3 to 6	3	7

All baskets and mattresses are of galvanized wire for corrosion protection. If the baskets are to be installed where abrasion from stream sediments is likely, PVC-coated material should be used. PVC coating adds significantly to the durability and longevity of the gabion installation. This coating provides long-term benefits for a relatively small increase in material costs.

It is important to use good quality rock of the proper size for gabion installation (table TS14K–1). Additional guidance on quality and sizing of rock can be found in ASTM 6711. Many manufacturers of gabions also provide guidance on the design and construction of their products.

Gabions can be delivered to the work site in a roll and in panels and can be partially or fully assembled. Assembly generally must be accomplished at the work site. Important in all aspects of assembly are the sizing, bracing, and stretching of the baskets or mattresses. Assembly and installation procedures are well covered in NRCS National Construction Specification (CS) #64 (USDA NRCS 2005). Details for assembly and placement of double-twisted, wire mesh gabions can also be found in ASTM D7014.

Important considerations in gabion placement are:

- The gabion is stretched and carefully filled with rock by machine or hand placement ensuring alignment, avoiding bulges, and providing a compact mass.
- Machine placement will require some hand work to ensure the desired results.
- The cells in any row shall be filled in stages so that the depth of stone placed in any cell does not exceed the depth of the stone in any adjoining cell by more than 12 inches.
- Along all exposed faces, the outer layer of stone shall be placed and arranged by hand to achieve a neat and uniform appearance (fig. TS14K–11).

The tops of gabions will also require some hand work to make them level and full prior to closing and fastening the basket lids. It is important that the gabion basket or mattress is full and the lids fit tightly. Appropriate tools need to be used in this operation and care taken not to damage the lids by heavy prying.

Various types of fasteners and lacing are used to assemble and secure gabion baskets and mattresses. The manufacturer's recommendations should be followed along with the applicable provisions in CS #64.

Vegetated gabion

In some locations, traditional gabions may be unacceptable from either an aesthetic or ecological perspective. A modification to traditional gabion protection that may satisfy these concerns is the vegetated gabion. A vegetated gabion incorporates topsoil into the void spaces of the gabion. The resulting gabion volume consists of 30 to 40 percent soil that allows root propagation between the stones. The resulting structure is interlocked with stone, wire, and roots (fig. TS14K–12).

Various commercial products, such as the Maccaferri Green Gabion™, provide improved shapes and an organic fiber matting to hold the soil in place while the plants become established. Figure TS14K–13 illustrates the assembly steps of such a gabion.

Grouted riprap

Grouted riprap is a riprap bed where the voids have been filled with concrete. It is often used where the required stone size cannot be obtained or at sites where a significant and damaging debris load is expected. Typical applications include grade protection, bank protection, spillways, inlets to debris basins, and as a repair to conventional riprap structures that have been damaged by high velocity flows. Culvert outfalls and ditch linings have also been constructed with grouted riprap. It has also been used to provide improved recreational access across riprap revetments.

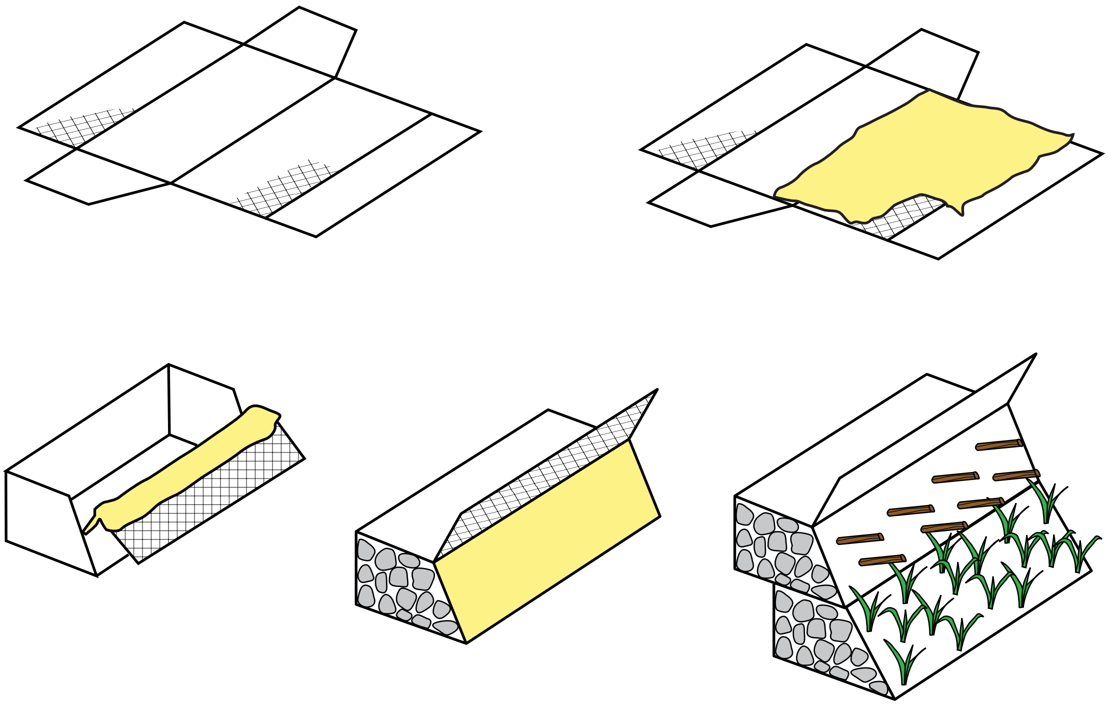
While the stone used for a grouted riprap installation can be smaller than what is required for a loose riprap installation, there is no available guidance that specifies a minimum size. Sizing is usually based on experience with similar projects in the area. The stone used should be as coarse as possible to allow for deep penetration of the grout. A general recommendation is that less than 5 percent of the stone should be less than 2 inches in diameter. Stone quality should be similar to that specified for conventional riprap structures.

