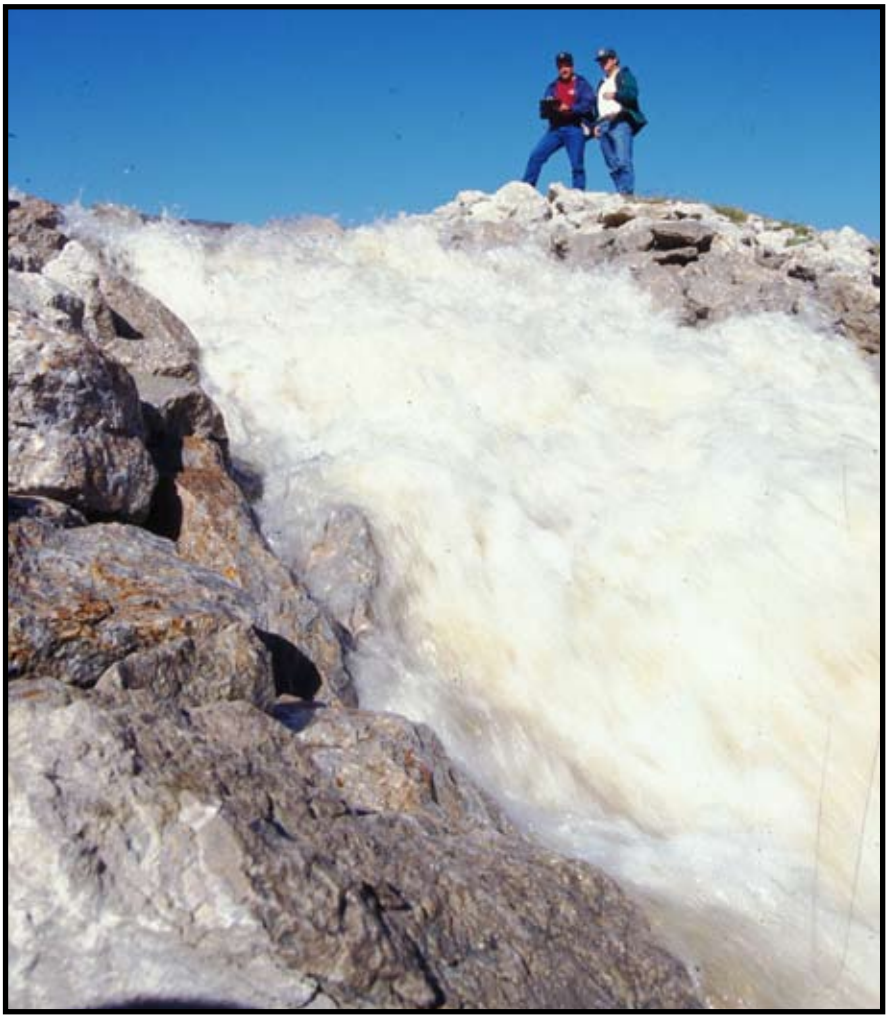
Technical Supplement 14G

Grade Stabilization Techniques



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Cover photo: Streamflow energy may need to be dissipated through the use of inchannel grade control structures.

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.

Technical Supplement 14G

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Grade Stabilization Techniques

Purpose

One of the most challenging problems facing river engineers today is the stabilization of degrading channels. Channel degradation leads to damage of both riparian infrastructure, as well as the environment. Bank protection is generally ineffective over the long term and will probably be a waste of resources if the channel continues to degrade. When systemwide channel degradation exists, a comprehensive treatment plan is usually required. A wide variety of structures has been employed to provide grade control in channel systems. The objectives of this technical supplement are to provide a description of some of the more common types of grade control structures that are frequently used throughout the United States and describe the various design factors that should be considered when selecting and siting grade control structures.

Introduction

Grade control is an essential component to stabilize a degrading stream or one that is subject to conditions that may cause degradation. Channel degradation leads to damage of bridges, culverts, petrochemical transmission lines, power lines, sewer and water lines, and other infrastructure. Channel degradation produces an overheightened and oversteepened condition of the channel banks that often leads to severe mass failures of both streambanks. The resulting channel widening and bank erosion cause severe land loss and damage to riparian infrastructure and habitat. As channel degradation continues, the ground water table may also be lowered along the stream, affecting riparian vegetation. Sediment eroded from the degrading channels is transported downstream, adversely impacting flood control channels, reservoir areas, and wetland habitat areas. This sediment also carries significant amounts of nutrients, particularly phosphorus, which may degrade water quality and habitat along the stream system. Consequently, channel degradation is not simply a local problem that only affects a few landowners, but rather, produces systemwide consequences that can impact all taxpayers.

When systemwide channel degradation exists, a comprehensive treatment plan is usually required. This treatment plan usually involves the use of one or more grade control structures to arrest the degradation process. In the widest sense, the term grade control can be applied to any alteration in the watershed that provides stability to the streambed. It can include stream realignments. The most common method of establishing grade control is the construction of inchannel grade control structures. A wide variety of grade control structures has been used in channel systems. These treatments range from simple loose rock structures to reinforced concrete weirs and vary in scale from small streams to large rivers. While some stream rehabilitation practitioners suggest that grade control cannot be constructed in incised channels, the authors have routinely participated in the design and long-term monitoring of successful grade control structures in severely incised channels.

The two primary engineering factors that promote channel stability are continuity of water and sediment through the stream reach and geotechnical bank stability. A series of well-designed grade control structures can adjust sediment transport capacity to sediment supply and can improve bank stability by reducing bank height and reducing shear at the bank toe. As with most water resources activities, there are positive and negative environmental impacts associated with grade control structures. The most serious negative environmental impact commonly associated with grade control structures is obstruction to fish passage. On the positive side, grade control structures can improve the channel stability, improve habitat, and reduce the supply of sediment and nutrients to the channel system. Fish passage issues, as well as other challenges, can be accommodated through appropriate engineering design and by close cooperation with biologists on the planning and design team. Fish passage is described further in NEH654 TS14N.

Grade control hydraulics

There are two basic types of grade control structures. A bed control structure is designed to provide a hard point in the streambed that is capable of resisting the erosive forces of the degradational zone. This is somewhat analogous to locally increasing the size of the bed material. The Lane relation (Lane 1955b) (fig. TS14G–1) illustrates the dynamic relationship, $QS^{+} \propto Q_s D_{50}+$, where the increased slope (S^{+}) of the degrada-

tional reach would be offset by an increase in the bed-material size (D_{50}^{+}) to become stable. Bed armoring controls bed degradation and scour and the increased hydraulic roughness of the bed control structure may dissipate a minor amount of hydraulic energy. A hydraulic control structure is designed to function by reducing the energy slope along the degradational zone to the degree that the stream is no longer competent to scour the bed ($QS^{-} \propto Q_s D_{50}$). The distinction between the operating processes of these two types is important whenever grade control structures are considered.

Energy diagrams (figs. TS14G–2, TS14G–3, and TS14G–4) illustrate the comparison of energy losses that may occur with bed control or hydraulic control grade control structures. Figure TS14G–2 is the preconstruction condition for gradually varied open-channel flow. In figure TS14G–3, a natural stone bed control structure is depicted in the bed between cross sections 2 and 3, reducing the energy gradient due to minor losses occurring with increased roughness. In figure TS14G–4, a hydraulic control structure is depicted in which critical depth for the discharge occurs near the structure crest. A hydraulic drop and a hydraulic jump occur between cross sections 2 and 3. The energy of the downstream reach is reduced by the energy dissipated in the jump, improving downstream stability. Upstream of the drop, the velocity head is reduced, and the pressure head is increased by the raised structure crest.

Because of the complex hydraulic behavior of the flow over grade control structures, it is difficult to designate a single function that applies without exception to each structure. For many situations, the function of a structure as a bed control structure or hydraulic control structure is readily apparent. However, the structure may actually have characteristics of both a bed control and a hydraulic control structure under some conditions. Hydraulic performance or function of the structure can vary with time and discharge. This can occur within a single hydrograph or over a period of years because of upstream or downstream channel changes.

Figure TS14G–1 Lane's balance for water discharge (Q), slope (S), bed-material load (Q_s), and median bed-material size (D_{50})

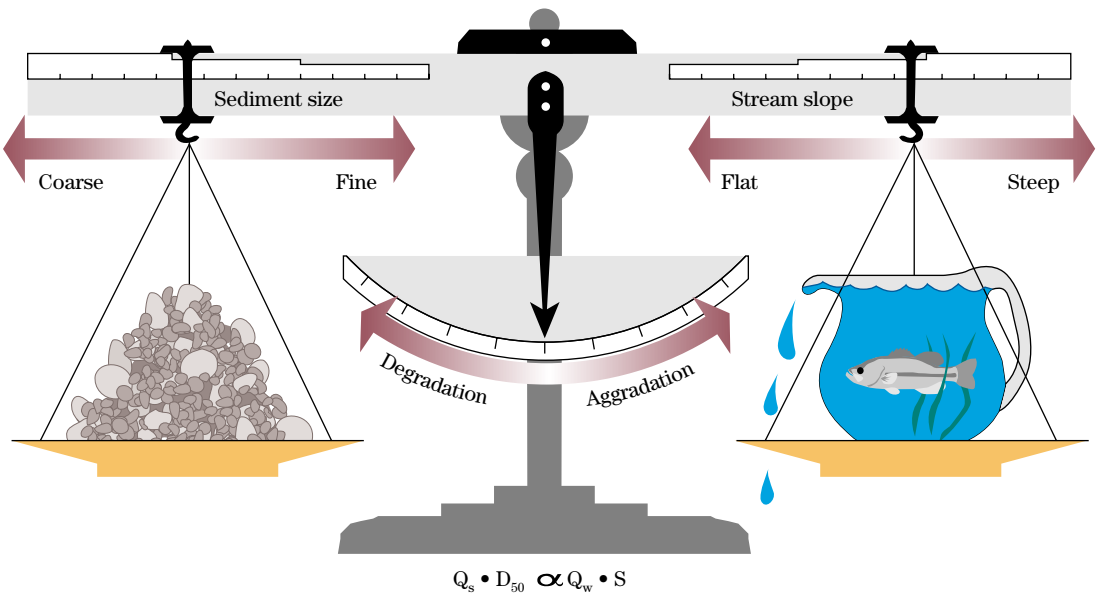


Figure TS14G–2 An energy diagram for the preconstruction condition

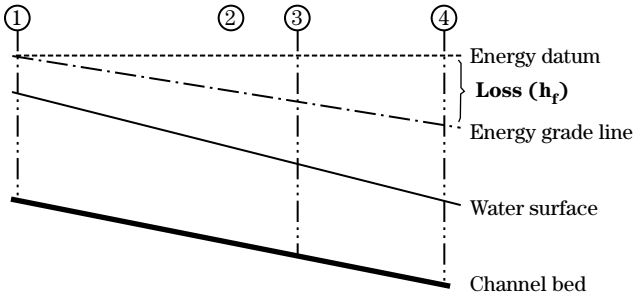


Figure TS14G–3 The modified energy diagram (shown in red) for a bed control structure

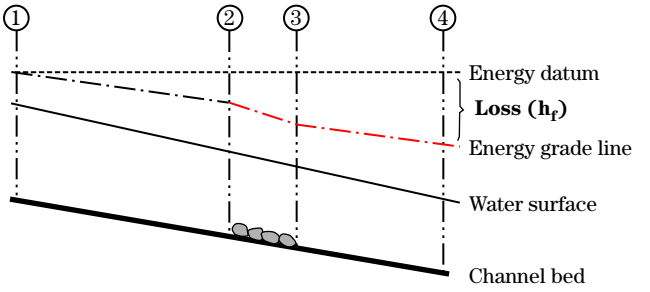
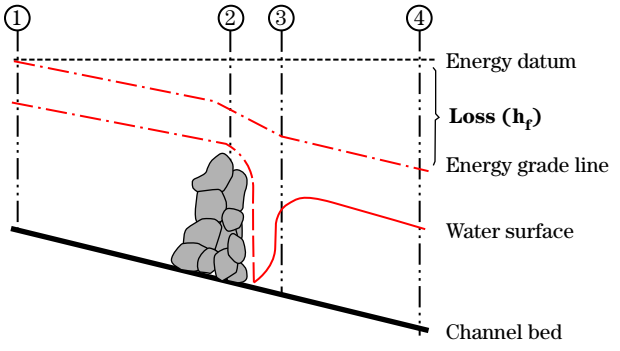


Figure TS14G–4 The modified energy diagram (shown in red) for a hydraulic control structure



Types of grade control structures

Selecting the type of grade control structure is an important general decision, as is the siting and spacing. Certain features are common to most grade control structures including a control section for accomplishing the grade change, an energy dissipation section, and protection of the upstream and downstream approaches. These protected areas often include stone key sections that tie into the banks to protect against flanking. Considerable variations exist in the design of these features. For example, a grade control structure may be constructed of riprap, concrete, sheet piling, treated lumber, logs, soil cement, gabions, compacted earthfill, or other locally available material.

