TDOT DESIGN DIVISION

DRAINAGE MANUAL

CHAPTER XI
NATURAL STREAM DESIGN

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SECTION 11.01 – INTRODUCTION

This chapter will present the procedures, methods, and available mitigation measures to be used by the Tennessee Department of Transportation (TDOT) Design Division for the proper design of stream relocation plans using natural stream design and construction methods. The information is presented with the assumption that the designer is familiar with road and bridge design and understands the basic principles of hydrology, hydraulics, and stormwater runoff typically encountered on a roadway project. In many circles, the terms “stream” and “channel” are used interchangeably; however, for the purposes of the content of this chapter, a stream or channel is generally considered any watercourse with flowing water and/or designated by an outside agency as a stream. For design guidance on smaller conveyances (roadside ditches, median ditches, etc.), the designer should refer to Chapter 5 of this Manual.

While the guidelines and criteria presented in this chapter are to be used for typical TDOT stream relocation designs, it is not an all-encompassing guidance document. Stream relocation and habitat restoration using natural stream design principles and procedures is a specialized design field, which requires an experienced designer. While this chapter seeks to simplify the standards of practice for typical stream relocations, there may be instances in which the designer may need to consult an outside reference to address a particular design issue or complexity. In particular, the Natural Resource Conservation Service’s *National Engineering Handbook, Part 654 Stream Restoration Design*, August 2007, may prove useful.

This chapter does not discuss watershed hydrology and hydrologic methods for determining flood discharges to be used in natural stream design. However, it does provide information necessary for determining the channel forming discharge and other low flow parameters. It is assumed that the designer has the prerequisite knowledge of watershed hydrology and a basic understanding of the available methods for determining flood discharges for a given watershed and frequency. Details on those methods are provided in Chapter 4 of this Manual.

The primary intent of a stream relocation design that incorporates natural design and mitigation measures is to minimize impacts to the stream that will be affected by a roadway project by mimicking the environmental features of the overall existing stream reach; thereby reducing the potential for adverse effects to the physical, biological, chemical, or habitat present in the existing water resource. The goal of this chapter is to assist the designer in formulating a stream relocation plan that will achieve the intended purpose and project goals at a reasonable cost. Towards that end, this chapter will provide information and guidance on:

- The fundamentals of natural stream relocation and channel design
- Guidelines and criteria for the project designer to meet project goals
- Mitigation practices available for use as part of a natural stream design plan
- The development of an sound and effective stream relocation plan
- Stream relocation plan requirements for TDOT projects

Natural stream design brings together many different factors that affect the physical and ecological characteristics of the stream; thus, a successful design will involve input from a number of divisions within TDOT. Table 11-1 provides a general summary of the typical roles filled by various TDOT divisions in the natural stream design process. Because every stream relocation project will present a unique set of circumstances, the specific role played by each division may vary based on the needs of the project. The Design Division’s role in the design development process will be to coordinate the needed inputs from each division and to develop the natural stream design sheets for the overall plan set. More information about the plan development steps presented in Table 11-1 may be found in Section 11.06.

	Plan Development Step	Division(s)	Plan Development Stage
1	Identify potential need for a stream relocation	Short Range Planning, Environmental Division	Planning
2	Determine whether natural stream design will be required	Environmental Division	Preliminary
3	Environmental Boundaries and Environmental Commitments	Environmental Division	Preliminary
4	Design planform, profile, and cross section of the stream	Design Division or Hydraulics Section	Right-of-Way
5	Develop mitigation features (planting schedule, stream mitigation measures, etc.)	Design Division or Hydraulics Section	Right-of-Way
6	Permits (ARAP, 404, etc.)	Environmental Division or Hydraulics Section	Right-of-Way
7	Construction	Construction Division	Construction
8	Monitoring	Environmental Division	Post-Construction
9	Maintenance	Maintenance Division	Post-Construction

Table 11-1
TDOT Division Inputs to the Natural Stream Design Process

SECTION 11.02 – DOCUMENTATION PROCEDURES

The designer will be responsible for the documentation of the design analyses of all stream relocations on the project. As a general principle, the documentation maintained should not be excessive. Rather, the documentation should be sufficient to answer any reasonable question that may arise in the future regarding the proposed stream relocation.

The documentation should be stored in a project folder and should be organized by roadway stationing from the beginning to the end of the project. It should include a discussion of any unusual features or conditions within the project and the assumptions and design decisions made to accommodate these special conditions. Further, any assumptions made during the design of stream relocations should be clearly and concisely documented. Where the relocation project is designed by other than normal or generally accepted engineering procedures, or if the design is governed by factors other than hydrologic or hydraulic factors, a narrative summary detailing the design basis should be included. Additionally, any environmental or other special considerations which may have influenced the natural design parameters of the stream relocation should be discussed.

The documentation requirements for stream relocations using natural stream design principles are similar to those for roadside ditches or other channels, but may necessitate additional information as follows:

- Method used for determining water surface elevations
- Reference reach measurements (bank full width, discharge and depth, valley slope, channel slope, bed material characterization)
- Water surface profiles through the study reach and methods used for computing
- Natural methods used in the stream and/or along the banks and reasoning for use
- Right-of-way and easement requirements for post-construction access
- Plant schedule with planting diagrams
- Post construction monitoring plan or schedule

If computations are performed by hand, copies of the completed worksheets and notes should be included in the project file. When computerized computations are employed, this information should be included along with the input data used for the program. Otherwise, it will be necessary to label output files by hand. Input and output files from computer analysis should be clearly identified with a project description, type of calculation, roadway station, name of designer, and date of computation. The following items should be included in the documentation file when computer calculations are performed:

- Printout of input data and program output, or a computer disk containing the input and output files. When the output file is only a few pages, both may be included.
- File names and dates
- Software used for analysis
- Written description of any methods used in spreadsheet computations, if necessary

SECTION 11.03 – FUNDAMENTALS OF NATURAL STREAM DESIGN

This section provides a basic introduction to the principles that should guide a natural stream design. The focus of this section is on the science of natural stream design, while Section 11.04 provides the guidelines and criteria which should govern the design decisions required for the process. The information presented in this section is not exhaustive, and a deeper understanding of the natural stream design process can be gained from the references listed in the Appendix.

Occasionally, environmental issues will necessitate natural stream design for the relocation of an existing stream or channel in order to ensure that the relocated stream will provide the same function and benefits which were available in the original stream. The designer's primary role in this process is to determine the physical characteristics of the relocated channel in terms of four basic elements:

- cross sectional shape and dimensions
- vertical profile of the stream flow line (or thalwag)
- horizontal planform of the channel
- mitigation practices

Usually it will not be sufficient to simply copy the form of the existing stream to the form of the relocated stream. A proper natural stream design should result in a stream reach which integrates well into the larger existing stream system. To accomplish this, the principles of sediment transport should be applied to ensure that the relocated stream will be stable, that is, that it will not change significantly over the long-term.

The form of an existing stream is the result of the combined effects over time of several factors acting in the stream corridor. Some of these are:

- the variability and intensity of the flow of water
- the quantity of sediment in the water
- geology of the stream bed
- shape and alignment of the channel
- slope of the channel and floodplain
- floodplain land uses
- vegetation

All of these factors are interconnected. If one factor is changed, an imbalance is created with the other factors. As a result, the form of the stream will change in such a way that balance is restored. Natural stream design should be conducted with an understanding of these factors and how they affect the form of the stream.

The completion of a natural stream design should be a cooperative effort between the designer and the Environmental Division. The designer should use the principles of sediment transport to determine the form of the relocated stream so that it will remain stable over time. In addition, the designer should select the stream mitigation measures needed to complete the natural design of the relocated stream. Once that has been accomplished, the biologist will add the vegetation. It is possible that the vegetation specified by the biologist will affect the assumptions made by the designer in the sediment transport analysis. Thus, the final natural stream design should be the result of coordination between the designer and the biologist.

11.03.1 CHANNEL TYPES

One of the most basic ways to classify a channel is to examine the nature of the interaction between the sediments within the channel and the flows which pass over them. This classification is important because it will determine the approach used to design a relocated channel. Under this method of classification, the two general categories for channels are *threshold* and *alluvial*.

A ***threshold channel***, as seen in Figure 11-1, is defined as a channel in which channel boundary (bed and bank) material has no significant movement during the design discharge. The term threshold is used because the shear forces imposed on the channel by the design discharge are below the threshold for movement of the boundary material. Threshold channels do not have the ability to quickly adjust their geometry because the material forming the channel boundary is not erodible within the normal range of flows. Thus, there is no significant exchange of sediments between the bed and the flowing water. Any sediments being carried by the water usually consist of fine particles which pass through and are thus termed wash load. Generally, wash load should not be considered part of the bed-material or sediment load for stability design purposes even if there are temporary deposits on the streambed at low flow.

Figure 11-1
Example of a Threshold Channel with Bedrock
Location: Furnace Branch, Wayne County, Tennessee (2010)

Threshold channels include cases where the bed is composed of coarse particles such as cobbles and boulders, or a vegetative lining, such as grass. Man-made channels are also usually threshold channels. Streams with exposed bedrock should not automatically be considered threshold streams. While the bottom of the channel may be considered immobile, the banks may be composed of unconsolidated material. Thus, the stream could be subject to lateral migration and might need to be analyzed as an alluvial stream.

An ***alluvial channel*** has a bed and banks which are composed of material that can be transported by the stream under design flow conditions. Thus, there is an exchange of material between the inflowing sediment load and the bed and banks of the stream. Because of this, natural alluvial channels adjust their width, depth, slope, and planform in response to changes that may occur in the amount of water or sediment discharged through the stream. Since these changes are part of the normal conditions of the stream, an alluvial channel can experience bank erosion or even lateral migration and still be considered stable. This is discussed in more detail in the following section. An example of an alluvial channel can be seen below in Figure 11-2.

Figure 11-2
Example of an Alluvial Channel
Location: Sulphur Branch, Overton County, Tennessee (2010)

The classification of a stream as threshold or alluvial is fundamental to the natural stream design process because it will determine the procedure to be used for the design of the relocated channel. However, the designer should consider factors which could affect this classification. For example, threshold streams can become alluvial for discharges greater than the design discharge (e.g. for a large flood event like the 50 or 100-year storm) since the greater shear stress may be sufficient to erode the channel materials. On the other hand, the removal of smaller sediment particles by a large flow may leave behind a layer of coarser particles which would not be moved by the design discharge. This armor layer can greatly reduce erosion in the channel for smaller, more frequent storm events.

11.03.2 DEFINITIONS OF CHANNEL STABILITY

A channel is considered stable when its average geometric properties (cross sectional area, depth, etc.) do not change significantly over time. In contrast, an unstable reach will experience aggradation, which is the net accumulation of sediment over time, or degradation, which is the net removal of sediment over time.

A threshold channel (as well as an engineered channel such as a roadside ditch) is considered stable because it will not be eroded by the shear forces imposed by the design discharge. Since the shear forces imposed by the design discharge are not sufficient to mobilize the material that make up the bed and banks, the planform, cross section, and longitudinal profile of the channel do not change significantly over time. On the other hand, the flows are sufficient to flush the wash load from the channel so that deposition will not occur.

The definition of stability for an alluvial channel is more complicated. An alluvial stream is considered stable when it has the ability to pass the incoming sediment load without significant degradation or aggradation. Because erosion and deposition can both occur in an alluvial channel at the design discharge, the channel shape, vertical profile, and planform, will change over time. However, because erosion and deposition occur in a dynamic equilibrium, the average values for the geometric parameters of the channel are generally constant.