The grout strength is typically 2,000 to 2,500 pounds per square inch. The grout must fully penetrate the stone to the subbase. Shoveling the grout over the stone may not fully penetrate the riprap. An immersion or pencil vibrator is often used to ensure that the voids between the stones are filled. The concrete mix should have a slump of 5 to 7 inches to allow for proper penetration. The maximum aggregate in the mix should be three-fourths inch. Typically, the grout is placed up to the top of the stones. However, in some applications,

Figure TS14K–11 Gabions showing a neat, compact, placement of stone with a uniform appearance

Figure TS14K–12 Vegetated gabions under construction

Figure TS14K–13 Assembly sequence of a Green Gabion™ (*Figure Courtesy of Maccaferri Gabions, Inc.*)



up to a third of the stone diameter is left exposed. This may be done for aesthetic reasons or to provide a more durable material to resist abrasion from sediment laden flows.

While the design of all rock structures must consider proper drainage to prevent hydrostatic pressure buildup, it is especially important for a grouted riprap design. Typically, relief holes composed of 3-inch-diameter pipes spaced at 10-foot intervals are set through the grouted structure and into the filtering system. Even well-designed grouted riprap structures will be subject to cracking, so the use of grouted riprap in areas that are subject to freeze-thaw action should be undertaken with caution. Further information on the design and construction of grouted riprap can be found in USACE ETL 1110–2–334 (USACE 1992).

The minimum thickness of the rock and grout is 12 inches. Thicker layers may be needed to prevent uplift of a structure during high flows. While guidance is limited concerning the required thickness, designers have balanced the uplift forces generated at maximum flow velocity against the weight of the cracked block size. In this analysis, the cracked units are assumed to have dimensions equal the thickness of the grouted riprap.

The ecological impacts of grouted riprap should be considered in the design. Since the voids in the riprap are filled, the structure will not provide refuge for small fish and macroinvertebrates. Plant growth through a grouted riprap structure is unlikely, and the thermal loading and lack of shade can contribute to increased stream water temperatures. Finally, grouted riprap is often viewed negatively from an aesthetics perspective, and this impact should be considered.

Habitat enhancement with stone

The designer should consider the habitat value when selecting stone gradations. For example, poorly graded, large stone may have limited habitat value for macroinvertebrates, since the openings are large. However, it may provide refuge for certain fish species.

Another application of habitat enhancement using stone is boulder clusters. These are sized using impinging flow design techniques. Boulder clusters or instream boulders provide structure and create hydraulic cover. Clusters are typically used in runs and glides in triangular-shaped groups of three to five boulders (EMSR–4–01, USACE 2005). The lee of the stones provides resting areas and inchannel refuge for fish during high-flow events. The turbulence generated by flows over and around the boulders diffuses sunlight and creates overhead cover. The tops of the boulders are typically just below the baseflow. They are generally not appropriate for use in sand-bed streams, since downstream scour may cause them to settle into the bed and disappear. Caution should also be exercised for use in braided streams. To avoid having the boulders cause excessive stress on the banks, they should not occupy greater than 10 percent of the channel area at bankfull flow or greater than a third of the width.

Conclusion

Many restoration designs require the use of rock in the stream. Riprap is one of the most effective protection measures at the toe of an eroding or unstable slope. Rock use has distinct advantages in terms of accepted design techniques and established contracting and construction procedures. In addition, many innovative bank stabilization and habitat enhancement projects use stone to perform important functions. Rock does present some drawbacks concerning cost, aesthetics, and ecological and geomorphic impacts. The challenge is to integrate more vegetative and geomorphic solutions without materially increasing the exposure time and risk of failure and meeting the goals of the project. This approach produces a long-term solution that will be complementary to the natural environment and will be more self-sustaining.