Also, the shape (sloping, stepped, or vertical drop) and dimensions of the structure can vary significantly, as can the various appurtenances (baffle plates, end sills). The applicability of a particular type of structure to any given situation depends on a number of factors such as hydrologic conditions, sediment size and loading, channel morphology, flood plain and valley characteristics, availability of materials, and project objectives, as well as the inevitable time and funding constraints. The successful use of a particular type of structure in one situation does not necessarily ensure that it will be effective in another. Some of the more common types of grade control structures are described in the following sections. Table TS14G–1 provides a brief summary of the advantages and disadvantages of each of these structures. Neilson, Waller, and Kennedy (1991) provide an international literature review on grade control structures, along with an annotated bibliography.

Table TS14G–1 Advantage and disadvantages of selected grade control structures

Structure type	Advantages	Disadvantages
Loose rock structures	Economical to design and build Limited environmental impacts Ease of construction	Generally limited to less than about 3 ft drop heights Potential for displacement of rock due to seepage flows
Channel linings	Provides for energy dissipation through the structure Can be designed to accommodate fish passage	Significant design effort Relatively high cost Larger construction footprint due to length of structure
Loose rock structures with water cutoff	Provides positive water cutoff that eliminates seepage problems and potential for rock displacement Higher drop heights (up to about 6 ft)	More complex design required Higher construction cost than simple loose rock structures More potential for fish obstruction at higher drop heights
Structures with preformed scour holes and water cutoffs	Improved energy dissipation Scour holes provide stable reproductive habitat Higher drop heights (up to about 6 ft)	Larger construction footprint More complex design effort required Increased construction cost More potential for fish obstruction at higher drop height
Rigid drop structures	Can accommodate drop heights greater than 6 ft Provides for energy dissipation Single structure can influence long reach of stream	High construction cost Large construction footprint Significant potential for obstruction to fish Potential for downstream channel degradation due to trapping of sediment
Alternative construction materials	Economically feasible where stone is costly and local labor force is inexpensive and available	Often lack detailed design guidance Increased monitoring and maintenance often required

Loose rock structures

Perhaps the simplest form of a grade control structure consists of placing natural stone or other erosion resistant elements across the channel to form a hard point. Some manufactured concrete products may be used in place of stone. This type of structure includes rock sills, rock sills with impermeable cutoffs, artificial riffles, and sloping rock structures. Various types of loose rock structures are presented herein along with rock sizing procedures and some methods for local scour protection.

Types of loose rock structures

Loose rock structures are generally most effective for drop heights that are less than about 2 to 3 feet. In many applications, a series of loose rock structures are placed relatively close together, effectively providing a greater drop height than a single structure. The series of loose rock structures then provides a degree of conservatism in the design, as one element may reduce stress on the upstream element. Loss of one element may not mean loss of function for the total treatment. The structures must be spaced close enough that channel degradation above one does not undermine the upstream structure. A series of rock sills, each creating a head loss of about 2 feet, was used successfully on the Gering Drain in Nebraska (Stufft 1965). The design concept presented by Whittaker and Jäggi (1986) for stabilizing the streambed with a series of rock sills is shown in figure TS14G–5. These sills are bed control structures that are simply acting as hard points to resist streambed erosion.

Construction of bed sills is sometimes accomplished by placing the rock along the streambed to act as a hard point to resist the erosive forces within the degradational zone. In other situations, a trench may be excavated across the streambed and then filled with rock. A critical component in the design of these structures is ensuring that there is a sufficient volume of erosion resistant material to resist the general bed degradation, as well as any additional local scour at the structure. This is illustrated in figure TS14G–6, which shows a riprap grade control structure designed to resist both the general bed degradation of the approaching nickpoint, as well as any local scour that may be generated at the structure. In this instance, the riprap section must have sufficient mass (layer thickness) to launch into the anticipated scour hole.

A unique type of loose rock structure is used by Newbury and Gaboury (1993). These are often referred to as Newbury riffles. The structures are placed at 5 to 7 channel widths spacing to emulate the spacing of

Figure TS14G–5 Channel stabilization with rock sills

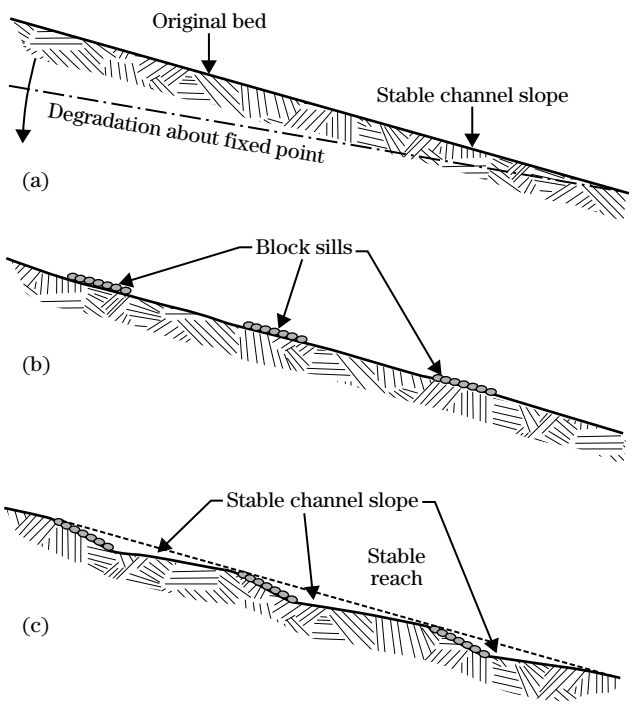
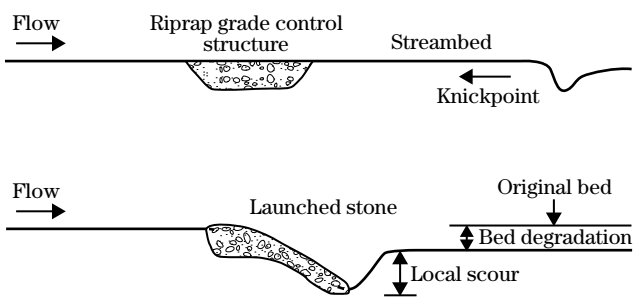


Figure TS14G–6 Top—riprap grade control structure; Bottom—subsequent launching of riprap at the grade control structure in response to advancing bed degradation and local scour

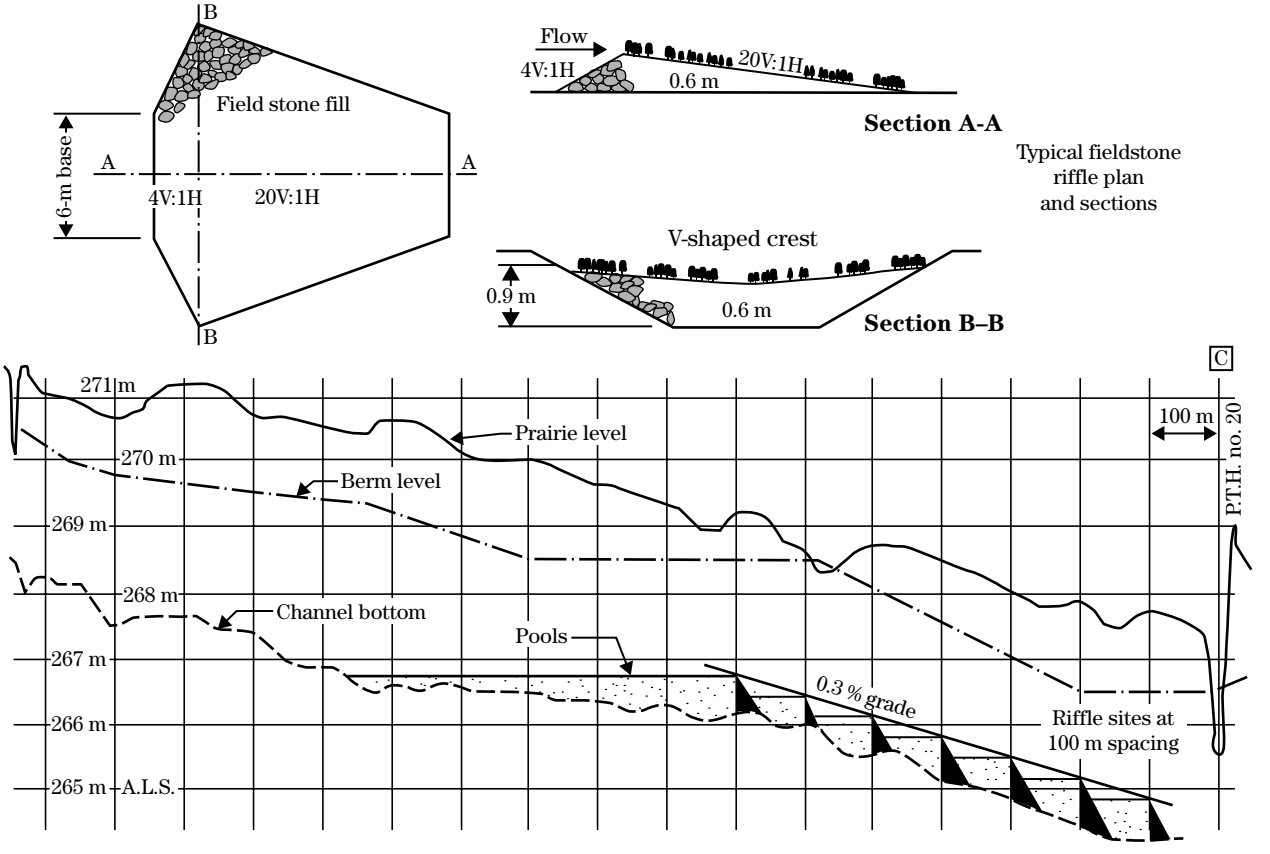


natural riffles. For the Mink Creek example shown in figure TS14G–7 (Newbury 2002), the structures were designed to a height of 0.6 meter that would impound shallow pools for passage of young walleye fry. No cutoff walls or filters were used in this installation, but the structure was sealed by infilling the front slope with shale gravel scraped from the bed.

Rosgen (2001e) describes a cross vane rock structure (fig. TS14G–8) that provides grade control and a pool for fish habitat. Streamflow is shown by the red arrow, and the lowest portion of the structure is located along line A–B, being constructed at the thalweg elevation. As described by Rosgen, no drop in bed elevation exists across the structure, however, a drop in water surface and energy gradient occurs due to lateral constriction. The distance A–B is approximately a third of the stream width, and the structure widens at a 20 degrees to 30-degree angle, expanding to the bankfull width. The vertical angle of the expanding legs is approximately 2 degrees to 7 degrees. The top layer of stones is underlain by footer stones, with the depth of the footer foundation being adjusted to the estimated depth of scour. A pool is excavated within the downstream legs of the structure and may be maintained by the flow turbulence.