11.03.2.1 FACTORS AFFECTING ALLUVIAL CHANNEL STABILITY

E. W. Lane proposed a conceptual model that can be used as an aid to qualitatively assess stream responses to changes in flow, slope, and sediment load. This model is known as Lane's Balance and is based on the general theory that if the force applied by the flowing water on an alluvial channel boundary is balanced with strength of the channel boundary and the delivered sediment load, the channel will be stable and neither aggrades nor degrades. This equilibrium condition can be expressed as a balance of four basic factors:

- sediment discharge, Q_s
- median grain size of bed material, D_{50}
- dominant discharge such as the channel forming discharge, Q_{cf}
- thalweg slope or energy slope, S

As shown in Figure 11-3, this balance can be expressed in the proportional relationship

$$(Q_s)\times(D_{50})\propto(Q_{cf})\times(S) \tag{11-1}$$

Lane's relationship suggests that a stream will remain in equilibrium as along as these four variables are kept in balance. If one variable changes significantly, the stream will respond by aggrading or degrading, until another variable has been adjusted to restore the balance. For example, if changes to side ditch grading for a road project were to increase the drainage area of a stream, the increased stream flows would create a disequilibrium condition for which an increased sediment supply would be needed. This sediment supply would be obtained by eroding the channel and banks, with the result that the channel would begin to degrade. This degradation of the channel would continue until the slope of the stream is sufficiently reduced to rebalance the equilibrium.

Lane's Balance is a conceptual relationship that is applicable to most streams and rivers. However, experience and sound judgment are required in order to properly use the relationship to predict the response of a stream to a given change. Because it is a conceptual model, Lane's Balance does not indicate which variable will adjust, the magnitude of the adjustment, or the timeframe that would be involved. An analytical sediment transport analysis would be needed to make detailed predictions.

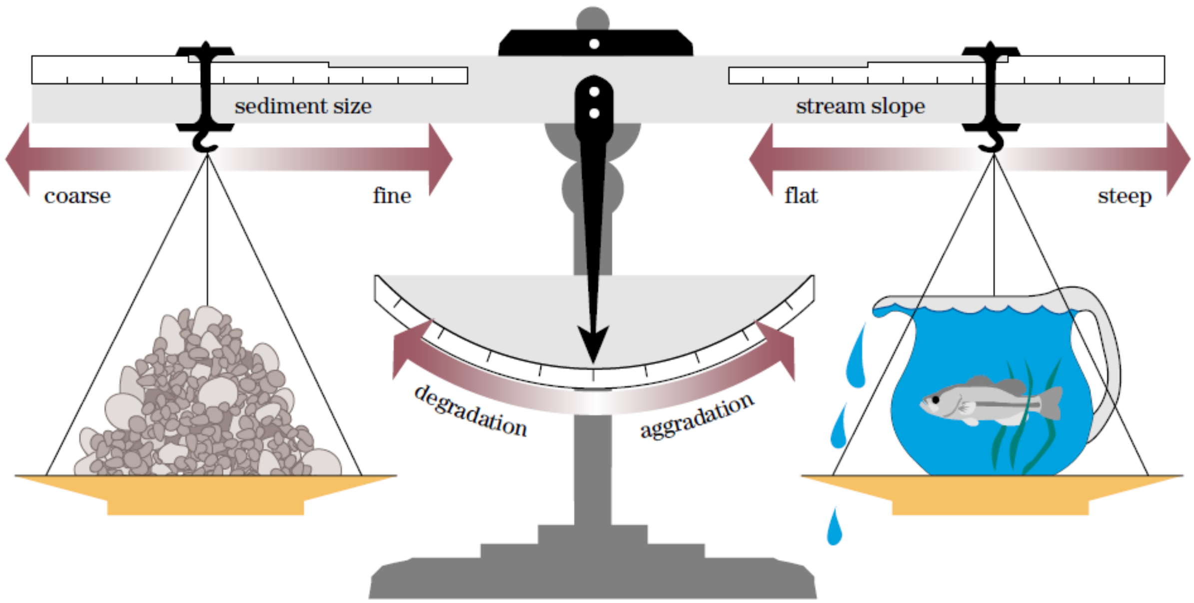


Figure 11-3
Lane's Balance Depicted
Reference: NRCS, NEH 654, Federal Interagency Stream Restoration Working Group (FISRWG) (1998)
(From Rosgen (1996), from Lane, Proceedings (1955), published by ASCE).

11.03.2.2 SEDIMENT TRANSPORT

Although the analysis of sediment transport is an essential element of natural stream design, it can be complicated due to the wide variety of mechanisms which can occur as sediment is carried in stream flow. An understanding of these complexities is needed to be able to select appropriate methods and successfully conclude an analysis. Ideally, the sediment analyses required for alluvial channel design should be conducted by individuals who have sufficient background and experience in the principles of sediment transport.

The science of sediment transport can be summarized simply as the study of the interaction between flowing water and the soils in a stream channel. As discussed in Chapter 5, the movement of water across a surface such the bottom of a channel exerts a shear force which is able to erode (or mobilize) the soil particles on that surface. The sediments that form the channel of an alluvial stream are typically composed of particles which have a variety of sizes, and each particle size has a characteristic level of shear stress at which it would become mobilized. Thus, as the depth or velocity increases in a channel, the size of a particle that can be mobilized by that flow will become greater.

While the flow in a channel may impose sufficient shear to mobilize soil particles of a given size, it may not have the capability of carrying all of the particles of that size that would be available in the stream bed. The capability, or power, of a given flow condition to carry sediment will depend on the flow velocity and the quantity of discharge. Once a soil particle has been mobilized, it will tend to settle back out of the flow at a fall velocity which is a characteristic of the size and shape of the particle. Thus, for a given size of particle in a given flow condition, an equilibrium will be reached between the soil particles being mobilized and the particles settling out. Typically, soil particles will be mobilized from one area within the channel and then settle out in a different area, with the effect that the shape and location of the channel will change over time. Because of this interaction, the channel boundary (i.e. – the interface between the water and the sides and bottom of the channel) for an alluvial channel is not as clearly defined as it would be for a threshold channel.

The quantity of sediment present in a stream flow is measured in different ways depending on the methods used for the sediment transport analysis. The two most common means of measuring sediment discharge are either as a concentration in parts per million (PPM) or as some measure of weight per time. Weight per time is essentially the quantity of sediment that would pass through a channel cross section in a given period of time, and is usually expressed as tons per day or pounds per day. However, some methods may be based on sediment discharge per unit width, which is the weight of sediment which would pass through a one (1) foot wide slice of the channel. This is usually expressed as pounds per second-foot (lb/sec-ft). Section 11.05 presents methods for converting between the various units used to measure sediment discharge.

Sediment can be transported by a stream in three different modes:

Wash load usually consists of fine particles such as silts or clays. Because these particles have relatively low fall velocities, they are typically carried through a stream reach with negligible interaction with the stream bed. Because of this, wash load is typically not a part of sediment transport analysis for evaluating stream stability.

Suspended load typically consists of sand-sized particles which are carried in the flow above the stream bed. Because these particles have a somewhat greater fall velocity, the rates at which they are mobilized and settle will be in some type of equilibrium as described above. In sand bed streams, this equilibrium results in regular patterns on the bottom of the channel known as bed forms. As described below, bed form can have a significant impact on the analysis of sediment transport.

Bed load typically consists of gravel, cobbles, or larger particles which cannot be fully taken up into suspension. These particles move along the channel bottom by rolling, sliding or even hopping.

The interaction between flowing water and the sediments in sand bed streams usually results in distinct types of bed forms, as shown in Figure 11-4. In smaller streams with relatively flat slopes, these bed forms frequently appear as ripples, which may be only a few inches to a few feet in length. Larger streams with greater discharges can demonstrate the same type of form on a larger scale, and these forms are known as dunes. Streams with higher velocity flows can form either a plane bed, or antidunes. Anitdunes are unique in that the water surface will tend to follow the form of the antidunes, whereas the water surface profile is relatively independent of the other types of bed form (although there are reasons for arguing that the flat water surface profile on a plane bed is actually following the bed form).

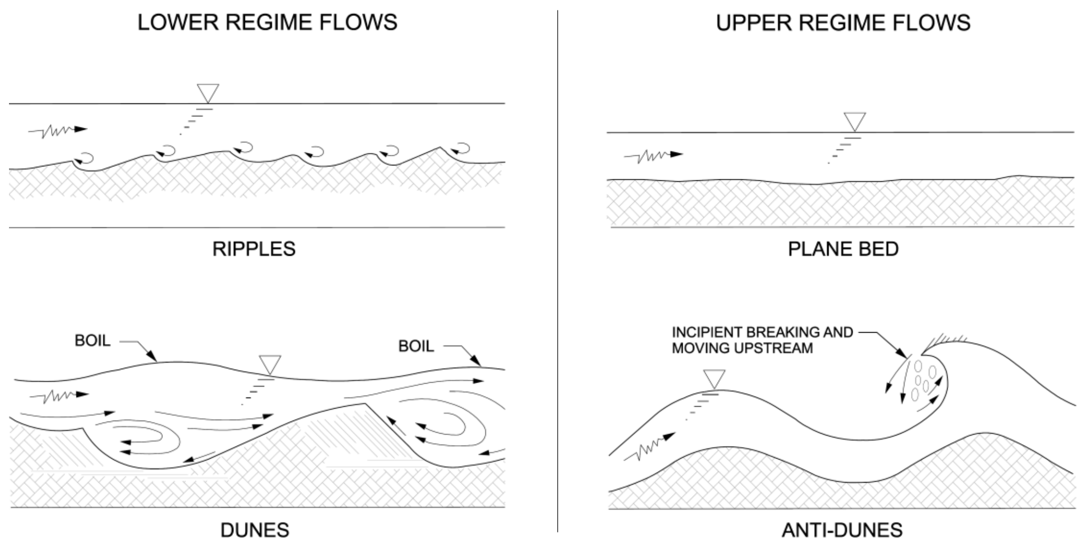


Figure 11-4
Possible Bed Forms in Sand Bed Streams
Reference: Adapted from Dept. of Interior, USGS, Fort Collins, Colorado (1963)

Bed form is important to the analysis of sediment transport because of the effect that it has on the roughness of the channel. Ripples and dunes can significantly increase the total roughness of a stream channel, while antidunes or a plane bed may affect the overall roughness to a much lesser extent. One of the results of this is that the sediment transport characteristics of one type of bed form are quite different than the characteristics of the other type. A further complication is that the bed forms of a river can evolve during a large flood event. As the discharge increases, the bed forms can go through a process in which they change from ripples to dunes, from dunes to a plane bed, and from a plane bed to antidunes. This process may then be reversed during the falling limb of the runoff hydrograph.

Flow in sand-bed streams can generally be divided into two main regimes with a transition zone in between. Because ripples and dunes occur on streams with flatter slopes, they are associated with **lower regime flows** (tranquil flow). With lower regime flows, the resistance to flow is relatively large and caused mainly by the form roughness which causes turbulence and energy dissipation. The amount of sediment transport is expected to be small in the lower regime. Both ripples and dunes are characteristic of subcritical flow (Froude number below 1) and generally migrate downstream.

Upper regime flow is normally characterized by significant sediment transport and a relatively small resistance to flow. Plane beds and anti-dunes occur with higher velocity flows (but not necessarily supercritical flow) and are associated with the upper regime flows. The most common type of anti-dune migrates in the upstream direction, and typically shows little, if any asymmetry. With upper regime flow, the method of transport for sediment is generally for the individual grains to roll continuously downstream in sheets, one to two diameters thick.

In order to deal with these regime complexities, most methods for the analysis of sediment transport evaluate the roughness of the stream bed separately from the rest of the channel. In other words, the bottom and sides of the channel are conceptually divided into separate elements, each having a distinct roughness value. These roughness factors can then be used in a re-arranged version of Manning's equation (see Section 11.05.4) to derive separate values for hydraulic radius, which are then used in the sediment transport equation. In this way, the sediment transport analysis accounts for both hydraulic conveyance and sediment transport. It is important to note that the hydraulic radius values determined in a sediment transport analysis are conceptually different than the hydraulic radius which may be computed for a normal depth calculation and the two types of calculation should not be confused.

The definition of the bed versus the banks of a channel should also be considered. For the purposes of sediment transport analysis, the bed of the channel is the area over which the majority of the sediment transport takes place. It is the area over which bed load is transported as well as where smaller particles are taken up into suspension or settle out. The sloping sides of the channel contribute to the overall channel roughness, but usually have a much smaller role in the interaction between the sediments and the flowing water. Where a sediment transport analysis requires a value for the bottom width of the channel, the value used should be representative of the width over which active sediment transport will occur.

Two different sediment transport computation methods are recommended for use with TDOT stream relocation projects. Each of these methods consists of a basic sediment transport equation which is supplemented by a set of equations for evaluating the roughness of the bottom and sides of the channel. The ***Brownlie*** method is considered a total load model in that it accounts for both suspended and bed loads. It also is able to account for the varying roughness that occurs with different bed forms. However, because this method was developed using data from sand bed channels, its applicability to gravel bed streams is questionable. The ***Meyer-Peter and Müller*** method is recommended for gravel bed streams. This method accounts for the roughness of the material on the bed of the stream (as opposed to bed form) and was developed for particle sizes as large as 1 inch in diameter. Details on applying these methods are provided in Section 11.05.4.

The results of any sediment transport analysis should be interpreted with caution. In general, the reliability of the results from a sediment transport analysis may be relatively poor. It has been found that the sediment loads predicted by even the best methods may yield results that are 50 percent lower, to as much as 200 percent more, than that of the actual observed sediment loads only about 75% of the time. Even this conclusion is subject to the difficulties inherent in measuring the sediment present in a stream flow. The sediment transport equations and the available software packages are rather sophisticated and may give the impression that the results are accurate. However, the results of these methods should be checked against the actual conditions noted in the field.

11.03.3 FLOW REGIMES

The concept of flow regime refers to the amount of time that a stream will experience sustained flows. The most common sources of stream flow are direct runoff from a rainfall event, or base flow, which is the result of ground water that seeps into the stream channel. The flow regime can have a significant effect on the methods used to design the channel relocation. Thus, streams can be classified into three different regimes based on the source of the flows they experience.

A ***Perennial*** stream has flowing water year-round during a typical year. The flow line of a perennial stream usually intersects the water table in the localities through which it flows. This provides a relatively constant supply of base flow which sustains the flow between rainfall events. For these streams, runoff from rainfall is only a supplemental source of stream flow. One way to define a perennial stream is that it will exhibit a measurable discharge more than 80 percent of the time.

An ***Intermittent (or seasonal)*** stream flows only at certain times of the year when seasonal high ground water levels intersect the stream flow line and groundwater is available to provide base flow. During dry periods, intermittent streams may not have flowing water. Runoff from rainfall may be a larger component of the stream flow, but is still considered to be a supplemental source. One way to define an intermittent stream is that it typically will flow continuously for periods of at least 30 days.

An ***Ephemeral*** stream has flowing water only during, and for a short duration after, precipitation events. There is no base flow component for an ephemeral stream because its flow line is above the water table year-round. Thus, runoff from rainfall is the only source of stream flow.

11.03.4 INFORMATION NEEDED FOR NATURAL STREAM DESIGN

To provide a complete natural stream design for a channel relocation project, the designer should gather the data necessary to:

- evaluate the stability of the existing channel
- classify the existing channel as threshold or alluvial
- complete an hydraulic analysis of the existing and proposed stream channels
- design revetments to ensure the stability of the relocated channel
- conduct a sediment analysis, if needed
- coordinate the natural stream design with the Environmental Division

The required information can be obtained from a variety of sources. Much of it will already be contained in the project plans or site survey. A larger view of the overall stream corridor can be obtained from aerial photography and USGS quadrangle mapping. Ground level photography of the site is also an essential source of information. In addition, the Environmental Boundaries (EB) document provided by the Environmental Division should be consulted. Finally, it is also strongly recommended that the designer conduct a site visit to evaluate the existing site conditions and gain a personal familiarity with the site.

The following sections deal with the specific types of data that should be obtained before designing a stream relocation. One of the most fundamental factors to be considered in the process of collecting data on any stream is whether the existing channel is stable. If the existing channel shows evidence of aggradation or degradation the designer should approach the proposed design with caution so that an existing stability problem will not be duplicated in the relocated channel.

11.03.4.1 LENGTH, SLOPE, AND SINUOSITY

Length, slope and sinuosity are the basic parameters which define the planform of a stream. Each of these parameters has an effect on the hydraulic performance and habitat values offered by a stream. Thus, determining values for these parameters that will be consistent with the overall stream system is one of the important goals of a natural stream design. Thus, measuring these parameters for the existing stream should be one of the first steps of the design process.

Although measuring the length of the existing stream may seem to be straightforward, there are two ways to approach this measurement. The first way to measure the length is along the flow line (thalweg) of the channel. This measurement will help ensure that the length of the relocated reach will match the length of the existing reach. This will also help ensure that the slope of the proposed channel will match the slope of the existing channel. The second way to measure the length of the stream is along the valley. This is usually the length measured along a straight line connecting the ends of the reach to be relocated. However, when the valley itself is curved, it may be preferable to measure along the valley centerline. These two ways of measuring length are used in computing the sinuosity of the stream, as described below.

The slope of the stream is used in a variety of calculations in support of a natural stream design. Just like the length of the stream, slope should be considered at two scales: along the overall floodplain and along the centerline of the existing stream channel. While these two slopes may often be similar, they may be different on a stream with a significant degree of sinuosity. In addition, the slopes will be used for a variety of different purposes which will affect the means by which they are measured.

The longitudinal slope of the existing floodplain is primarily used to determine the starting elevation for the hydraulic analysis of the stream. This analysis is used to determine flood elevations for the design discharge for both the existing and proposed conditions. Thus, it is important for this slope to be representative of the overall slope of the water surface at flood stage. In order to achieve this, the designer should consider both the project survey and larger scale topographic mapping. Typically, the project survey should include flow line points (or at least cross sectional data) both upstream and downstream of the reach being relocated, and these points should be considered in determining the slope. However, the stream slope determined from the project survey should be evaluated before it is applied in the hydraulic analysis of the stream. This slope should be examined for consistency with the overall valley slope as determined from topographic mapping. If the local slope determined from the cross sections is significantly different than the slope determined from the mapping, the generalized slope from the topographic mapping may yield a more accurate hydraulic analysis.

Where possible, the hydraulic model should include a number of cross sections downstream of the reach to be relocated. This will allow the hydraulic model to stabilize prior to the start of the project reach and will provide a more accurate assessment of the water surface elevations in the project area.

It is also important to determine the slope of the stream along the flow line of the channel. This is the slope that is used in sediment transport calculations and in the hydraulic computations needed to determine the bankfull discharge. In longer reaches, it may be necessary to consider the overall consistency of the channel slope. If different parts of the profile are at different slopes, it may be necessary to evaluate each of them separately.

Calculating the slope along the flow line may also require an evaluation of the structure of the existing profile. On a stream with a significant pool and riffle structure, the slope should be evaluated based on the elevations of the stream at the beginning of each riffle section, as shown in Figure 11-5. Where pools and riffles are not present in the stream profile, the lowest streambed elevations should be used to compute the slope of the channel bed.

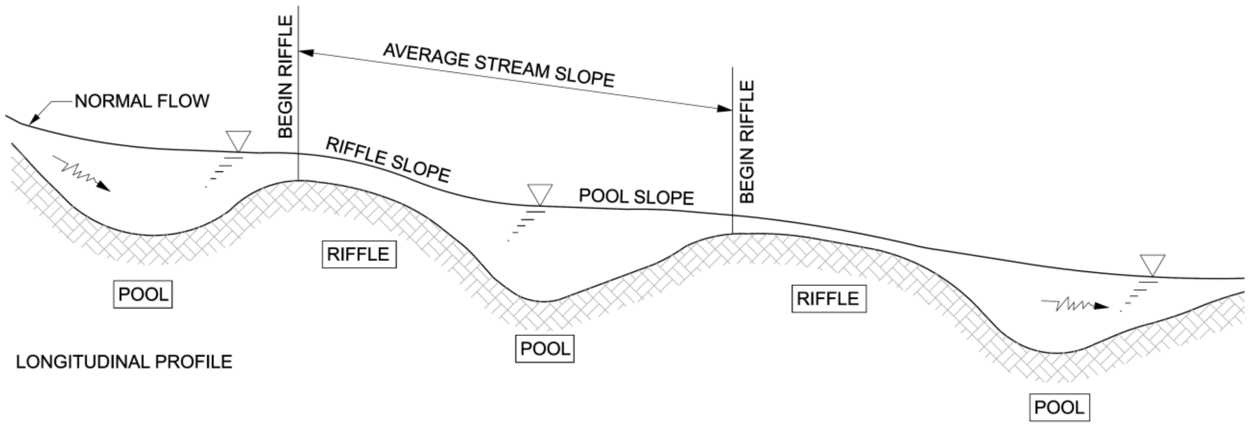


Figure 11-5
Computing Stream Slope for a Pool and Riffle Stream Structure

In designing a relocated stream, it is not sufficient to simply duplicate the length of the existing stream. Within the limits imposed by the site, an effort should be made to match the sinuosity of the existing planform. As shown in Figure 11-6, sinuosity is the ratio of the length of channel measured along its centerline to the length measured along a straight line connecting the ends of the reach to be relocated. When the valley itself is curved, it may be preferable to measure along the valley centerline. Straight stream reaches have a sinuosity ratio of one, and the maximum value of sinuosity for a natural stream is approximately four.

In attempting to match the sinuosity of the existing stream, the designer should also consider four parameters, which further describe the meandering of the stream. As shown in Figure 11-7 these meander characteristics are wavelength, amplitude, radius of curvature, and arc angle. Procedures for calculating sinuosity and determining the other meander characteristics are provided in Section 11.05.

When measuring the planform of an alluvial stream, an effort should be made to consider the effect that the proposed stream relocation would have on the morphology of the overall stream system. An alluvial stream system can be stable but still subject to lateral migration. Thus, an effort should be made to consider the effect of the proposed stream relocation on both location and likely direction of any future planform changes. This should include considering the composition of channel bed materials, as well as noting the presence of large point bars or channel “cutoffs.” These factors should be considered to ensure that changes to flow patterns due to the channel relocation will not result in unintended consequences to the morphology of the relocated stream channel as well as to the overall stream system.