A J-hook structure (Rosgen 2001e) is shown in figure TS14G–9. Although primarily developed for bank stabilization, the application shown extends across the low-flow stream and may act as a grade control structure. As shown, the flow is between stones placed near the center of the stream. Notice that both the J-hook and the cross vane rock structures are tied back into the bank to prevent flanking.

Figure TS14G–7 Loose rock structures are shown in plan and profile for Mink Creek, Manitoba, CA



Rock sizing for loose rock structures

A common factor in all loose rock structures is determining the proper stone size. While a more comprehensive description of rock sizing can be found in TS14C, six methods are presented:

Method 1: U.S. Army Corps of Engineers (1994f)

The U.S. Army Corps of Engineers (USACE) developed criteria for sizing steep slope riprap where unit discharges are low and slopes range from 2 to 20 percent. A typical application would be a rock-lined chute. The stone size equation is:

$$D_{30} = \frac{1.95\, S^{0.555} q^{2/3}}{g^{1/3}} \qquad \text{(eq. TS14G–1)}$$

where:
S = bed slope
q = unit discharge

Equation TS14G–1 is applicable to thickness = 1.5 D_{100}, angular rock, unit weight of 167 pounds per cubic foot (lb/ft^3), D_{85}/D_{15} from 1.7 to 2.7, slopes from 2 to 20 percent, and uniform flow on a downslope, with no tailwater. The following steps should be used for this application:

Step 1 Estimate q = Q/b, where b = bottom width of chute.

Step 2 Multiply q by flow concentration factor of 1.25. Use greater factor if approach is skewed.

Step 3 Compute D_{30} using equation TS14G–1.

Step 4 Use uniform gradation having $D_{85}/D_{15} \leq 2$.

Step 5 Restrict application to straight channels with side slopes of 1V:2.5H or flatter.

Method 2: Abt and Johnson (1991)

Abt and Johnson conducted near-prototype flume studies to determine riprap stability when subjected to overtopping flows. Typical uses are for spillway flow or for loose rock grade control structures. Riprap design criteria for overtopping flows were developed for two conditions: stone movement and riprap layer failure. Criteria were developed as a function of stone shape, median stone size, unit discharge, and embankment slope. Stone movement occurred at approximately 74 percent of layer failure. It was determined from testing that rounded stone fails at a unit discharge approximately 40 percent less that angular stone, for

Figure TS14G–8 Cross vane rock grade control structure

Figure TS14G–9 A J-hook grade control structure

the same median size of stone. The resulting equations for angular riprap developed by Abt and Johnson are:

$$q_{design} = \frac{q_f}{0.74} = 1.35 q_f \qquad \text{(eq. TS14G–2)}$$

$$D_{50} = 5.23 S^{0.43} q_{design}^{0.56} \qquad \text{(eq. TS14G–3)}$$

where:
q_f = stone size at failure (in)
q_{design} = design discharge ($ft^3/s/ft$)
S = slope of the riprap layer

Method 3: Whittaker and Jäggi (1986)

$$\frac{q}{\sqrt{g D_{65}^3 (G_S - 1)}} \le \frac{0.257}{J^{\frac{7}{6}}} \qquad \text{(eq. TS14G–4)}$$

where:
q = specific discharge over the ramp ($m^3/s \times m$)
D_{65} = characteristic block diameter of the block mixture (m)
G_S = specific gravity of the blocks compared to that of the water (e.g., 2.65)
J = ramp gradient
g = acceleration due to gravity (m/s^2)

Method 4: Newbury and Gaboury (1993)

tractive force (kg/m^2) = incipient diameter (cm)

(eq. TS14G–5)

Method 5: Robinson, Rice, and Kadavy (1998)
A two-part prediction equation was developed by Robinson, Rice, and Kadavy to determine the highest stable discharge as a function of the median rock size and bed slope. Therefore, knowing any two of the three variables (D_{50} rock size, bed slope, or highest stable discharge) allows calculation of the third. Tests were performed in large flumes and full-size structures with a median rock size up to 11 inches. These large scale rock chutes were tested to failure to develop the following relationships:

$$q = 0.52\, D_{50}^{1.89}\, S_o^{-1.50} \text{ for } S_o < 0.10 \qquad \text{(eq. TS14G–6)}$$

$$q = 4.30\, D_{50}^{1.89}\, S_o^{-1.50} \text{ for } 0.10 < S_o < 0.40$$

(eq. TS14G–7)

where:
q = unit discharge ($ft^3/s/ft$)
S_o = bed slope (ft/ft)
D_{50} = median rock size (ft)

These equations apply to rock chutes constructed with angular riprap with a rock layer thickness of $2D_{50}$. This research was performed on a relatively uniform rock gradation that exhibited a geometric standard deviation ranging from 1.15 to 1.47. These relationships have not been verified for slopes less than 2 percent or greater than 40 percent.

Method 6: Rosgen (2001e)
The Rosgen relationship was developed to determine minimum size of rock for the cross vane and J-hook structures at bankfull flow conditions:

minimum rock size (m) =
0.1724 ln (bankfull shear stress, kg/m^2) + 0.6349

(eq. TS14G–8)

Application of this relationship is limited to river discharges ranging from 0.56 cubic meters per second to 113.3 cubic meters per second, and bankfull depth from 0.26 meter to 1.5 meters.

Rock sizing summary

Figure TS14G–10 compares the six different procedures using a 5 percent sloping (1V:20H) loose rock structure at a unit discharge varying from 1 to 10 cubic meters per meter of width. It should be noted that the D_n varied between the methods, so an absolute comparison was not possible. For instance, Chervet and Weiss (1990) specified D_{65}, Abt and Johnson (1991) and Robinson, Kadvey, and Rice (1998) specified D_{50}, USACE (1994a) specified D_{30}, Newbury and Gaboury (1993) did not specify a rock size within the gradation, and the Rosgen (2002) method calculates the minimum rock size. However, comparison of the curves in figure TS14G–10 indicates that, with the exception of the Rosgen method, there is general consistency among the other five methods. It is important to note that the Rosgen (2002) relationship determines the minimum size of rock required and unlike the other methods, does not calculate a stone gradation. Therefore, it is not surprising that Rosgen's results are not compatible

with the other methods. If the sloping loose rock structures are to be constructed in a location that will encounter completely submerged conditions, traditional riprap-sizing methods (USACE 1994f; U.S. Department of Transportation Federal Highway Administration (FHWA) 2001a) should be used to check structure stability. An example design procedure for a sloping loose rock drop structure, adapted from Watson and Eom (2003), is provided at the end of this technical supplement.

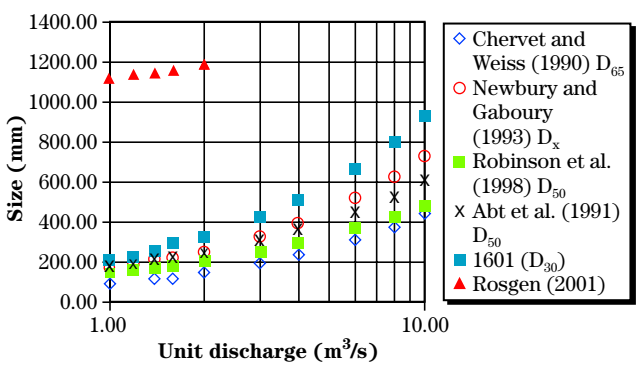
Local scour protection for loose rock structures

Chervet and Weiss (1990) reviewed work by Whittaker and Jäggi (1986) and developed a relationship for predicting local scour at the downstream extent of a loose rock structure, referred to by the authors as a block ramp.

The maximum scour depth (t) can be estimated using the following approach (Tschopp-Bisaz, modified in accordance with Whittaker and Jäggi (1986)):

$$t + h_U \cong 0.85q^{0.5}\left(\frac{q}{h_N}\right)^{0.5} - 7.125D_{90} \qquad \text{(eq. TS14G–9)}$$

Figure TS14G–10 Comparison of rock sizing methods for a 1V:20H sloping face structure



where:

h_U = tailwater depth (m);

h_N = normal supercritical discharge depth over the ramp (m), e.g., calculated according to Strickler's formula, using a coefficient of friction of $k = 21/D_{65}^{1/6}$ ($m^{1/3}/s$)

t = predicted scour depth (m)

Local scour depth is directly related to unit discharge, and an inverse relationship is shown for tailwater depth and the D_{90} of the bed material. Chervet and Weiss (1990) recommend that the downstream extent of the structure should extend below an anticipated local scour depth.

Bitner (2003) reviewed local scour depth, reporting that Castro (1999) defined bed key depth as the local scour depth to which the rock structure should be excavated to prevent undermining. Castro recommended that the scour depth may approach 2.5 times the drop height for gravel or cobble beds, and 3.5 times the drop height for sand beds.

Channel linings

Grade control can also be accomplished by lining the streambed with an erosion resistant material. These structures are designed to ensure that the drop is accomplished over a specified stream reach that has been lined with riprap or some other erosion-resistant material. Rock riprap gradient control structures have been used by the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) (formally the Soil Conservation Service (SCS) 1976) for several years. These structures are designed to flow in the subcritical regime with a constant specific energy at the design discharge, which is equal to the specific energy of flow immediately upstream of the structure (Myers 1982). Although these structures have generally been successful, some have had local scour problems. This precipitated a series of model studies to correct these problems and to develop a design methodology for these structures (Tate 1988, 1991). Plan and profile drawings of the improved structure are shown in figure TS14G–11 (adapted from Tate 1991).

Loose rock structures with water cutoff

One problem often encountered with channel lining structures is the displacement of rock (or rubble) due to the seepage flow around and beneath the structure. This is particularly a problem when the bed of the stream is composed primarily of pervious material. This problem can be eliminated by constructing a water barrier at the structure. One type of water barrier consists of simply placing a trench of impervious clay fill upstream of the weir crest (fig. TS14G–12). In general, this type of barrier has limited longevity due to susceptibility to erosion. This erosion can be avoided by using a concrete or sheet pile cutoff wall. The conceptual design of a riprap grade control structure with a sheet pile cutoff wall is shown in figure TS14G–13.

Structures with preformed scour holes and water cutoff

A scour hole is a natural occurrence downstream of any overfall. Sizing of the scour hole is a critical element in the design process, which is usually based on model studies or on experience with similar structures in the area.

The stability of rock structures is often jeopardized at low tailwater conditions. One way to ensure the stability of the rock is to design the structure to operate in a submerged condition. Linder (1963) developed a structure that is designed to operate at submerged conditions where the tailwater elevation (T) does not fall below 0.8 of the critical depth (d_c) at the crest section. Subsequent monitoring of the in-place structures confirmed the successful performance in the field (USACE 1981).

Little and Murphey (1982) developed a loose rock structure incorporating a sheet pile cutoff and weir, and a preformed scour basin lined with riprap that acts as an energy dissipation basin. They observed that an undular hydraulic jump occurs when the incoming Froude number is less than 1.7. Consequently, Little and Murphey developed a grade control design that included an energy dissipating baffle to break up these undular waves (fig. TS14G–14). This structure, referred to as the Agricultural Research Service (ARS)-type low-drop structure, has been used successfully in northern Mississippi for drop heights up to about 2 meters by both the USACE and the U.S. Department of Agriculture (USDA) SCS (USACE 1981). A recent modification to the ARS structure was developed following model studies at Colorado State University (Johns et al. 1993; Abt et al. 1994). The modified ARS structure, presented in figure TS14G–15, retains the baffle plate, but adopts a vertical drop at the sheet pile, rather than a sloping rockfill section as recommended by Little and Murphey.

Smith and Wilson (1992) provide guidance for design and construction of the ARS-type grade control structure. The guidance is replete with information, and several specific points follow:

- For selection of the final structure site, the stream should be straight for a distance of 10 stream widths upstream and for a minimum of 200 feet downstream.
- No gullies or lateral drains should occur in the site.
- The base width of the weir should be constricted to ensure that the water surface elevation of the 2-year discharge moves from critical depth near the weir crest to normal depth of flow in a short distance; for example, a few stream widths.
- The resulting flood-control impacts should not violate flood-control requirements.