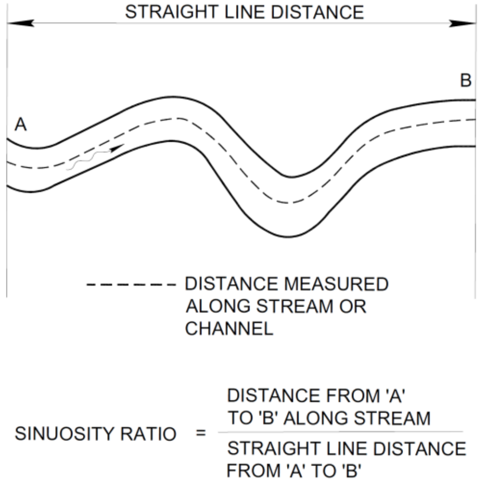
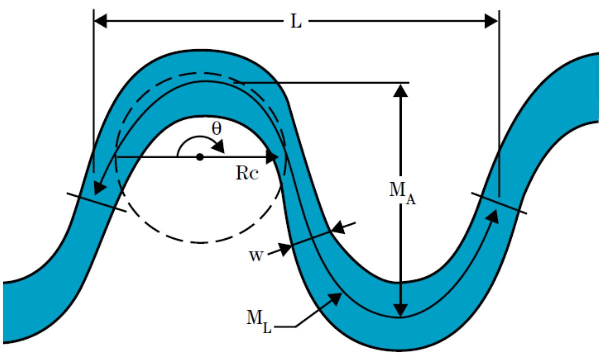


Figure 11-6
Sinuosity Ratio Illustrated



L Meander wavelength
M_L Meander arc length
w Average width at bankfull discharge
M_A Meander amplitude
Rc Radius of curvature
θ Arc angle

Figure 11-7
Meander Characteristics Defined
Reference: USDA, NRCS, NEH Part 654 (2007)

11.03.4.2 EXISTING CHANNEL CROSS SECTIONS

Cross sectional data on the existing stream will be used for two primary purposes. The first will be to collect data for the hydraulic analysis of the existing stream and the second will be as a guide for determining cross sections for the relocated channel. The type of cross sectional data to be obtained may be different for these two purposes.

The cross sections obtained for the hydraulic analysis should be representative of the overall shape of the channel and overbanks and should represent average conditions in the existing stream. Cross sections should be placed in the hydraulic model as needed to capture the effects of any expansions or contractions in the flow width and upstream and downstream of any bridges and culverts. They also should be long enough to extend across the entire 100-year floodplain. In some cases, it may be possible to supplement the surveyed cross section data with other existing topographic mapping to construct a complete valley cross section. Additional cross sections should be obtained beyond the reach being relocated to accurately determine the tailwater condition for hydraulic analysis. Extending the hydraulic model past the relocation reach will also assist in evaluating the impact of the relocation on the overall stream system and on any upstream properties that may be in the floodplain.

The existing channel cross sections should also be used as a guide in determining the typical cross section of the relocated channel. The cross sections obtained for this purpose should be selected based on a consideration of the existing channel structure. Where the existing channel shows a pool and riffle structure, cross sections should be obtained on each riffle and at the midpoint of each pool. The pool cross sections and the riffle cross sections should be considered separately so that the relocated channel can be provided with pools and riffles which match the existing condition.

Each of the cross sections should be examined to determine the width between the banks, bottom width, and depth. For longer reaches, there may be cross sections from multiple pools and riffles. Where practical, the relocated channel should be designed to duplicate the variability of these parameters for both types of cross sections.

11.03.4.3 EXISTING CHANNEL PROFILE

The profile of a channel usually exhibits a definite structure which helps to provide many of the habitat values available in a stream. Thus, determining the existing channel profile should be considered important when designing a relocated stream.

Although a number of possible types of channel profile structure can occur, the most common, especially in natural alluvial streams, is a pool and riffle structure, which is illustrated in Figure 11-8. A pool and riffle structure is characterized by alternating, regularly spaced, deep (pool) and shallow (riffle) areas. Pools typically form where the flow line approaches the outside bank of the channel at bends, whereas riffles usually form between channel bends in the zone where the flow line migrates from one side of the channel to the other. The composition of the sediments in the streambed affects pool and riffle characteristics, as well. Streams with coarse substrates (gravel to cobble-size particles) tend to have evenly spaced pools and riffles. In such systems, cobbles and large gravels accumulate in the riffle areas, while smaller particles tend to deposit in the pools. On the other end of the spectrum, streams with sand and silt-dominated substrates do not form true riffles due to the absence of coarse grain sizes. However, they still have evenly spaced pools connected by shallower runs or glides.

Figure 11-8
Characteristic Pool and Riffle Structure
Location: Little Indian Creek, Putnam County, Tennessee (2010)

Where the existing channel profile shows a pool and riffle structure, the approximate length of each pool and riffle should be measured, as well as the depth of each pool. For longer reaches, there may be multiple pools and riffles. Where practical, the relocated channel should be designed to duplicate the variability in lengths of the pools and riffles, as well as in the depth of the pools.

11.03.4.4 TAILWATER CONDITIONS

Usually, the tail water elevations experienced at the beginning of the relocated reach will be determined by the hydraulic conveyance and downstream slope of the stream. However, tailwater elevations can often be significantly increased by downstream conditions including impoundments, obstructions, channel constrictions, and junctions with other watercourses. Therefore, conditions which might promote high tailwater elevations during flood events should be investigated and evaluated before any hydraulic analysis of the stream is conducted. The presence of such conditions can often be determined from field observations or topographic maps.

When high tailwater conditions result from the existence of a stream junction near the project site, the designer should evaluate whether flood elevations on the receiving water body should be considered. In general, if flood discharges on the two streams are likely to peak at about the same time, it would be acceptable to consider the higher tailwater in the analysis of the stream relocation. However, if the peak discharge times are likely to be significantly different, the relocation could be designed based on the hydraulic capacity of the channel. Additional guidance on this topic may be found in the discussion of storm drain outfalls contained in the FHWA Publication *HEC-22, Urban Drainage Design Manual*.

11.03.4.5 CHANNEL STABILITY

As discussed earlier in this section, a disturbance in the existing stream system can result in some type of channel instability, which will result in either degradation or aggradation. If the existing stream is unstable, it may not be possible to provide a stable channel cross section for the proposed channel. Thus, the stability of the existing stream should be adequately evaluated before beginning a natural stream design for the relocated channel.

There are several indicators which can be used to evaluate the stability of a stream reach. If possible, these indicators should be assessed during a site visit. Stream-level photography of the site is also a useful means of documenting the assessment of the stream stability. Signs that either degradation or aggradation is taking place are as follows:

Evidence of degradation

- terraces (abandoned floodplains)
- headcuts and nickpoints
- exposed pipe crossings
- suspended culvert outfalls and ditches
- undercut bridge piers
- exposed or “air” tree roots
- leaning trees
- narrow/deep channel
- banks undercut, both sides (particularly for bedrock channels)
- armored bed
- failed revetments due to undercutting

Evidence of aggradation

- buried structures such as culverts and outfalls
- reduced bridge clearance
- presence of mid-channel bars
- buried vegetation
- significant backwater in tributaries
- uniform sediment deposition across the channel
- hydrophobic vegetation located low on bank or dead in floodplain

Evidence of stability

- vegetated bars and banks
- limited bank erosion
- older bridges, culverts, and outfalls with bottom elevations at or near grade
- no exposed pipeline crossings, bridge footings, or abutments

Failure of the channel banks can be a sign of both degradation and/or aggradation. For example, if a stream is degrading due to decreased sediment load or increased discharges, the lowering of the channel bottom will result in unstable slopes on the sides of the channel. On the other hand, where a stream has been dredged, the channel banks will frequently become unstable and “slump.” Since the stream discharges would not have sufficient power to remove the sediment from the channel banks, it collects on the bottom of the stream, resulting in aggradation.

When assessing the stability of a stream reach, the designer should look beyond the immediate relocation reach in an effort to identify outside influences in the watershed which might cause instability in the stream. These could include:

- An active construction project on the floodplain upstream of the project reach could result in a short-term increase in the sediment load.
- Recently completed construction projects which have converted a significant amount of area to pavement could result in a reduction of the sediment load, especially if runoff is contained in a detention basin.
- A new culvert or bridge crossing could result in a localized stream modification.
- Ongoing urbanization in the watershed beyond the floodplain could result in increased runoff volumes and lower but more sustained discharges in the stream due to detention basin.
- The dredging or channelization of a stream could have a variety of results due to increased flow velocity, steeper channel banks, etc.

Where any of these factors appear to be present in the watershed, Lane's Balance, as described in Section 11.03.2, can be used to qualitatively assess the impact on the stream from changes that may be occurring in the watershed. Various approaches for dealing with instability are suggested in Section 11.04.

11.03.4.6 EXISTING RIPARIAN VEGETATION

Because specific concerns regarding re-vegetation of the proposed channel will be addressed by the Environmental Division, the designer will not be required to conduct a detailed survey of the existing vegetation. The designer should coordinate with the Environmental Division with regard to the planting schedule and plant list to be added to the plans. However, during a site visit, it is useful to note locations where the existing vegetation appears to contribute to the stability of the stream channel.

11.03.4.7 HYDRAULIC ROUGHNESS

Manning's equation is an empirical relationship in which the roughness coefficient, n, is used to quantitatively express the degree of retardation of flow. The selection of a Manning's channel roughness coefficient is usually based on consideration of many factors, including the depth of flow, the season, the height of any obstructions, and the types of vegetation. Further, the selection of a coefficient for a natural stream channel is more dependent on engineering experience than for a man-made channel. USGS Water Supply Paper 1849, *Roughness Characteristics of Natural Channels,* contains photographs of channels with varying n-values and may serve a guide to the designer. This report is available on the internet by accessing the water supply papers website of the USGS. In addition, Table 5A-1 lists typical ranges of Manning's channel roughness coefficients for man-made and natural stream channels.

Manning's roughness coefficient reflects not only the roughness of the sides and bottom of the channel, but other irregularities of the channel and profile. The effect of these irregularities can be estimated for natural channels using the Cowan method. This method accounts for several primary factors in the selection of the roughness coefficients including the degree of irregularity in the channel shape and size, the types of bed materials involved, other obstructions, vegetation, and the degree of channel meandering. The method is considered reliable for cross sections with a hydraulic radius of 15 feet or less.

Cowan's equation for estimating Manning's roughness coefficients is as follows:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m_5 \qquad (11\text{-}2)$$

Where: n = Manning's channel roughness coefficient for a natural or excavated channel
n_0 = base n-value for the natural bed material
n_1 = coefficient for the degree of channel irregularity
n_2 = coefficient for variations in the channel cross section
n_3 = coefficient for relative effect of channel obstructions
n_4 = coefficient for channel vegetation
m_5 = correction factor for the degree of meandering

Table 11A-1 lists the values for use in the Cowan's equation, along with a brief description of the criteria used to select values. A more complete description of Cowan's method and Manning's channel roughness coefficients is typically available in other textbooks on open channel hydraulics.

The hydraulic roughness of the existing stream cross section may be determined by an assessment of the stream morphology, vegetation, and the composition of the materials in the stream bed. A procedure for determining Manning's n-values for the existing stream is contained in Section 11.05.4.