Figure TS14G–11 Rock riprap gradient control structure

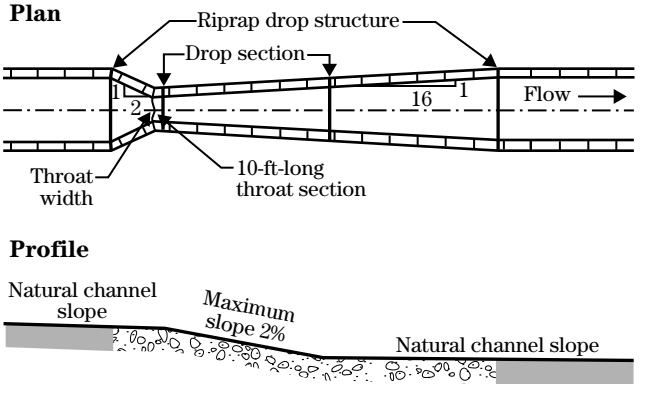


Figure TS14G–12 Top—built riprap grade control structure with an impervious fill cutoff wall; Bottom—launching of riprap at the grade control structure in response to bed degradation and local scour

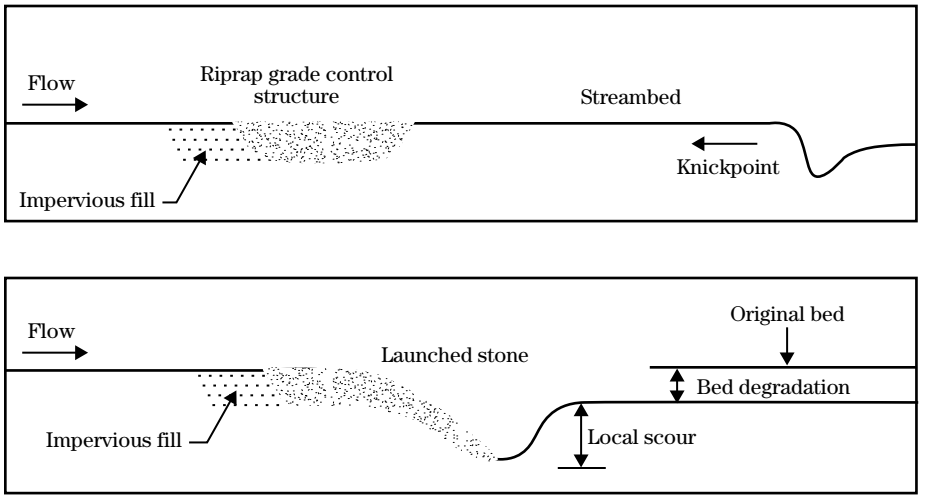


Figure TS14G–13 Top—built riprap grade control structure with a sheet pile cutoff wall (*top*); Bottom—launching of riprap at the grade control structure in response to bed degradation and local scour

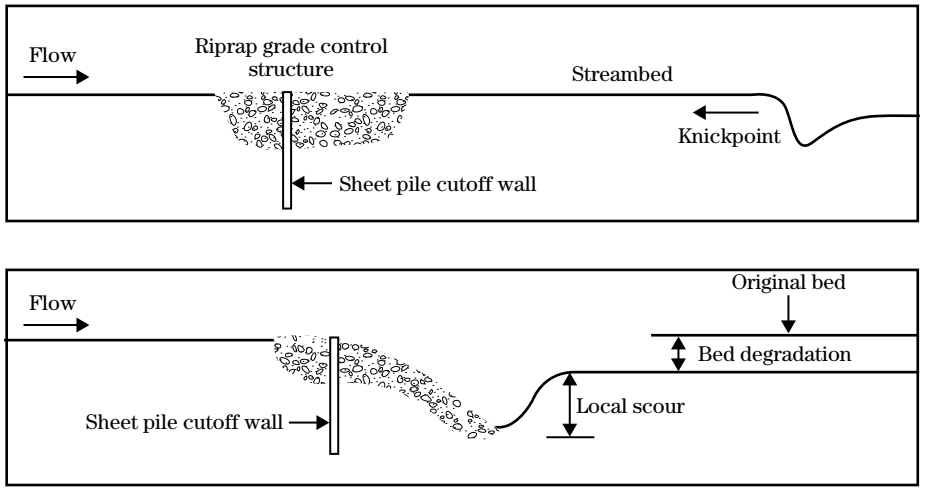
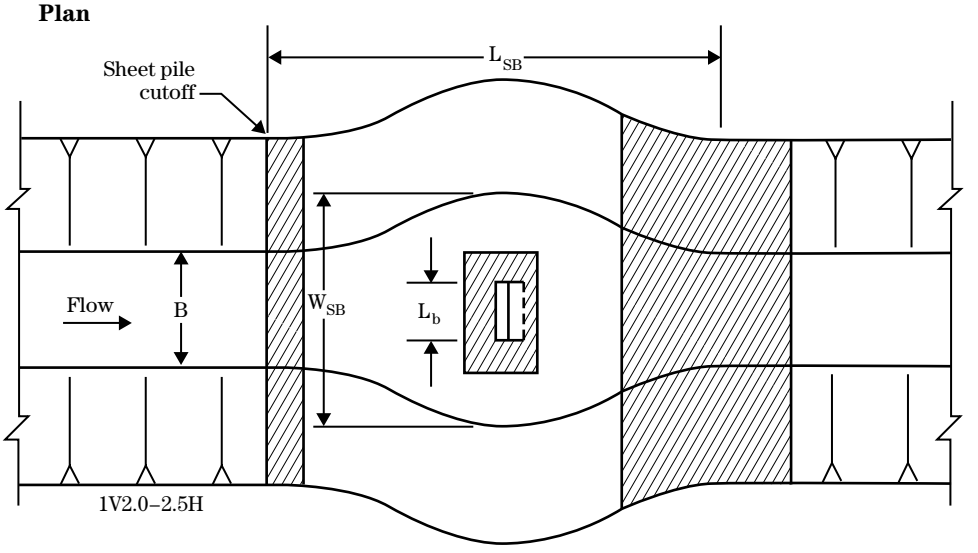
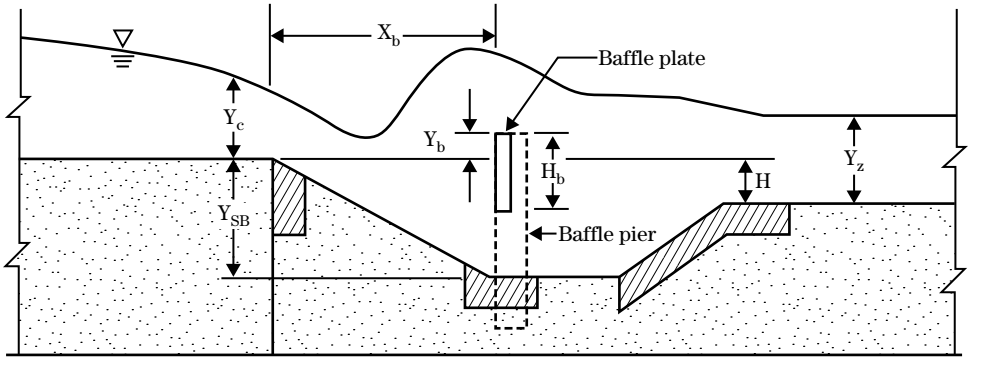


Figure TS14G–14 ARS-type grade control structure with preformed riprap-lined stilling basin and baffle plate

Plan



Profile



- The stilling basin dimensions should be based on the smaller of the bankfull discharge or the 100-year discharge.
- Downstream tailwater conditions should be based on normal depth calculations of an estimated future, degraded condition.
- Stilling basin riprap size is based on physical model studies referenced in the guidance. Approach stream protection and exit stream protection are specified.

Recent modifications to the ARS-type grade control structure by the USACE Vicksburg District replaced the vertical face downstream of the weir with a 1V:2H sloping face constructed of grouted riprap (fig. TS14G–16). Upstream riprap extends below the water; however, sediment filling of the stone as shown is supporting vegetation Other modifications included elimination of the baffle plate and the construction of an impervious fill section at the weir section in lieu of the sheet pile cutoff wall. Annual monitoring of these structures since the early 1990s has revealed no significant negative structural or channel impacts.

Rigid drop structures

In many situations where the discharge and/or drop heights are large, in excess of 2 meters, grade control structures are frequently constructed of concrete or a combination of sheet pile and concrete. There are many different designs for concrete grade control structures. Two described here are the California Institute of Technology (CIT) and the St. Anthony Falls (SAF) structures. Both of these structures were used on the Gering Drain project in Nebraska, where the decision to use one or the other was based on the flow and stream conditions (Stufft 1965). Where the discharges were large and the stream depth was relatively shallow, the CIT-type drop structure was used. The CIT-type structure is generally applicable to low-drop situations where the ratio of the drop height to critical depth is less than 1; however, for the Gering Drain project this ratio was extended up to 1.2. The original design of this structure was based on criteria developed by Vanoni and Pollack (1959). The structure was then modified by model studies at the USACE Waterways Experiment Station (WES) in Vicksburg, Missis-

Figure TS14G–15 Schematic of modified ARS-type grade control structure

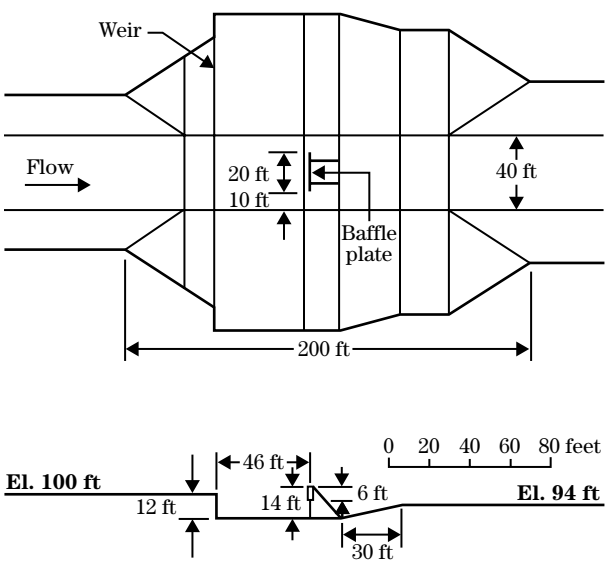


Figure TS14G–16 ARS-type grade control structure with grouted riprap face

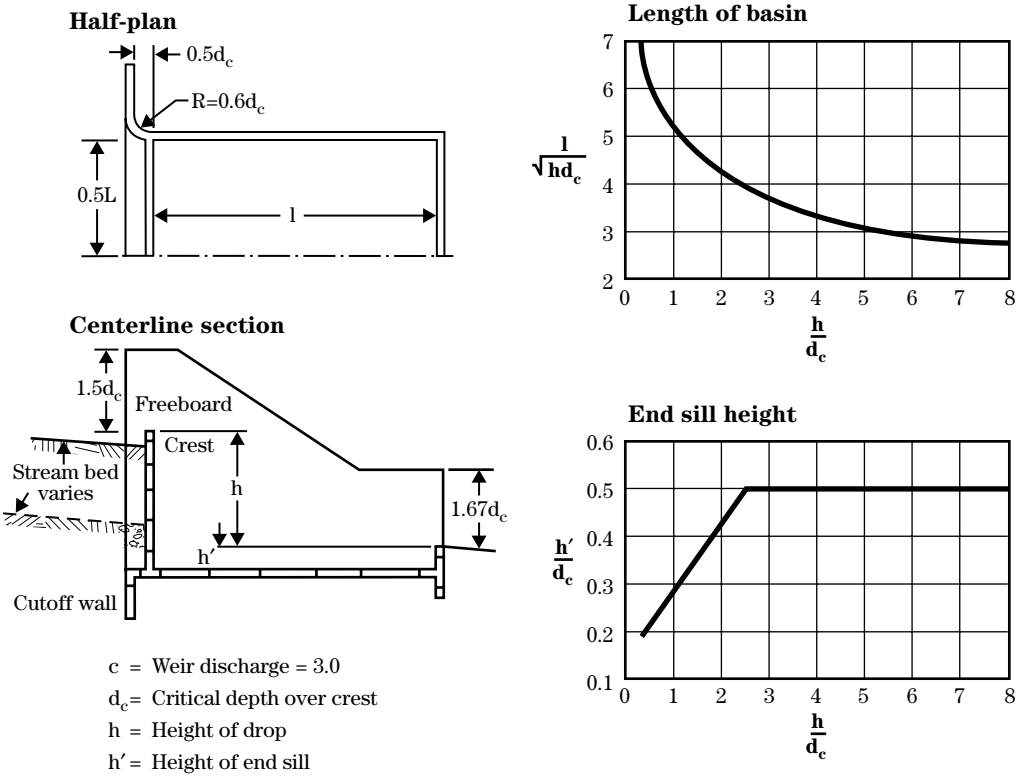
sippi, and is shown in figure TS14G–17 (Murphy 1967). Where the stream was relatively deep and the discharges smaller, the SAF drop structure was used. This design was developed from model studies at the SAF Hydraulic Laboratory for the SCS (Blaisdell 1948). This structure is shown in figure TS14G–18. The SAF structure is capable of functioning in flow conditions where the drop height to critical depth ratio is greater than 1 and can provide effective energy dissipation within a Froude number range of 1.7 to 17. Both the CIT and the SAF drop structures have performed satisfactorily on the Gering Drain for more than 25 years.