11.03.5 NATURAL STREAM DESIGN PROCESS

The approach used to perform a natural stream design for a stream relocation project will vary based on whether the existing channel is classified as threshold or alluvial. In either case, it may be useful to think of the design process in terms of beginning with the given information and then following a design process to determine the design parameters. (In some sources, the given information is termed the independent variables, while the parameters to be determined are referred to as the dependent variables). The design process consists of the procedures and equations needed to move from the given information to a set of completed design parameters that meet the desired design objectives.

Table 11-2 provides a summary of the design processes for threshold and alluvial streams. The given information for the design of a threshold channel usually includes a design flood discharge such as the 50-year peak flow rate. The design process then yields a channel and floodplain configuration adequate to convey the discharge at an acceptable elevation and that is lined with materials which will not be eroded in the design event. Thus, this process requires only hydraulic analysis since the design parameters (width, depth, and slope) all relate to the hydraulic conveyance of the channel. Even though this process may require some trial and error, it is relatively straightforward.

In contrast, the design process for alluvial channels is more complex, since it requires that the proposed channel be adequate in terms of both hydraulic conveyance and sediment transport capacity. While there might be any number of channel configurations that would offer sufficient hydraulic capacity within the overall stream system, not all of these configurations would be stable in terms of the sediment transport that would occur. Thus, the design of an alluvial channel will require both hydraulic and sediment transport analyses.

	Threshold channel	Alluvial channel
Channel Boundary	Immobile at design discharge	Mobile
Design Discharges	Flood event (e.g. – Q_{50})	Flood event (e.g. – Q_{50}) Channel forming discharge Flow duration curve Long-term flow record
Bed material sediment inflow	Usually small or negligible	Significant
Given Information	Design discharge channel roughness	Design hydrograph Channel-forming discharge Bed material sediment inflow Bed material Stream bank characteristics
Design Parameters	Width Depth Slope (Roughness, if there is a choice of lining materials)	Width Depth Slope Planform Bank roughness
Design Equations	Hydraulic conveyance	Hydraulic conveyance Sediment transport
Design goal with respect to channel stability	Pass the design discharge at an acceptable elevation without eroding the channel	Pass the incoming sediment load without aggradation or degradation or significant planform change

Table 11-2
Summary of the Natural Stream Design Process
Reference: Adapted from USDA, NRCS, NEH Part 654 (2007)

For an alluvial channel reach to remain stable, the sediment outflow from the reach must be equal to the sediment inflow. The width, depth, and slope of a channel have inter-related effects on its sediment carrying capacity. Thus, these three factors must be balanced so that the proposed channel will have sufficient capacity to transport both the quantity and types of sediment that will flow into it. In the initial stages of the design, it is often necessary to develop a range of stable configurations for width, depth, and slope for a given discharge, usually the channel-forming discharge. These are then plotted on a stability curve which is then used as an aid in determining a configuration that will best fit any site-specific constraints. Usually, the configuration of the existing channel is checked against this curve and is used as the basis for selecting the configuration of the relocated channel. As the design progresses, sediment transport analysis is conducted for the full range of discharges which could occur at the site. This analysis is called a sediment impact analysis and is the final check the designer should make to ensure that the relocated alluvial channel will remain stable over time.

Specific design procedures for threshold and alluvial channel design are provided in Section 11.05.

SECTION 11.04 – GUIDELINES AND CRITERIA

11.04.1 NATURAL STREAM DESIGN GUIDELINES

During project planning, the Environmental Division will go through the National Environmental Policy Act (NEPA) process to consider the environmental impact of various alternate roadway alignments. This process involves consideration of a number of alternatives including on-site natural stream design (normally the most-strongly preferred), payment of in-lieu fees to the Tennessee Stream Mitigation Program (TSMP) or mitigation on a nearby degraded stream reach. The results of this process will typically be communicated to the Design Division through the Environmental Boundaries (EB) document, which will normally include the Ecology Report, the Mitigation Memo and the Environmental Commitments. The designer may refer to the Environmental Division for more information.

Because TDOT's mission is focused on transportation, projects to enhance the habitat offered by an existing stream would not be within the scope of a normal TDOT project. Natural stream design for TDOT projects will have the goal of returning the impacted reach of the stream to a condition consistent with the existing configuration and habitat values offered by the larger stream system. Thus, the first step in designing a stream relocation project should be an assessment of the needed stream values in order to establish a basis for determining the goals of the natural stream design.

11.04.1.1 MINIMIZING OR AVOIDING IMPACTS TO STREAMS

As a general practice, the designer should make an effort to minimize or avoid impacts to a stream. To accomplish this, the designer should evaluate the information in the EB document based on the site-specific conditions encountered during the detailed design process. It may be possible to further avoid or minimize stream impacts by modifying the proposed roadway design to include steeper slopes or retaining walls.

11.04.1.2 LIMITATIONS ON STREAM RELOCATIONS

Natural stream design will be conducted by the Design Division at sites where the peak discharge for the 50-year flood event is less than 500 cfs. Design for locations where the peak 50-year discharge is 500 cfs or greater should be referred to the Hydraulics Section of the Structures Division. Further, streams listed as Outstanding National Resource Waters or Exceptional Tennessee Waters should be avoided where possible.

11.04.2 GOALS OF NATURAL STREAM DESIGN

The general goal of natural stream design for a relocated stream reach is to preserve the conditions which exist within the larger stream system. While stream enhancement is beyond the scope of TDOT's mission, the principles of natural stream design should be used to provide a relocated reach with habitat values that are consistent with the conditions found in the stream reaches upstream and downstream of the project. The relocated reach should match the existing stream in terms of:

- planform
- profile
- habitat features

- floodplain features

Although these aspects are discussed separately in this section, they should be considered to be interrelated. It may not be sufficient to simply duplicate the existing stream features. Stream systems can be extremely complex, and the designer should consider the interaction between these factors in designing a relocated channel.

11.04.2.1 PRESERVE EXISTING STREAM FUNCTION AND HABITAT

As described in Section 11.03.4, a variety of stream features contribute habitat value to a stream, including:

- channel substrate
- channel structure (both vertical profile and horizontal planform)
- channel dimensions
- variability and magnitude of flows
- frequency and extent of flows on the floodplain
- riparian vegetation

The goal of a natural stream design will be to duplicate the ecological values provided within the existing stream system. Because of the interrelationship between the features listed above, the designer should review the Ecology Report and EB as well as any environmental commitments to ensure that appropriate features are properly integrated into the relocated stream reach.

Of the features listed above, the principal role of the designer will be to determine the channel dimensions, structure, and substrate. The frequency and extent of flooding will be determined by the dimensions of the channel and the magnitude of flood discharges. Since the variability and magnitude of the discharges are a given, the designer's only means of preserving the existing behavior of the stream will be in the design of the channel. Further, the required riparian vegetation will be specified on the Planting Schedule provided by the Environmental Division.

The designer should evaluate the materials making up the channel bottom of the existing stream and, if possible, ensure that similar materials will be provided through the relocated reach. The use of native materials from the existing stream would be preferred where construction methods will allow. In many streams, the materials composing the channel bottom may vary across the existing stream reach. Riffles may be composed of gravel or coarser materials while the bottom of the pools may be lined with silts or other fine materials.

In an alluvial stream, the distribution of these sediments, both vertically and horizontally may be the result of long-term fluvial sorting processes that have taken place in the channel. Typically, it will not be practical to duplicate the exact layering of sediments, although it should be possible to duplicate the coarser materials found in the riffles. Rather, the designer should obtain the soils report and attempt to duplicate the particle size distribution found within the existing stream and then allow the natural fluvial processes to sort the materials over time.

11.04.2.2 RE-ESTABLISH STREAM PLANFORM (LENGTH AND SINUOSITY)

The two main factors related to the planform of the stream relocation are length and sinuosity. One of the goals of a natural stream design is to preserve both of these parameters in the relocated channel. Length is important because it is integral to maintaining the flood routing characteristics and stream profile.

Not all streams follow a sinuous alignment. Where present, the designer should attempt to duplicate the existing sinuosity ratio in addition to all of the meander characteristics described in Section 11.03.4. Additionally, the proposed design should be based on the relationship between sinuosity and vertical stream structure, since pools tend to form in the outside portions of the bends, while riffles tend to form in the straight sections between them.

11.04.2.3 RE-ESTABLISH STREAM VERTICAL PROFILE

The slope of a stream is vitally important due to its relationship with flow velocity, and in turn, the overall stability of the relocated channel. When considering the slope of the existing stream, the designer should consider both the overall slope and the vertical structure of the existing reach.

A natural channel will only rarely follow a continuous smooth profile. Usually, it will exhibit some type of vertical structure, which is important to the habitat value provided by the stream. There are two common types of vertical structure:

Pool and riffle structure is most often associated with alluvial streams on a sinuous alignment. As illustrated in Figure 11-5, the structure consists of a series of one or more deep pools interspersed with riffles composed of rock or gravel. When an existing stream shows this type of structure, the designer should examine the existing channel bottom profile and note:

- length and depth of the pools
- length and local slope of riffles

Step structure is most often associated with steep natural threshold streams flowing through boulders or bedrock. It consists of a series of short comparatively flat reaches followed by steep drops. When an existing stream shows this type of structure, the designer should note:

- length and local slope of each step
- drop height between steps
- materials (bedrock, boulders, etc.) forming each step

As described in Section 11.03.4, the designer may also need to evaluate the overall floodplain (valley) slope in addition to the local channel slope. These two slopes can be different for streams with a high degree of sinuosity. The floodplain slope is necessary for determining flood elevations for large discharge events. On the other hand, the local channel slope is used to determine the channel forming discharge which is then used for a number of design parameters, including the selection and design of mitigation practices.

11.04.2.4 MAINTAIN EXISTING FLOODPLAINS

A natural stream usually consists of a channel section which conveys low flows and overbanks which will convey flows when the stream is at flood stage. Where this situation exists, the goal of the natural stream design for a relocated channel should be to maintain the existing stream cross section. While it is recognized that this may not be practical in all situations, this would include duplicating the existing top of bank elevations, as well as the floodplain widths.

There may be a temptation by the designer to increase the size of the channel in order to decrease the required size of the floodplain. However, this is not recommended since it may lead to stability problems, especially for alluvial streams. In addition, there may be ecological impacts if the frequency of flooding on the overbanks is reduced.

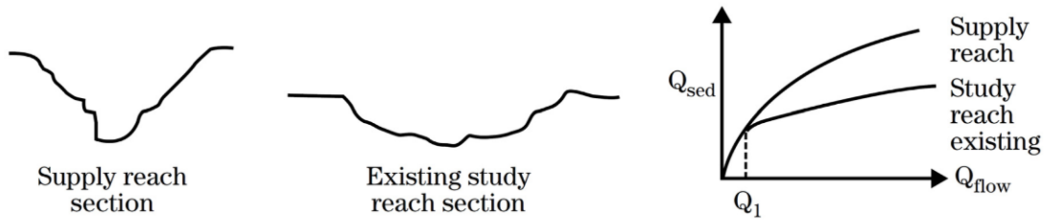
Another goal of the design is to ensure that flood elevations in the proposed condition will not exceed the existing flood elevations in both the relocated reach as well as upstream of the project. The designer should conduct hydraulic analyses for both the existing and proposed conditions to check flood elevations for both the design discharge (usually the 50-year event) and the 100-year discharge. These analyses should assume that floodplain conditions, including riparian vegetation, are the same in the proposed condition as they are in the existing condition. Additional details on these analyses are provided in Section 11.04.5.