The design for a large, rigid structure should include consideration of slope stability including sudden drawdown. Slope stability should also be investigated for the site, approach, and downstream channels. Stability analyses should include sliding stability of the structure, underseepage, and allowance for bearing capacity and settlement. As the hydraulic capacity and drop height of the structure increases, the complexity of design and construction increases.

Alternative construction materials

While riprap, sheet pile, and concrete may be the most commonly used construction materials for grade control structures, cost or availability of materials may prompt the engineer to consider other alternatives.

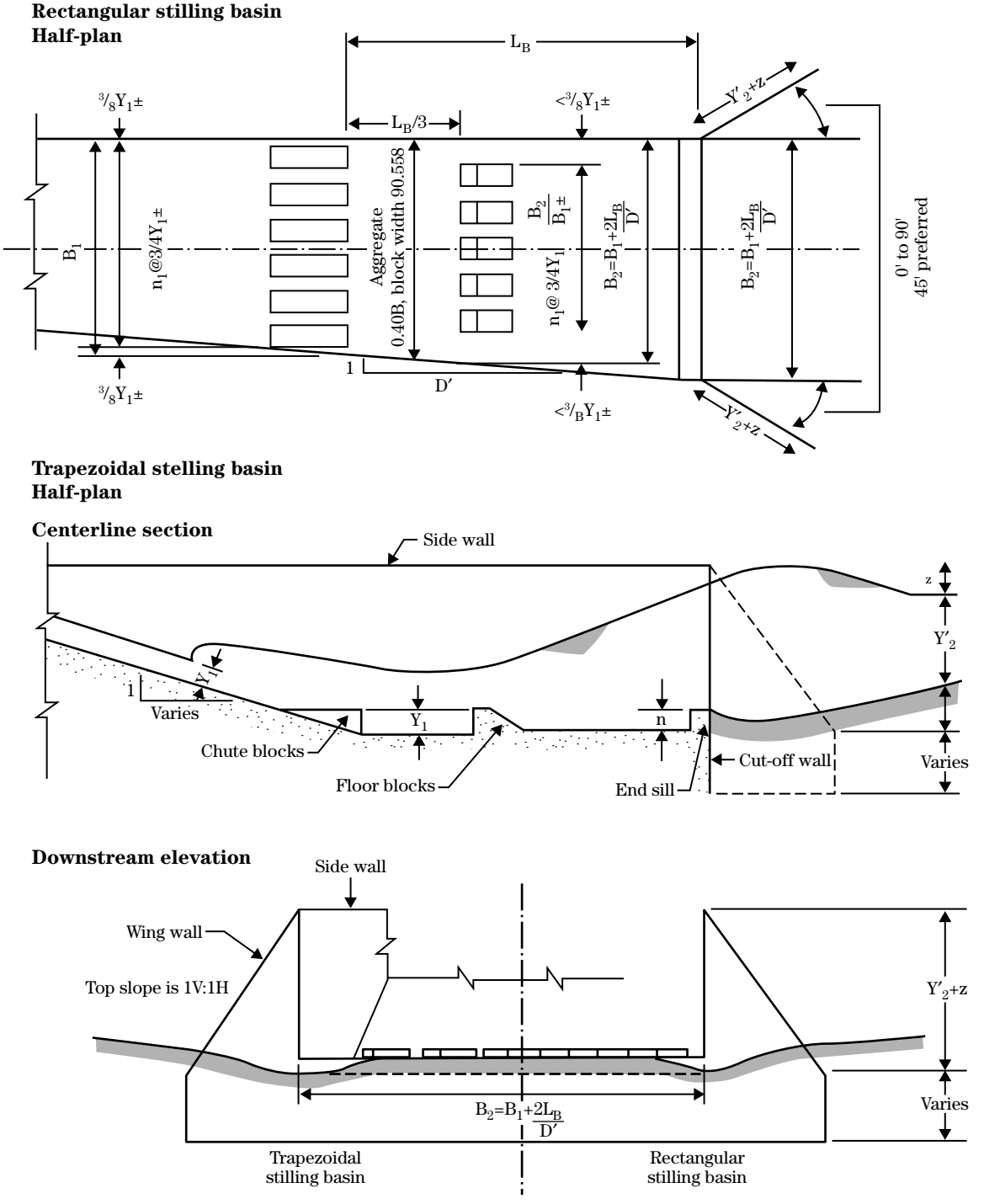
Figure TS14G–17 CIT-type drop structure



c = Weir discharge = 3.0
d_c = Critical depth over crest
h = Height of drop
h′ = Height of end sill
H = Head on weir = 3/2(d_c)
l = Length of basin
L = Length of weir crest
Q = Discharge, $CLH^{3/2}$

Details and design chart for typical drop structure

Figure TS14G–18 SAF drop structure



Gabion grade control structures are often an effective alternative to standard riprap or concrete structures (Hanson, Lohnes, and Klaiber 1986). Guidance for the construction of gabion weirs is also provided by the USACE (1974). Gabion mattresses consist of rectangular-shaped wire-mesh baskets filled with rock (FHWA 1989). Current applications of gabion mattresses include streambed and bank stabilization. Further information on small grade control is provided in NEH654 TS14P; and the use of gabions for bank stabilization is described in NEH654 TS14K. Table TS14G–2 (adapted from FHWA (1989)) presents the advantages and disadvantages of gabion mattresses when used in an erosion control application. Other, more detailed design guidelines for rock gabions can be found in FHWA (1989), USACE (1974), and Maynord (1995).

Bitner (2003) pointed out that an alternative to the conventional riprap or concrete structure that has gained popularity in the Southwestern United States is the use of soil cement grade control structures. These structures are constructed of onsite soil-sand in a mix with Portland Cement to form a high quality, erosion-resistant mixture. Soil cement grade control structures are most applicable when used as a series of small drops, in lieu of a single large-drop structure. Experience indicates that a limiting drop height for these structures is on the order of 1 meter. Design criteria for these structures are presented by Simons and Li (1982).

Thornton et al. (1999) have developed shear resistance criteria for A-Jacks®, an interlocking concrete armor unit manufactured by Armortec Erosion Control Solutions. Current applications of A-Jacks® include coastal shoreline protection, streambed and bank protection, and pier scour mitigation. Depending on their intended application, A-Jacks® vary between 2 to 8 feet in size.

Stone riprap can be bound with cement grout, forming grouted riprap. The apparent advantage in grouted riprap is to increase the shear resistance of individual stone particles. In their review of grouted riprap, Przedwojski, Blazejewski, and Pilarczyk (1995) cited three basic methods of grouting (Rÿkswaterstaat 1995):

- Surface grouting fills approximately 30 percent of the surface voids, with mortar penetrating the surface layer without completely sealing the construction.
- Pattern grouting fills 50 percent to 80 percent of cover-layer voids and penetrates the full thickness of the riprap. Eventually, a mesh of stone-cement aggregates is formed.
- Full grouting fills 100 percent of the cover-layer voids, resulting in an impermeable layer.

They caution that as voids are filled with grout and permeability diminishes, the stability of the layer is adversely affected by excess pore pressures occurring during high discharges or from ground water. Weep holes or other positive drainage should be provided to avoid massive failure. Grouted riprap is addressed further in NEH654 TS14K.

McLaughlin Water Engineers (1986) report that grout has been successfully used to stabilize loose riprap. Many failures have been reported that were associated with seepage and uplift. They recommend that seepage be controlled by constructing a vertical cutoff immediately upstream of the crest, constructing the cutoff by excavating a trench below the riprap subgrade, and placing steel and concrete to form the cutoff wall. Their view of grouted riprap is different from Przedwojski, Blazejewski, and Pilarczyk (1995). McLaughlin Water Engineers recommend that regular

Table TS14G–2 Advantage and disadvantages of gabion mattresses when used in an erosion control application

Advantages	Disadvantages
• Ability to span minor pockets of subsidence without failure • Interlock to allow use of smaller, lower quality rock in the baskets • Economically feasible where riprap-sized rock is not readily available	• Susceptibility of the wire baskets to corrosion, abrasion damage, and vandalism • High labor cost associated with fabrication and filling the baskets • More difficult and expensive repair than standard rock protection

riprap should not be used with grout and that rock with all dimensions greater than the grout thickness be required and placed on a firm subgrade. Grout is then pumped into the voids and vibrated, filling the voids between rocks. The method results in the appearance of a concrete slab with large stones spaced evenly, protruding through the slab. Toe and lateral drains are included for drainage of the grouted area.

General design considerations for siting grade control structures

Design considerations for siting grade control structures include determination of the type, location, and spacing of structures, along with the elevation and dimensions of the structures. Siting grade control structures is often considered a simple optimization of hydraulics and economics. However, these factors alone are usually not sufficient to define the optimum grade control siting conditions. In practice, hydraulic considerations must be integrated with a host of other factors that vary from site to site to determine the final structure plan. Some of the more important factors to be considered when siting grade control structures are described in the following sections. This does not represent an all-inclusive list, since there may be other factors that may be locally important. For example, maintenance requirements, debris passage, ice conditions, or safety considerations may be controlling factors. Consequently, there is no definitive procedure for siting grade control structures. However, consideration of each factor in an analytical and balanced fashion can lead to a more effective design process that will ensure that the plan accomplishes the long-term project goals.

Hydraulic and sediment transport considerations

One of the most important steps in the siting of a grade control structure or a series of structures is the drop height determination. This requires some knowledge of the ultimate stream morphology, both upstream and downstream of the structure, which involves assessment of sediment transport and stream morphologic processes.

The hydraulic siting of grade control structures is a critical element of the design process, particularly when a series of structures is planned. The design of each structure is based on the anticipated tailwater or downstream bed elevation, which in turn, is a function of the next structure downstream. Heede and Mulich (1973) suggested optimum spacing of structures, so that the upstream structure does not interfere with the deposition zone of the next downstream structure. Mussetter (1982) showed that the optimum spacing should be the length of the deposition above the structure, which is a function of the deposition slope (fig. TS14G–19 (adapted from Mussetter). Figure TS14G–19 also illustrates the recommendations of Johnson and Minaker (1944), that the most desirable spacing can be determined by extending a line from the top of the first structure, at a slope equal to the maximum equilibrium slope of sediment upstream, until it intersects the original streambed.