11.04.2.5 STABLE CHANNEL DESIGN FOR ALLUVIAL STREAMS

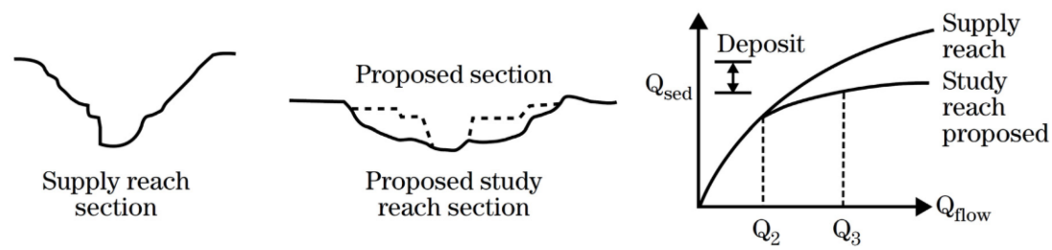
As described in Section 11.03.2, a reach of alluvial channel is considered stable when the flow of sediment through the reach is balanced. That is, the rate of deposition in the reach is equal to the rate of erosion so that the channel neither aggrades nor degrades. An alluvial channel can change its shape and alignment due to fluvial processes such as lateral migration and still meet this definition of a stable stream.

Because of this definition of channel stability, sediment transport analysis is an important part of the natural stream design for a relocated alluvial channel. Initially, the dimensions of the relocated channel will be determined based on a stability analysis for a single discharge, usually the channel forming discharge. Once the average dimensions of the cross section and vertical structure of the relocated channel have been determined, a sediment impact analysis should be conducted to evaluate the long-term stability of the relocated channel under the full range of discharges which could occur in the stream system. Two methods are available for conducting a sediment impact analysis:

Sediment Rating Curves: This method involves computing rating curves of sediment discharge versus water discharge for the range of flows that is expected to occur in the channel. This method is simpler than a full sediment budget analysis (see below) in that it requires only a flow duration curve and the sediment grain size analysis from the geotechnical report. Curves should be prepared for one or more cross sections in the relocated reach as well as in the reach upstream of the relocation project. As shown in Figure 11-9, the rating curve from the project reach is superimposed on the curve from the upstream portion of the stream. If the two curves do not significantly deviate from each other for discharges up to the design discharge, the proposed cross section design will be acceptable. Otherwise, the proposed channel cross section should be modified as needed to increase the level of agreement between the curves. A detailed procedure for computing sediment rating curves is provided in Section 11.05.4.



Existing Project Conditions – *Sediment Load is Transferred Through the Reach up to Q_1*



Proposed Project Conditions *– Sediment Load is Transferred Through the Reach up to Q_2*

Figure 11-9
Sediment Rating Curve Analysis
Reference: Adapted from USDA, NRCS, NEH Part 654 (2007)

Sediment Budget Analysis: The sediment budget analysis method involves a detailed sediment transport analysis using a computer program. Analysis involves creating a hydraulic model of the stream from upstream through the project reach and then computing the quantity of sediment eroded or deposited in a series of stream segments through the study area. This analysis requires at least a simplified discharge hydrograph, and a detailed description of the grain size classifications in the channel boundary materials. Beginning with version 4.0 the U. S. Army Corps of Engineer's program HEC-RAS includes a full sediment transport module that is based on the previous program HEC-6. A detailed description of this application or any other computer software is beyond the scope of this Manual. The designer should refer to the HEC-RAS Reference Manual for full documentation.

The rating curve method for sediment impact analysis requires much less effort and should be adequate for evaluating relocations on most small to medium sized streams. A complete sediment budget should be only performed for large streams or streams judged to be high risk.

The risk associated with a stream relocation project can be judged based on the value of any facilities which might be affected by future meanders and the rate at which lateral migration is expected to occur. A high-value facility might be a residence, a barn used to store equipment, or a multi-lane roadway with a high traffic count. Rapid migration of a stream would be indicated by visibly "fresh" erosion areas, vertical banks on the outside of existing meander bends, or large point bars relative to the channel width.

11.04.2.6 EFFECTS OF RELOCATION ON OVERALL STREAM CORRIDOR

The shape and alignment of a stream channel is the result of many influences that occur within a stream corridor. The channel stability is affected by a complex system of factors that includes rainfall, stream discharge, bed materials, stream slope, riparian vegetation, and even land use within the watershed. A change in any one of these factors represents a disturbance that could result in a period of instability in the channel.

One of the goals of natural stream design for a channel relocation project is to minimize the potential for disturbance to the overall stream system. Meeting the other goals outlined in this section for natural stream design will help in minimizing this disturbance. The designer should consider the overall stream system when evaluating the potential effects of the relocation. Lane's balance as presented in Section 11.03.2 can provide a framework for considering potential impacts. Also, a curved channel alignment at the ends of the relocated reach could affect the alignment of the flow, which may result in lateral migration of the channel at those locations.

11.04.2.7 APPROACHES FOR AN UNSTABLE STREAM REACH

TDOT's normal practice is to duplicate the conditions in the existing stream system as much as possible. Where the existing stream channel is unstable, the designer should not duplicate the existing problem within the proposed relocated channel. The proposed relocation should be designed to remain stable, even if the upstream or downstream reaches are actively aggrading or degrading. Otherwise, instability in the relocated channel could result in the overall failure of the relocation project or damage to the roadway facility or surrounding property.

Achieving a stable natural stream design where the larger stream system is unstable requires a considerable amount of judgment and experience and is thus beyond the scope of this Manual. This section provides a framework for approaching this problem as well as suggestions for obtaining additional information.

Before attempting to design the relocated channel, an effort should be made to identify and understand the causes of any observed problems. This involves assessing the overall watershed as well as the local project area. It may be possible to address a local or short-term instability problem as a part of the stream relocation project. On the other hand, the stream's condition may be a reflection of a larger, overall watershed problem that is beyond the Department's ability to repair or control. In this case, the project design should account for potential future changes in the relocated reach.

Accounting for future changes in an unstable stream reach requires a scientifically based prediction of the direction and rate of those changes. An unstable stream will tend to evolve toward a state of equilibrium determined by its current flow and sediment load characteristics. Thus, the proposed relocation design should be compatible with an unstable stream's tendency to evolve towards particular channel forms. A number of channel evolution models have been developed to assist in predicting future upstream or downstream changes in stream morphology. Because streams will tend to follow different evolution patterns based on site-specific conditions, appropriate use of channel evolution models requires a system for classifying streams based on their planform, channel boundary sediments, etc. More information about stream classification and channel evolution models can be obtained from NEH 654 published by the NRCS, as well as several publications by Dr. David Rosgen.

The design strategies employed for a stream relocation project in an unstable stream will largely depend on the site-specific conditions. These strategies will usually serve to isolate the relocated reach from the larger unstable stream system through the use of mitigation measures to control the grade of the relocated channel. In some situations, it may be necessary to design the relocated channel as a threshold channel. The relocated channel should be designed for the expected long-term conditions in the stream system. For example, the evolution of the larger stream system could result in substantial changes in the sediment load. If the relocated channel had been designed to pass the short-term sediment load, the future evolution of the stream would result in instability in the relocated channel.

A special case of channel instability is an incised stream. This is a stream that has been deepened due to past channelization, dredging, or increased discharges due to urbanization in the watershed. This deepening causes the stream to become disconnected from its original floodplain. One of the consequences of this is that storm flows are more confined to the incised channel. This increases the shear stresses and velocities in the channel, resulting in bank and bed erosion, channel widening, and habitat degradation. In rural watersheds, it may be possible to mitigate these effects by developing a two-stage channel design as described in *NEH 654*. However, channel incision is also frequently associated with urban streams, which are discussed later in this Chapter.

11.04.3 STORM FREQUENCIES FOR STREAM RELOCATION DESIGNS

The discharge data required for a natural stream design will vary depending on whether the existing channel is classified as threshold or alluvial. As described in Table 11-2, the design procedures for threshold and alluvial channels require different types of discharge data. In particular, stable alluvial streams may require a determination of the channel forming discharge and a flow duration curve. Both of these parameters can be difficult or time-consuming to derive and the designer should verify the channel type to ensure what data is required before proceeding.

This section describes each of the types of discharge data that may be required for a natural stream design.

11.04.3.1 CHANNEL FORMING DISCHARGE

Although the channel forming discharge concept can be used for many stability assessment tools and channel design techniques, its primary applicability is to alluvial streams. The channel-forming discharge concept is based on the idea that for any given alluvial stream it is possible to determine a single hypothetical discharge which represents the combined channel forming effects of the variable flows which naturally occur in the stream. In other words, if this theoretical single discharge were to persist in the stream indefinitely, it would produce a channel similar to the natural channel in terms of geometry (i.e. width, depth, slope, etc…).

To estimate the channel forming discharge, it will be necessary for the designer to evaluate two other discharges; both of which are related to transport of sediment in an alluvial channel. These two other discharges are termed the bankfull discharge and the effective discharge.

Bankfull Discharge is determined based on the depth below which it appears that most of the fluvial activity is taking place in the channel and is considered to be a key to proper stream classification. This bankfull depth is usually determined by examining the site to look for typical indicators of fluvial activity. It is important to distinguish this from what the surveyor would call the top of the channel bank, even though the two elevations may be similar. Field indicators of bankfull depth include:

- top of bank elevation, particularly for smaller streams
- highest elevation of gravel or sand bars in the channel
- the presence of benches in the channel cross section
- the presence of a break in the bank slope
- lowest elevation of perennial vegetation (i.e. grasses or shrubs)
- a change in bank material from sand-sized particles to soil

Where these indicators are difficult to determine, it may also be possible to compute a curve of channel top width divided by depth for increasing depths. The point at which the ratio of top width to depth is at a minimum may be an indicator of the bankfull depth.

Figure 11-10
Stream with Bankfull Width and Depth Shown
Location: Sulphur Branch, Overton County, Tennessee (2010)

The bankfull depth should be determined at a number of locations in the project reach, preferably at the upstream ends of any riffles that may be present. At each of these locations, the slope-conveyance method (see Section 5.03.4) should be used to determine the corresponding discharge. The slope used in these calculations should be the local channel slope, as discussed in Section 11.03.4. The bankfull discharge can then be taken as the average of the discharges computed at each of the cross sections. As a rule-of-thumb for the designer, the bankfull discharge frequently has a recurrence interval between 1 and 2 years in Tennessee.

Effective Discharge is conceptually a combination of both the magnitude of a flow event, and its frequency of occurrence. As illustrated in Figure 11-7, effective discharge can be viewed as the average of the discharge increment that transports the largest fraction of the annual sediment load. Essentially, the flow duration curve (as described in Section 11.04.3.2) is divided into increments, and the increment that transports the largest fraction of the annual sediment load is considered the effective discharge. An advantage of effective discharge as compared to the bankfull discharge is that it is a calculated value, not subject to the inaccuracies associated with determining indicators in the field. However, it requires the determination of both a flow duration curve and a sediment rating curve, which may be difficult to determine with certainty.

The channel forming discharge for an alluvial stream reach should be based on comparing the bankfull discharge to the effective discharge and determining a final value based on appropriate judgment. For a stable alluvial stream, the bankfull discharge should be similar to the effective discharge. If not, it may indicate that the existing channel is unstable.

A number of attempts have been made to simplify the process of determining channel forming discharge by relating it to some frequency of peak flood flow occurrence. It has been found that the return period can vary widely from 1.5 to 5 or more years for typical alluvial streams. Further, for streams with coarse sediments, the return period can be much longer. Thus, the concept of channel forming discharge should not be linked to a specific flood event.