Theoretically, the hydraulic siting of grade control structures is straightforward and can be determined by:

$$H = (S_o - S_f)X \qquad \text{(eq. TS14G–10)}$$

where:
H = amount of drop to be removed from the reach
S_o = original bed slope
S_f = final, or equilibrium slope
X = length of the reach (Goitom and Zeller 1989)

The number of structures (N) required for a given reach can then be determined by:

$$N = \frac{H}{h} \qquad \text{(eq. TS14G–11)}$$

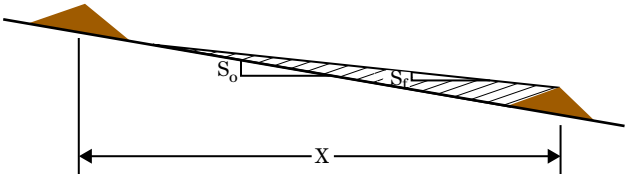
where:
h = selected drop height of the structure

It follows from equation TS14G–10 and figure TS14G–19 that one of the most important factors to consider when siting grade control structures is the determination of the equilibrium slope (S_f). Unfortunately, this is also one of the most difficult parameters to define with any reliability. Equilibrium slope is defined as the channel slope that is required to transport the bed material supplied through the reach, without significant aggradation or degradation of the channel.

With respect to grade control design, this is the slope that is anticipated to develop through time, upstream of the structure. Failure to properly define the equilibrium slope can lead to costly, overly conservative designs, or an inadequate design, resulting in continued maintenance problems and a possible structure failure. The primary factors affecting the final equilibrium slope upstream of a structure include the incoming sediment concentration and load, the channel characteristics (slope, width, depth, roughness), and the hydraulic effect of the structure. Another complicating factor is the amount of time it takes for the equilibrium slope to develop. In some instances, the equilibrium slope may develop over a period of a few hydrographs, while in others, it may take many years.

Many different methods exist for determining the equilibrium slope in a channel (Mussetter 1982; FISRWG 1998; Watson and Biedenharn 1999). These can range from detailed sediment transport modeling (Thomas, Copeland, et al. 1994; USACE 1993c) to less elaborate procedures involving empirical or process-based relationships, such as regime analysis (Lacey 1931; Simons and Albertson 1963), tractive stress (Lane 1953a, b; Simons 1957; Simons and Sentürk 1992; USACE 1994a), or minimum permissible velocity (USDA SCS 1977). In some cases, the equilibrium slope may be based solely on field experience with similar channels in the area. Regardless of the procedure used, the engineer must recognize the uses and limitations of that procedure before applying it to a specific situation. The decision to use one method or another depends on several factors such as the level of study (reconnaissance or detail design), availability and reliability of data, project objectives, and time and cost constraints. Equilibrium is addressed further in NEH654.13.

Figure TS14G–19 Spacing of grade control structure



Geotechnical considerations

The previous description focused only on the hydraulic aspects of design and siting of grade control structures. In some cases, the geotechnical stability of the reach may be an important or even the primary factor to consider when siting grade control structures. This is often the case where stream degradation has caused, or is anticipated to cause, severe bank instability due to exceedance of the critical bank height (Thorne and Osman 1988). When this occurs, bank instability may be widespread throughout the system, rather than restricted to the concave banks in bendways. Traditional bank stabilization measures may not be feasible where systemwide bank instabilities exist. In these instances, grade control, aimed at preventing the onset of incision-triggered mass wasting, may be the more appropriate solution.

Grade control structures can enhance the bank stability of a stream in several ways. Bed control structures indirectly affect the bank stability by stabilizing the bed, thereby reducing the length of bankline that achieves an unstable height. With hydraulic control structures, two additional bank stability advantages are that bank heights can be reduced due to sediment deposition upstream of the structure, increasing bank stability, and by creating backwater conditions, velocities and scouring potential are reduced, which can minimize or eliminate the severity and extent of basal clean out of the failed bank material, thereby promoting self-healing of the banks (Thorne 1990). Therefore, if systemwide bank instability is a significant concern, consideration might be given to raising and/or constricting the weir invert to promote bank stability.

Additional references pertaining to streambank stability include the American Society of Civil Engineers (ASCE 1998); Bishop (1955); Coppin and Richards (1990); Gray and Leiser (1982); Hagerty (1991); Huang (1983); Kouwen, Unny, and Hill (1969); López and Garcia (1997); Morgenstern and Price (1965); Osman and Thorne (1988); Sands and Kapitzke (1998); Simon, Wolfe, and Molinas (1991); Simon et al. (1999); Terzaghi (1943); and Terzaghi and Peck (1967). In addition, geotechnical issues are described in NEH654 TS14A.

The flow of water through a pervious foundation can be a serious problem for a grade control structure. As the drop height of the structure increases, the driv-

ing force increases for subsurface flow and possible erosion beneath the structure. Very silty and sandy soils are the least resistant to seepage or piping failures (McLaughlin Water Engineers 1986). Seepage pressures and velocities must be controlled to prevent internal erosion and particle migration. In extreme cases, seepage may cause failure of the structure foundation and sloughing of the streambank downstream of the crest of the structure. Seepage theory and analysis is addressed in Cedergren (1977), and embankment flownets are addressed in depth by Sherard et al. (1963) and Volpe and Kelly (1985), as referenced in Novak et al. (1997).

Common methods of seepage control include cutoff trenches filled with an impervious material, sheet pile curtains, upstream impervious blankets, and downstream filter blankets. The U.S. Department of Interior, Bureau of Reclamation (1987) provides an intensive description of these methods. Sheet pile is addressed further in NEH654 TS14R, and geosynthetics is addressed in NEH654 TS14D.

Flood control impacts

Stream improvements for flood control and stream stability often appear to be mutually exclusive objectives. For this reason, it is important to ensure that any increased postproject flood potential is identified. This is particularly important when hydraulic control structures are considered; the potential for causing overbank flooding may be the limiting factor with respect to the height and amount of constriction at the structure. Grade control structures are often designed to be hydraulically submerged at flows less than bankfull so that the frequency of overbank flooding is not affected. However, if the structure exerts control through a wider range of flows, including overbank, the frequency and duration of overbank flows may be impacted. When this occurs, the impacts must be quantified and appropriate provisions should be implemented such as acquiring flow easements or modifying structure plans.

Another factor that must be considered when designing grade control structures is the safe return of overbank flows back into the stream. This is particularly a problem when the flows are out of the bank upstream of the structure, but still within the bank downstream. The resulting head differential can cause damage to the structure, as well as severe erosion of the streambanks, depending on where the flow reenters the stream. Some means of controlling the overbank return flows must be incorporated into the structure design. One method is simply to design the structure to be submerged below the top bank elevation, thereby reducing the potential for a head differential to develop across the structure during overbank flows. If the structure will impact overbank flows, a more direct means of controlling the overbank return flows must be provided. One method is to ensure that all flows pass only through the structure. This may be accomplished by building an earthen dike or berm extending from the structure to the valley walls that prevents any overbank flows from passing around the structure (Forsythe 1985). Another means of controlling overbank flows is to provide an auxiliary high-flow structure, which will pass the overbank flows to a specified downstream location, where the flows can reenter the stream without causing significant damage (Hite and Pickering 1982).

Environmental considerations

Projects must work in harmony with the natural system to meet the current needs without compromising the ability of future generations to meet their needs. Engineers and geomorphologists are responding to this challenge by developing new and innovative methods for incorporating environmental features into stream projects. The final siting of a grade control structure is often modified to minimize adverse environmental impacts to the system.

Grade control structures can provide direct environmental benefits to a stream. Cooper and Knight (1987) conducted a study of fisheries resources below natural scour holes and manmade pools below grade control structures in northern Mississippi. They concluded that although greater species diversity occurred in the natural pools, increased growth of game fish and a larger percentage of harvestable size fish were recorded in the manmade pools. They also observed that the manmade pools provided greater stability of reproductive habitat. Shields, Hoover, et al. (1990) reported that the physical aquatic habitat diversity was higher in stabilized reaches of Twentymile Creek,

Mississippi, than in reaches without grade control structures. They attributed the higher diversity values to the scour holes and low-flow channels created by the grade control structures. The use of grade control structures as environmental features is not limited to the low-gradient sand-bed streams of the Southeastern United States. Jackson (1974) documented the use of gabion grade control structures to stabilize a high-gradient trout stream in New York. Jackson observed that following construction of a series of bed sills, trout density increased significantly. The increase in trout density was attributed to the accumulation of gravel between the sills, which improved the spawning habitat for various trout species.

Perhaps the most serious negative environmental impact of grade control structures is the possible obstruction to fish passage. In some cases, particularly when drop heights are small, fish are able to migrate upstream past a structure during high flows (Cooper and Knight 1987). However, as drop heights increase, the structures may restrict or completely block passage of some or all fish and other aquatic organisms, based on their individual species' abilities to jump over or swim through impediments. Therefore, fish passage may be a primary consideration in the selection of structure types and drop heights. For instance, it may be necessary to provide for fish passage to select a series of sloping riprap structures with small drops, in lieu of a single high-drop structure. However, if other factors dictate that a high-drop structure is required, the structure may need to be modified to provide for fish ladders or other passageways (Nunnally and Shields 1985). Various methods of accomplishing fish movement through structures are addressed in NEH654 TS14J. Interested readers are also referred to Nunnally and Shields (1985), Clay (1961), and Smith (1985) for more detailed information.

The environmental aspects of the project must be an integral component of the design process when siting grade control structures. A detailed study of all environmental features in the project area should be conducted early in the design process. This will allow these factors to be incorporated into the initial plan, rather than having to make costly and often less environmentally effective last-minute modifications to the final design. Unfortunately, very little guidance is published concerning the incorporation of environmental features into the design of grade control structures. A source of useful information is found in the following technical reports published by the USACE Environmental Laboratory, WES: Shields and Palermo (1982), Henderson and Shields (1984), and Nunnally and Shields (1985).

Existing structures

Bed degradation can cause significant damage to bridges, culverts, pipelines, utility lines, and other structures along the channel perimeter. Grade control structures can prevent this degradation, thereby providing protection to these structures. For this reason, it is important to locate all potentially impacted structures when siting grade control structures. The final siting should be modified, as needed, within project constraints, to ensure protection of existing structures.

Grade control structures can have adverse, as well as beneficial, effects on existing structures. This may be a concern upstream of hydraulic control structures due to the potential for increased flood stages and sediment deposition. The possibility of submerging upstream structures, such as water intakes or drainage structures, may become a deciding factor in the siting of grade control structures.

Whenever possible, the designer should take advantage of any existing structures that may already be providing some measure of grade control. This usually involves culverts or other structures that provide an erosion-resistant surface across the streambed. Unfortunately, these structures are usually not initially designed to accommodate any significant bed lowering and, therefore, cannot be relied on to provide long-term grade control. However, it may be possible to modify these structures to protect against the anticipated degradation. These modifications may be accomplished by simply adding some additional riprap with launching capability at the downstream end of the structure. In other situations, more elaborate modifications, such as providing a sheet-pile cutoff wall or energy dissipation devices, may be required. Damage to and failure of bridges is the natural consequence of channel degradation. Consequently, it is not uncommon in a channel stabilization project to identify several bridges that are in need of repair or replacement.

Therefore, it is often advantageous to integrate the grade control structure into the planned improvements at the bridge. If the bridge is not in immediate danger of failing and only needs some additional erosion protection, the grade control structure can be built at or immediately downstream of the bridge, with the riprap from the structure tied into the bridge for protection. If the bridge is to be replaced, it may be possible to construct the grade control structure concurrently with the new road crossing.

Local site conditions

When planning grade control structures, the final siting is often adjusted to accommodate local site conditions such as the planform of the stream or local drainage. A stable upstream alignment that provides a straight approach into the structure is critical. Since failure to stabilize the upstream approach may lead to excessive scour and possible flanking of the structure, it is desirable to locate the structure in a straight reach. If this is not possible (as in a very sinuous channel), it may be necessary to realign the channel to provide an adequate approach. Stabilization of the realigned channel may be required to ensure that the approach is maintained. Even if the structure is built in a straight reach, the possibility of upstream meanders migrating into the structure must be considered. In this case, the upstream meanders should be stabilized prior to or concurrent with, the construction of the grade control structure.

Local inflows from tributaries, field drains, roadside ditches, or other sources often affect the siting of grade control structures. Failure to provide protection from local drainage can result in severe damage to a structure (USACE 1981). During the initial siting of the structure, all local drainage should be identified. Ideally, the structure should be located to avoid local drainage problems. However, there may be some situations where this is not possible. The local drainage should either be redirected away from the structure or incorporated into the structure design.

Downstream channel response

Since grade control structures affect the sediment delivery to downstream reaches, it is necessary to consider the potential impacts to the downstream channel when grade control structures are planned. Bed control structures reduce the downstream sediment loading by preventing the erosion of the bed and banks, while hydraulic control structures have the added effect of trapping sediments. The ultimate response of the channel to the reduction in sediment supply varies from site to site. The effects of grade control structures on sediment loading may be so small that downstream degradational problems may not be encountered. However, when a series of hydraulic control structures is planned, the cumulative effects of sediment trapping may become significant. It may be necessary to modify the plan to reduce the amount of trapped sediment or consider placing additional grade control structures in the downstream reach to protect against the induced degradation. If downstream sediment problems are anticipated, a sediment budget analysis should be performed to ensure that the grade control structures will not create channel instability.

Geologic controls

Geologic controls often provide grade control in a similar manner to a bed control structure. A grade control structure can actually be eliminated from the plan if existing geologic control can be used to provide a similar level of bed stability. Caution must always be used when relying on geologic outcrops to provide long-term grade control. Where geologic controls are to be used as permanent grade control structures, a detailed geotechnical investigation of the outcrop is needed to determine its vertical and lateral extent. This is necessary to ensure that the outcrop will neither be eroded, undermined, nor flanked during the project life.

Effects on tributaries

When siting grade control structures, the effects of main stem structures on tributaries should be considered. As degradation on a main stem channel migrates

upstream, it may branch up into the tributaries. If possible, main stem structures should be placed downstream of tributary confluences. This will allow one structure to provide grade control to both the main stem and the tributary. This is generally a more cost-effective procedure than having separate structures on each channel.

Grade control siting summary

The selection of the location, type, and number of grade control structures is the most important aspect of grade control design. As illustrated in this technical supplement, a wide range of grade control designs can be used to satisfy the hydraulic and sediment transport requirements of the stream, and the selection of the appropriate one will generally reflect the consideration of a number of related factors. For instance, one of the most commonly faced questions is whether to provide grade control to a degradation reach with a series of small low-drop type structures or by a single high-drop structure. To select the most appropriate scheme, the engineer must consider a number of factors.

Single high-drop structure

Advantages

- less right-of-way required for a single structure versus several smaller structures
- improved bank stability due to decreased bank heights
- possible reestablishment of hydraulic connection between channel and flood plain
- possible flood attenuation if flows are stored in flood plain behind structure
- ability of single main stem structure to provide grade control to tributaries
- potential habitat benefits associated with large pool area upstream of structure

Disadvantages

- obstructions to fish passage
- potential for downstream degradation due to trapping of sediments
- high cost of large structure
- complex detailed design effort
- potential flood control impacts
- potential for safety problems at high-drop structures

Multiple low-drop structures

Advantages

- less cost for design and construction
- less environmental impacts due to fish passage
- less potential for morphological impacts
- no significant alterations of flows and sediment transport

Disadvantages

- limited impact on bank stability
- difficulty in determining the appropriate siting of a series of structures
- potential environmental destruction associated with construction (access, site preparation) at numerous locations along the channel
- no reconnection of channel and flood plain

In the final analysis, the engineer must weigh all the advantages and disadvantages of the two schemes and determine which approach achieves the project goals at the least cost and with the smallest potential for adverse environmental impact.

Conclusion

Grade control structures have been used effectively as erosion control features in water resources projects for many years. Unfortunately, these structures have often been considered rehabilitative features to be used only after the channel system has been destabilized. A more effective use of these structures is to incorporate them into the initial plans for the channel system in a proactive, rather than a reactive manner. As water resources projects become more and more complex, grade control structures need to be considered in a much broader sense to provide for environmental sustainability, as well as erosion control.

Example: Loose rock structure example design procedure

Many variations are available for the design of sloping loose rock structures. An example design procedure is presented to illustrate a typical design process associated with sloping loose rock drop structures. Inclusion here should not be considered as an endorsement of this particular approach over other approaches or structure types since, as noted earlier, there is no single approach that is applicable to all situations. The following is an example of the design of a series of sloping loose rock grade control structures on Blue Creek in Illinois (Roseboom et al. 2000).

Blue Creek is located approximately 5 miles outside of the town of Pittsfield, Illinois, and has a drainage area of about 3 square miles. Headcutting along Blue Creek was causing severe channel instability and loss of instream habitat. In response to this problem, a series of sloping, loose rock grade control structures were constructed in 1998 for channel stability and habitat restoration. Figure TS14G–20 (Watson and Eom 2003) shows the 1997 preconstruction thalweg profile and structure crests for the 12 grade control structures along the 3,500-foot-long study reach. As shown in figure TS14G–20, the reach average thalweg slope in 1997 was about 0.0029. During a 2002 resurvey, the water surface slope between structures averaged about 0.0012 (fig. TS14G–21 (Watson and Eom 2003)).

The grade control structures generally followed the Newbury and Gaboury (1993) design. The height of structures above the preconstruction bed varied from 2 to 5 feet, and the average elevation difference between structure crests in 1998 was about 1.1 feet. Crest stone diameters averaged 3 feet, but the crest stones were highly variable. The downstream slope of each structure was 1 on 20 (5%), and the upstream face of the weir extended upstream on a 1V:4H slope. Figure TS14G–22 (Watson and Eom 2003) shows photographs of one of the structures 1 month and 18 months following construction. Figure TS14G–23 (Watson and Eom 2003) shows a sketch of a typical structure. Roseboom et al. (2000) stated that no additional stabilization efforts have been required since construction; the eroding streambanks have revegetated, and the pools have deepened.

The following is a design procedure for the sloping rock grade control structures (modified from Watson and Eom 2003):

Step 1 The crest stone is to be constructed of quarry stone (approximately 3 ft by 3 ft by 2 ft) with the approximate center of the structure at the crest elevation specified. The remainder of the crest stone should be constructed to form a shallow V-shape with 0.5 to 1.0 foot of relief. The bed for the crest should be excavated to firm material. If the structure is to be placed on pervious material, consideration should be given to providing an impervious fill section to prevent seepage through the structure.

Step 2 The crest should be keyed into both banks using a riprap-filled trench, which extends to the greater of the top bank elevation or the 2-year flood. A desirable slope for the key trench is 3H:1V. A gravel blanket should be placed in the key trench and over the riprap if sandy material or piping of ground water is observed.

Step 3 Upstream and downstream of the crest is filled using riprap, sized in accordance with EM 1110–2–1601 (USACE 1994a revisions on 1991 version). Recommended slopes are 4H:1V upstream and 20H:1V downstream. The following rock size example is from one of the structures on Blue Creek. The unit discharge (q) was calculated from the bankfull flow of about 13 cubic meters per second and a width of 6 meters to be 2.2 cubic meters per second per meter. From equation TS14G–5, a D_{30} value for the riprap was determined to be 331 millimeters, or 1.09 feet. Figure TS14G–24 (Watson and Eom 2003) shows where the Blue Creek D_{30} value plots with respect to several commonly used riprap gradations. As shown in figure TS14G–24, the Blue Creek D_{30} value plots near the lower limit of both the B-Stone and R–400 stone and is centered within the R–650 stone limits. Therefore, the R–650 stone appears to be the most appropriate for this situation. However, the final choice must be tempered by other factors such as cost, availability, filter requirements (B-Stone might not require addition of filter), and the designer's experience.

Step 4 Spacing of structures along the stream was designed to ensure that the crest elevation of the downstream structure is at or above the toe of the thalweg elevation of the downstream face at

the location of the upstream structure weir crest. Spacing of the structures becomes closer as the existing bed slope steepens and increases where the bed slope is flatter. This is a conservative spacing that assumes that the final stable channel may not create a significant backwater that would cause sediment deposition upstream of the structure.

This is justified because the structures are low in height and do not provide a flow constriction. If the structures were higher or provided a significant flow constriction, a steeper equilibrium slope might develop through sediment deposition, and then the structures could be spaced further apart.

Figure TS14G–20 Blue Creek, IL, 1997 thalweg profile and structure locations and elevations