Because the channel-forming discharge is based on a theoretical constant discharge, it may not be applicable to intermittent or ephemeral streams. Procedures for determining channel forming and effective discharges are included in Section 11.05.4.

11.04.3.2 FLOW DURATION CURVES

A flow duration curve is a statistical tool which collects all of the daily flows which have been recorded at a stream gauging station and arranges them in numerical order so that each level of discharge can be associated with the percentage of the total number of discharges which are greater. Thus, for a given discharge, the flow frequency curve will indicate what percentage of time that discharge has been exceeded at that gauge. For example, at USGS Gauging Station Number 03423000 on the Falling Water River near Cookeville, Tennessee, a discharge of 9.3 cfs is exceeded 80 percent of the time, while a discharge of 228 is exceeded 10 percent of the time. As illustrated in Figure 11-11, the higher the discharge, the less frequently it is exceeded.

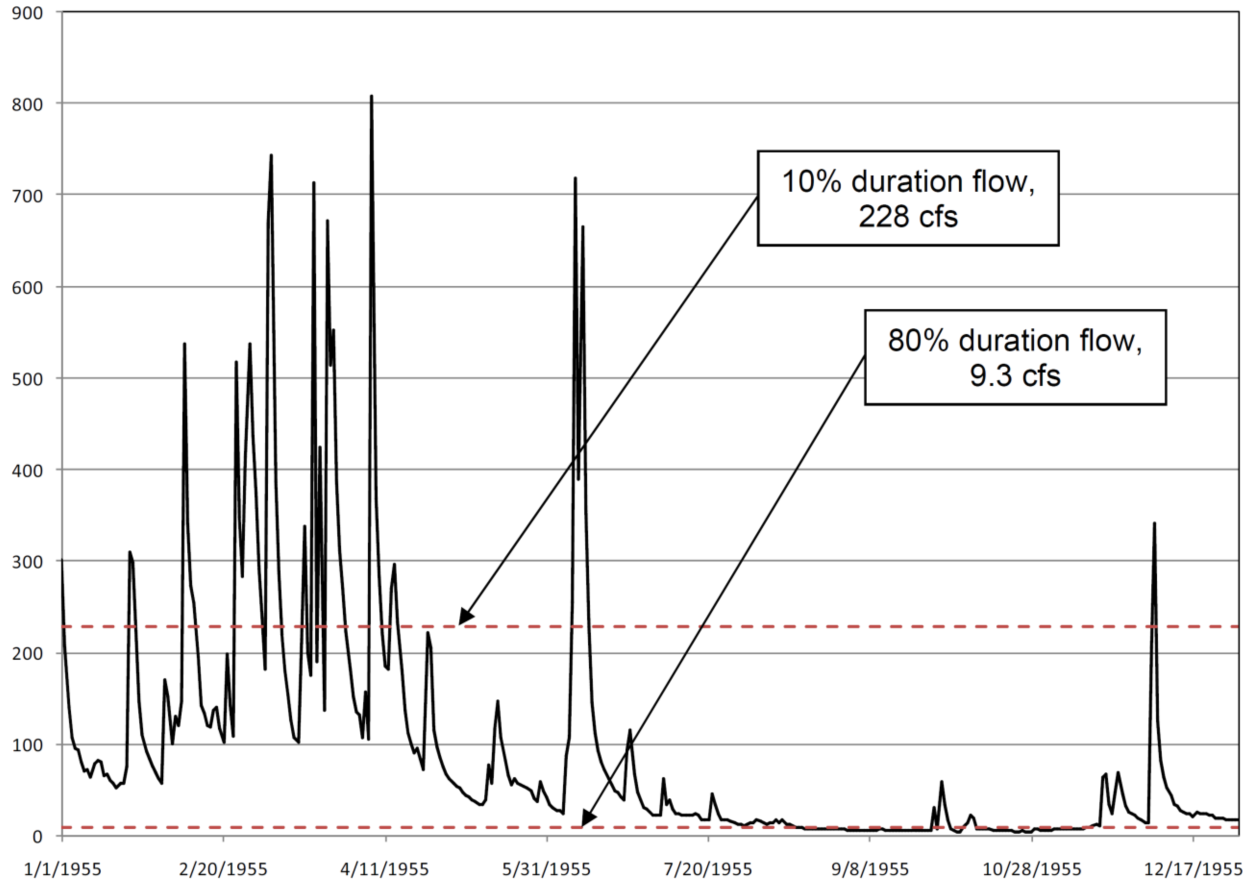


Figure 11-11
Daily Stream Flows, January 1 through December 31, 1955
Falling Water River near Cookeville, Tennessee
Reference: USGS, Tennessee Water Science Center

Flow duration is often an important element in the sediment analyses needed to support the design of a stable alluvial channel. Flow duration data for gauging stations in Tennessee have been published by the USGS and may be found at:

http://pubs.er.usgs.gov/

Since a stream relocation site may not have a gauging station, the designer should make an effort to relate the flow duration curves for nearby gauging stations to the flow duration at the project site. In order to accomplish this, a minimum of three nearby stream gauging stations should be identified which have watersheds with physiographic characteristics similar to the watershed at the project site. Typically, there will be a linear relationship between a given exceedance value (e.g. – the 80% exceedance discharge) and the drainage area. It is thus possible to define this relationship for each level of probability and then determine the corresponding discharges for the site based on its drainage area.

Flow duration curves should not be confused with peak flood flows, which are expressed in terms of their percent chance of occurrence in a given year (1% or 10%, for example). Peak flood flows are ***instantaneous*** values which reflect extreme events. In contrast, flow duration curves are based on daily average flows and represent the normal day-to-day flows which occur in a stream.

11.04.3.3 FLOOD DISCHARGES

Typically, the flood discharges needed for the natural stream design for a relocated channel will be the 50-year and 100-year discharges.

The 50-year discharge should be used to:

- evaluate the freeboard on the roadway
- evaluate the stability of the channel lining materials where the relocated stream will have a threshold channel
- design revetments used on the floodplain to protect the roadway or another structure from erosion

The hydraulic capacity of the existing stream and the proposed relocated stream should be checked for the 100-year flood to ensure that the existing floodplain elevations will be maintained.

11.04.4 DATA REQUIREMENTS

The data required to support a natural stream design will vary depending upon whether the project reach is in a threshold or an alluvial stream. The typical data needed to complete a design is discussed in Section 11.03. That section also includes a general discussion on the processes used to complete a natural stream design.

11.04.5 HYDRAULIC CONSIDERATIONS

Often, properties adjacent to the right-of-way will lie within the floodplain of a stream being relocated. The designer should consider the effect of the proposed stream relocation on any property outside of the TDOT right-of-way or drainage easements. In general, the proposed relocation should not increase the 100-year flood elevation or increase the flooded area on these properties. However, this criteria should not be applied where the relocated stream includes cross drains or side drains since Section 6.04.2 of this Manual allows some increase in water surface elevation for culverts. In this situation, the designer should verify that the water surface elevation upstream of the cross drain will comply with the criteria provided in Chapter 6 of this Manual.

The designer should check the hydraulic capacity of the relocated stream by means of water surface profile computations using the standard step backwater method as described in Section 5.03.4. At least two profiles will be needed for the 100-year event; one for the existing stream, and one for the proposed relocation. The study reach should begin downstream of the channel relocation as far as is practical, and should include a minimum of three stream cross sections beyond the downstream limits of the project to increase the accuracy of the hydraulic model results. The study reach should extend far enough upstream of the stream relocation to show that the profile of the relocated stream is converging with the existing flood profile. A minimum of two stream cross sections is recommended upstream of the project limits.

11.04.5.1 CURVED CHANNEL ALIGNMENTS

Flow conditions in a channel bend are complicated by the distortion of flow patterns which occurs in the vicinity of the bend. In long, relatively straight channels, the flow conditions are uniform and symmetrical about the center line of the channel. However, in channel bends, centrifugal forces and secondary currents lead to non-uniform and non-symmetrical flow conditions.

Under ideal conditions with subcritical flows, the general flow pattern through a curvilinear section of channel will resemble a spiral vortex. Laboratory investigations have shown that the strength of this vortex is related to the ratio of radius of curvature, R_C, of the bend to the bottom width of the channel, B. As the radius of curvature decreases with respect to the channel width (that is, at the ratio R_C / B decreases in value), the strength of the vortex increases moderately. However, the strength of the vortex will increase more sharply where the value of the ratio becomes less than 3. Thus, a value of 3 for R_C / B represents an ideal balance between the need to minimize the right-of-way acquisition for the channel relocation and the need to minimize the adverse impacts that would result from flows around a sharp bend.

Two aspects of flow in channel bends affect the design of revetments for a relocated stream. First, the flows around a channel bend impose higher shear stresses on the channel sides and bottom compared to a straight reach. This is shown in Figure 11-12. At the beginning of the bend, the maximum shear stress is near the inside and moves toward the outside as the flow leaves the bend. This increased shear stress persists downstream of the bend for a distance L_P. The maximum shear stress in a bend is a function of the ratio of the radius of the curve, R_C, to the channel bottom width, B. As the ratio R_C / B decreases, (i.e. as the bend becomes sharper) the maximum shear stress in the bend tends to increase. To determine the shear stress in the bend, the maximum shear for a straight alignment, τ_{max}, is first computed from Equation 5-10. This value is then multiplied by a dimensionless factor, K_b, which accounts for the increased stress:

$$\tau_{bend} = K_b\left(\tau_{\max}\right) \tag{11-3}$$

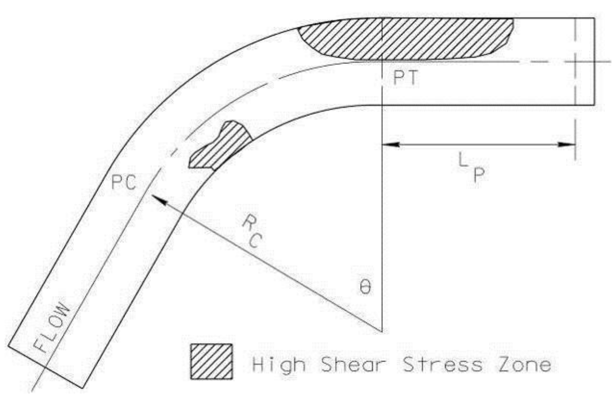


Figure 11-12
Shear Stresses in Channel Bend
Reference: USDOT, FHWA, HEC-15 (1988)

Values of K_b may be determined from the relationship:

$$K_b = 2.36e^{-0.082(R_c/B)} \tag{11-4}$$

Superelevation of flow in channel bends is a second consideration in the design of revetments for stream relocations. It should be noted that superelevation in subcritical flows are driven by different mechanisms than the superelevation in supercritical flows. Subcritical flows around bends tend to establish spiral vortices which result in increased water surface elevations around the outside of the bend. On the other hand, superelevations in supercritical flows are usually a result of conflicting cross waves established in the curvilinear flows. In addition, hydraulic jumps can occur in severe bends.