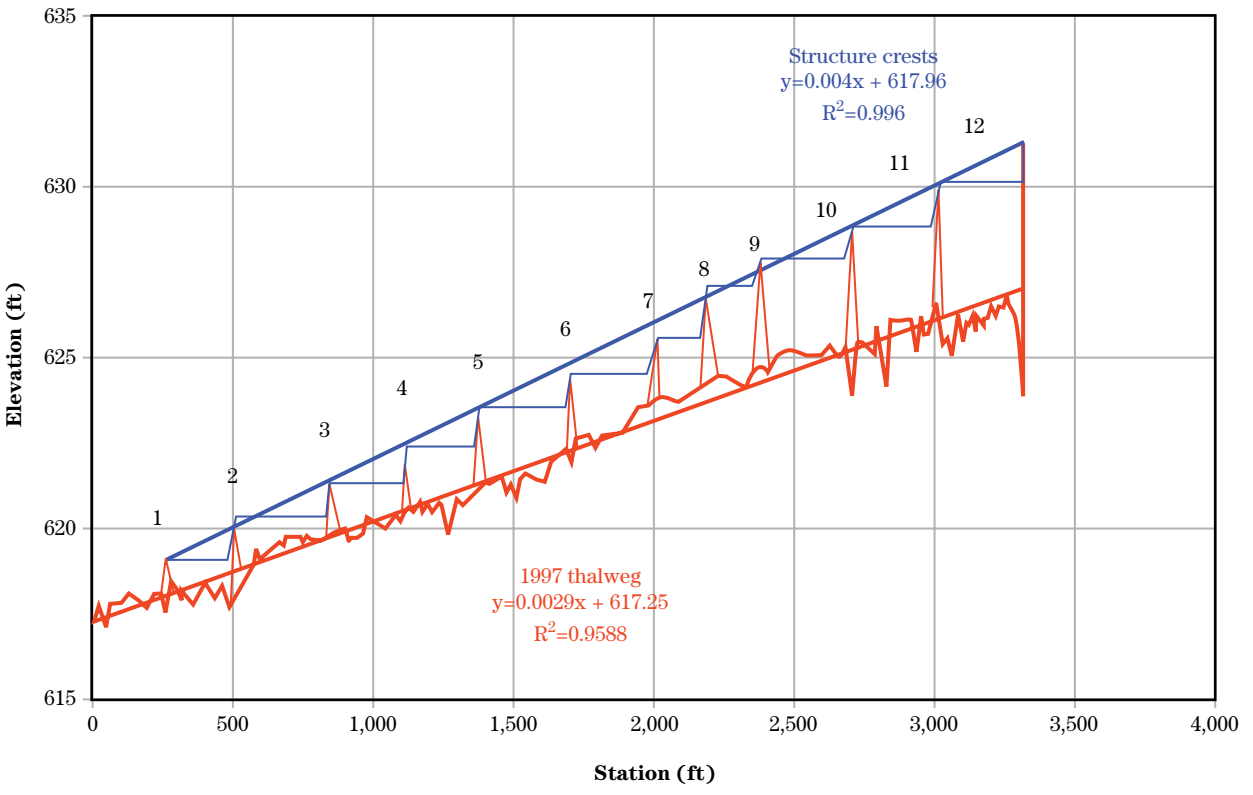


Figure TS14G–21 Blue Creek, IL, thalweg profile surveyed in 2002

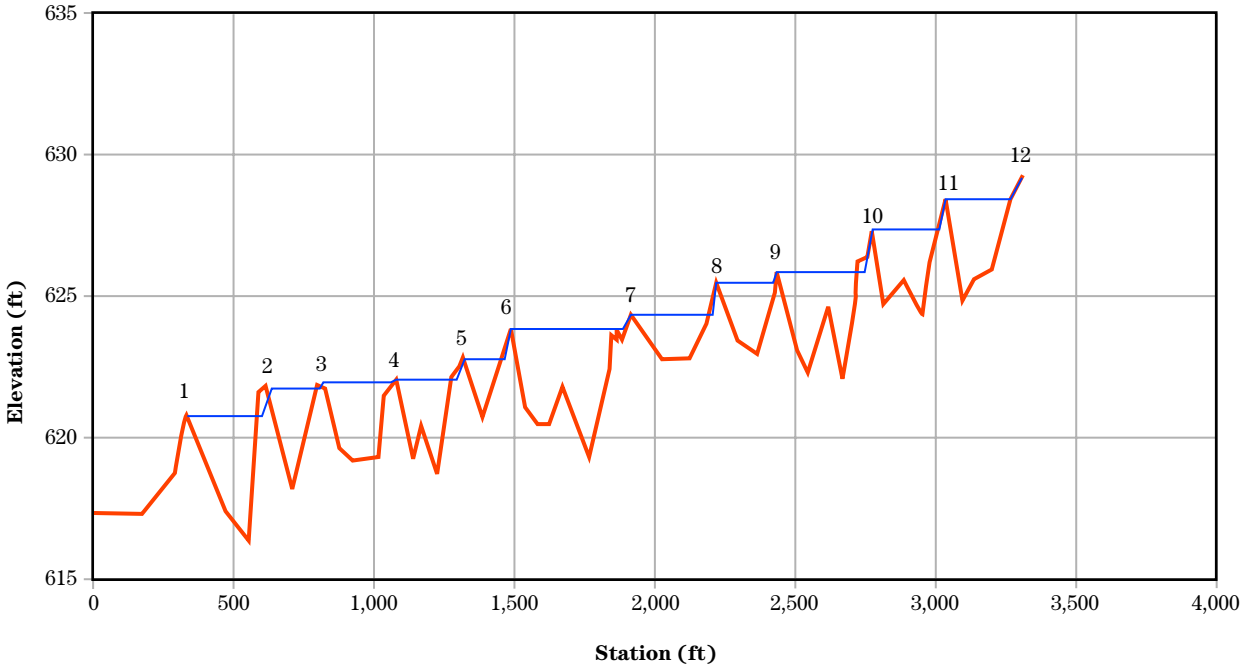


Figure TS14G–22 Grade control structure 1 month and 18 months after construction (Blue Creek, IL)

Figure TS14G–23 Grade control design (Blue Creek, IL)

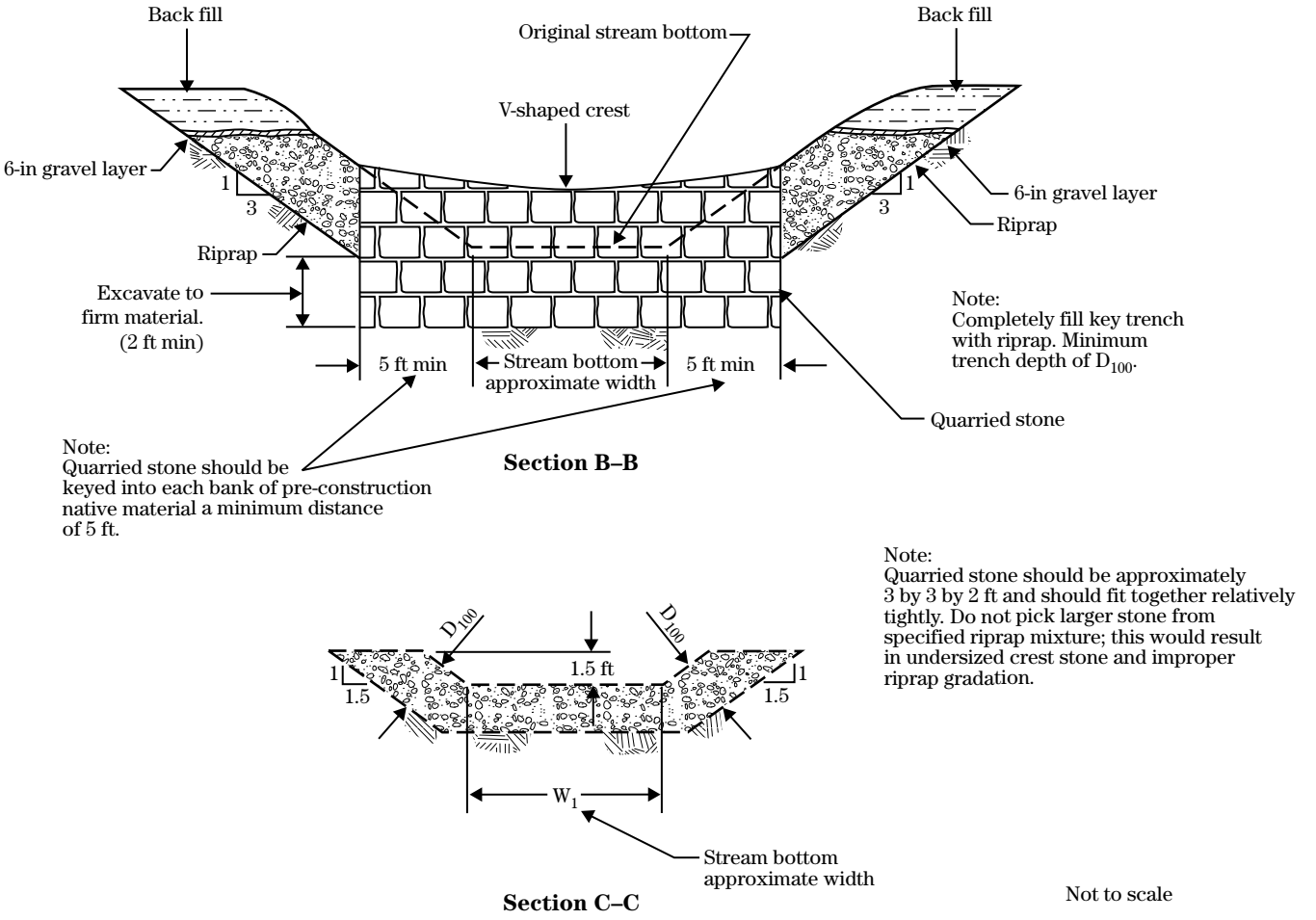
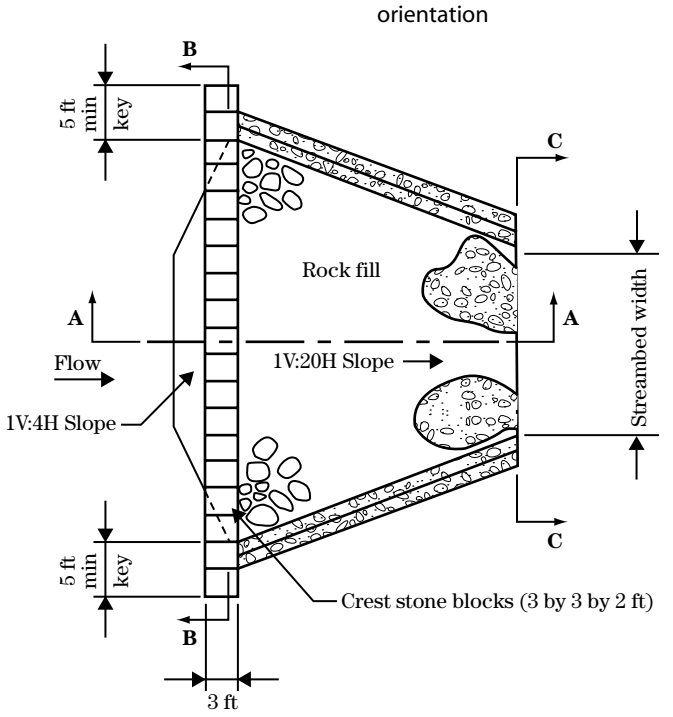
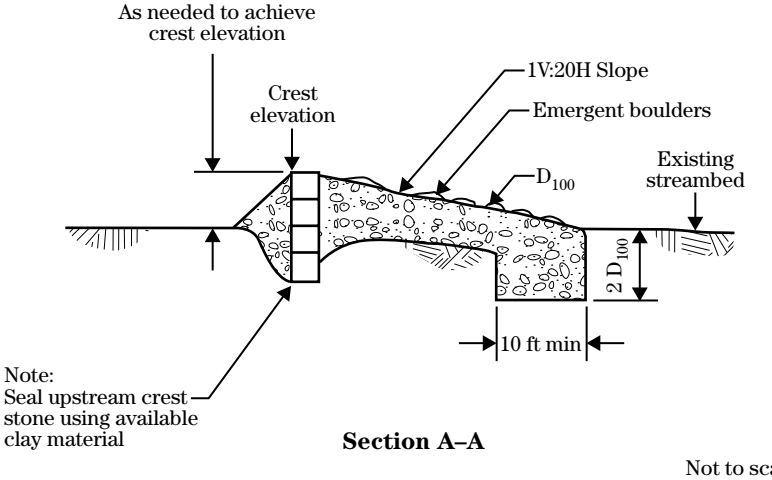


Figure TS14G–24 Grade control design (Blue Creek, IL)



Plan



Section A–A

Not to scale

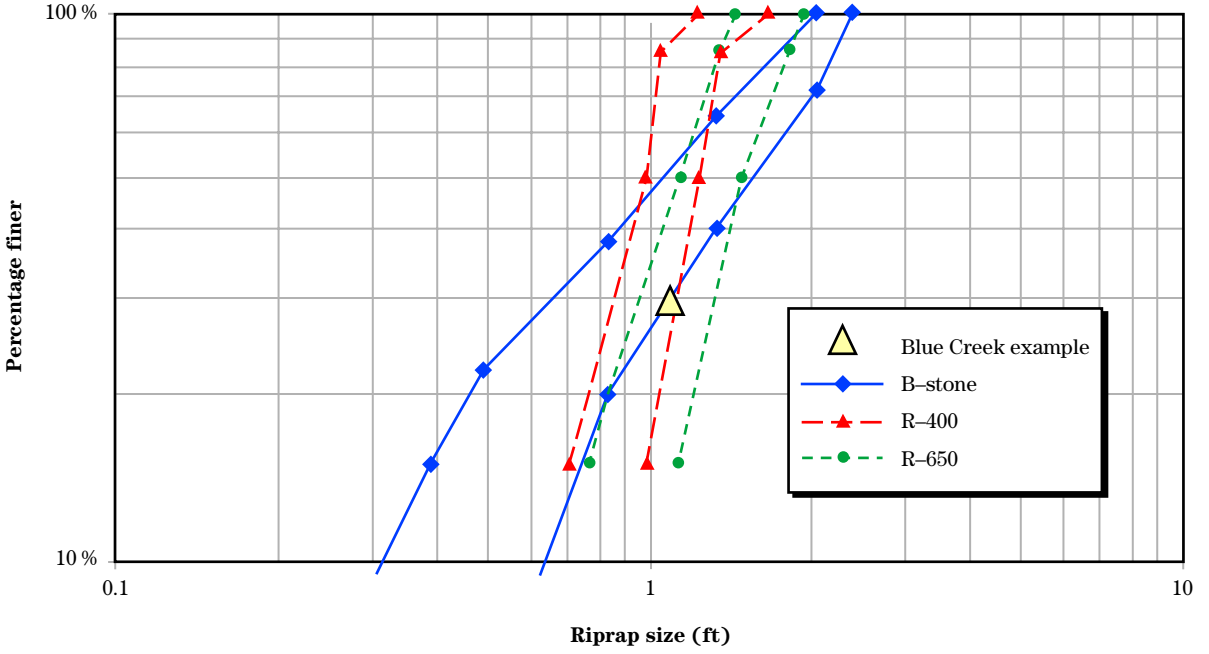



Figure TS14G–25 Riprap gradations for B-Stone, R–400, R–650, and D_{30} from the Blue Creek example