The magnitude of superelevation is relatively small in subcritical flows, but can be significant for supercritical flows. When considering freeboard for revetments on bends, the designer should allow for at least 1 foot of superelevation in subcritical flows. Where flows are supercritical, the magnitude of the superelevation may be estimated by the following equation:

$$Z = C\left[\frac{{V_a}^2 \times T}{g \times R_c}\right] \tag{11-5}$$

Where: Z = superelevation of the water surface, (ft)
C = coefficient that ranges between 0.5 and 3.0, with an average of 1.5
V_a = mean channel velocity, (ft/s)
T = water-surface width at the section, (ft)
g = acceleration due to gravity, (32.2 ft/sec^2)
R_c = the mean radius of the channel centerline at the bend, (ft)

11.04.5.2 CHANNEL TRANSITIONS

Ideally, the cross section of the relocated channel will be similar, if not identical to, the channel cross section of the existing stream. Where this is not possible, adequate transitions should be provided between the unaffected portions of the existing stream and the relocated stream reach. The length of these transitions may be determined based on the top width of the flow at the channel forming discharge. The top width in the existing stream should be compared with the top width in the relocated channel and the length of the transition should be equal to twice the difference. In other words, the transition should be based on an expansion or contraction ratio of 2:1.

The centerline of the relocated channel should be continuous with the centerline of the existing channel. Further, if a curved alignment is necessary at either end of the relocated stream reach, the transitions should be placed outside of these curved areas. That is, the transition to the relocated stream cross section should be complete before the beginning of the curved alignment.

11.04.6 MITIGATION PRACTICES FOR NATURAL STREAM DESIGN

Mitigation measures are structural or vegetative practices that may be installed along a relocated stream reach to eliminate, or reduce to acceptable levels, the adverse effects of a proposed stream relocation project. For TDOT projects, the purpose of these measures will not necessarily be for stream enhancement rather; they are intended to stabilize the bed and banks and provide stream structure and habitat values that are consistent with the conditions found in the larger stream system.

Mitigation measures may be specified by the Environmental Division as a result of the NEPA process. This information will normally be transmitted to the Design Division via Form J of the Environmental Boundaries and any environmental commitments. The Environmental Boundaries should identify potentially impacted features of the stream and provide mitigation measures to be placed on the plans by the Design Division. Where this is not the case, it will be the responsibility of the designer to select and design the proposed mitigation measures in coordination with the Environmental Division.

11.04.6.1 SELECTION OF MITIGATION PRACTICES

Within the realm of feasibility, the proposed relocated stream should be provided with a channel structure and habitat values that will integrate into the overall stream system. In order to select a set of measures that will be effective for this purpose, it will be necessary to carefully evaluate conditions not only in the existing reach to be relocated, but also in the upstream and downstream reaches. In selecting the proposed mitigation measures, the designer should carefully consider the mitigation measures specified in the Environmental Boundaries together with the commitments made in coordination with state and federal agencies during the NEPA process. The use of any mitigation practices required by regulatory agencies will be crucial to the approval of project permit applications. Thus, any modifications to the required measures should only be for the purpose of more fully meeting the environmental commitments and should be coordinated with the Environmental Division.

The mitigation measures presented in Section 11.08 for TDOT projects can be grouped into two broad categories: hydraulic control and stabilization. Hydraulic control measures are on or across the bottom of the channel and are used to direct current away from erodible channel banks, control flow velocity, or create complexity in the channel profile. Stabilization measures are typically applied on the channel banks and are used to prevent erosion and help establish riparian vegetation. While the mitigation measures in this document are given as separate practices, the designer should be aware that it is common practice to combine multiple measures into one application so that the strengths of measure can work together to meet the goals of the natural stream design. Further, not all mitigation measures are designed to be permanent structures. A number are intended to provide short to medium-term protection while permanent vegetation established. Once mature, the permanent vegetation will provide the protection temporarily afforded by the mitigation measure. Other temporary mitigation measures are intended to artificially create horizontal or vertical complexity in the channel profile until natural fluvial processes can take over.

11.04.6.1.1 HYDRAULIC CONTROL PRACTICES

As the name implies, hydraulic control measures are intended to control the flow of water in order to prevent damage by erosion or provide other habitat benefits. Because these measures are intended to function at discharges equal to or less than the channel forming discharge, they are typically applied on the bottom of the channel. Hydraulic control measures can be used to redirect flow away from channel banks or other areas where erosion would be undesirable. However, at the same they can be used to concentrate flows where erosion would be expected or desirable, such as a pool in a stream with a pool and riffle channel structure. These measures can also be used to create sudden drops in the stream profile, especially for streams with steep slopes where they serve to help control the flow velocity.

Hydraulic control structures can also be used to enhance the habit offered by the relocated stream for aquatic organisms. They can accomplish this by creating scour pools, zones of alternating swift and slow currents or causing coarse sediments to be sorted into riffles.

Selection of hydraulic control measures should be based on a consideration of the characteristics of the existing channel bed, both in the reach to be relocated and in the larger stream system. The hydraulic control measures for a relocated stream reach should be designed to imitate the existing natural stream profile. It would not be effective to attempt to create vertical profile features if they are not found elsewhere in the stream system.

Section 11.08.1 provides a set of hydraulic control measures that may be used on TDOT stream relocation projects

11.04.6.1.2 STABILIZATION PRACTICES

Stabilization measures are intended either to prevent erosion or to provide structural stability for slopes subject to failure. These measures rely heavily on the use of live or dormant woody vegetation, degradable manufactured natural fiber products, or a combination of both. Many either directly incorporate vegetation or serve as a temporary cover while permanent vegetation establishes. Thus, they are typically applied above, along, on, or at the toe of a stream bank.

Because of their role to prevent erosion on the stream bank, stabilization measures should be designed to appropriately withstand the shear forces imposed by the design flood event, typically the 50-year flood, especially along the outside of a channel bend. Where site conditions allow, stabilization measures which employ vegetation are preferred over traditional rigid structural measures.

The designer may select stabilization measures from those described in Section 11.08.2.

11.04.6.2 REVETMENT TYPES FOR CURVED ALIGNMENTS

Revetments are erosion resistant or hard materials placed in a channel or floodplain to maintain a desired alignment or cross section. They have two principal uses in natural stream design. The first is as lining materials for a relocated threshold channel on straight or curved alignment. The second is as a means of constraining the alignment of an alluvial channel. By their nature, alluvial channels will tend to meander. Over time, changes in a channel alignment could begin to pose a risk to the roadway or other structures adjacent to the stream. In this situation, revetments could be placed at critical areas along the edges of the floodplain to reduce the risk of damage due to the lateral migration of the channel.

11.04.6.2.1 PREFERENCE FOR REVETMENT MATERIALS

As a general rule, the preferred revetment materials will be materials that naturally occur in the project reach, or equivalent materials. Where this is not feasible, other materials may be used. The following sections list acceptable materials in order of preference.

11.04.6.2.1.1 VEGETATION

Although vegetation cannot be considered an actual type of revetment, it is the preferred method of providing stabilized channel banks. Section 11.04.2 indicates that the riparian vegetation in the existing channel should be replicated in the relocated stream channel as much as possible. Thus, the designer should investigate the allowable shear stress for the existing riparian vegetation. If the tractive force of the flows around the bend will be greater than the allowable shear stress, the designer should coordinate with the Environmental Division to determine an appropriate course of action. Possible options include:

- modify the vegetation proposed for the relocated stream banks to include more erosion resistant species
- increase the radius of the bend to reduce the tractive force that would be experienced on the outside of the bend
- provide permanent turf reinforcement mats
- use some form of hard revetment as described in the following sections

The designer’s determination for the best course of action should reflect a balance between the hydraulic conditions, environmental commitments, economic considerations, and the availability of right-of-way.

11.04.6.2.1.2 MACHINED RIPRAP

Although machined riprap revetments are allowable for stream relocations, it is generally preferable to utilize naturally occurring stone, where feasible. Detailed descriptions of the various classes of riprap available are provided in Section 5.04.7. Although it is extremely difficult to predict the maximum velocity that will occur along the outside of a curved section of channel, the velocity criteria provided below reflect an allowance for this uncertainty. Thus, the selection of riprap should be based on the average flow velocity as follows:

- Machined Riprap (Class A-1) should be used for average flow velocities up to 5 feet per second
- Machined Riprap (Class B) should be used for average flow velocities up to 10 feet per second
- Machined Riprap (Class C) should be used for average flow velocities greater than 10 feet per second up to 12 feet per second

Situations where the average flow velocity is greater than 12 feet per second may be supercritical and present an extremely complex design problem. The designer should make every reasonable effort to avoid curved alignments in areas of such high velocity.

11.04.6.2.1.3 PRECAST CONCRETE FORMS

Precast concrete forms can consist of “jacks” or of concrete blocks which are tied together with steel cables. “Jacks” differ from concrete block riprap or stacked sand-cement bags in that they usually provide an arm or other type of structure that protrudes into the flow field. These structures act by creating additional flow resistance to reduce velocities in areas where turbulent flows might create erosion. These structures are usually placed in a tight pattern on filter fabric. In many installations, these structures reduce velocities sufficiently so that sediment will be deposited in the voids between the individual precast units. This in turn can encourage the growth of vegetation which may serve to enhance the erosion resistance of the revetment. Cable-tied blocks placed on filter fabric and may be used in areas of high velocity flows where machined riprap may not otherwise be stable.

At this time, no standard design exists for these structures and a variety of forms are available from various manufacturers. Specific design guidance for these structures usually can be obtained from the manufacturers. However, this design data is often based on laboratory studies and the designer should seek to obtain information on the performance of any given structure in an actual field installation. Before specifying these structures, the designer should check the Qualified Products List. The use of any structure not on the Qualified Products List must be coordinated with the Materials and Tests Division and be approved by the Design Manager.

Precast concrete forms are typically shipped in pieces and assembled on-site. The designer should consider labor costs in determining whether these units should be used at a specific site.

11.04.6.2.1.4 REVETMENT TYPES TO BE AVOIDED

Because of the potential impact on in-stream habitat and other problems, the following revetment types should be avoided on channel bends for stream relocations:

- **Wire Enclosed Stone (Gabions):** The flow velocities experienced at the outside of a channel bend can be relatively high, even in situations where the average stream velocity is moderate. Thus, granular sediments carried by the flows in these areas can quickly abrade the coating on the wire used to enclose the stone. The resulting rust can cause the wire to break, resulting in the premature failure of the structure.
- **Concrete Block Riprap:** This type of revetment normally provides erosion protection by providing a smooth continuous wall. However, it is particularly vulnerable to failure due to undermining. The displacement of a few blocks, often at the upstream edge of the wall, can lead to increased erosion behind the wall and the progressive failure of more blocks. Providing an interlocking form of concrete block does not seem to significantly improve the performance of the wall.
- **Concrete Pavement:** Concrete slope walls tend to increase the overall velocity of flow in the channel. This can lead to increased erosion downstream as well as other unintended geomorphic consequences. In addition, the increased flow velocities that would occur in a concrete-lined channel may significantly reduce the flow time in certain situations. This may tend to increase the peak flow rate or have other unintended consequences on the receiving stream.

Section 11.08 provides a number of measures which could be used to provide erosion protection on channel bends.

11.04.6.2.2 LONGITUDINAL EXTENT OF PROTECTION

The longitudinal extent of protection required for a particular revetment installation is highly dependent on local site conditions. In general, the revetment should be continuous for a distance greater than the length that is impacted by channel flow forces severe enough to cause erosion.

The following general criteria provide a starting point for the determination of the longitudinal extent of the revetment. Where the ratio of the radius of channel curvature to the width of the channel is 3 or greater (R_C / B ≥ 3), the revetment should extend upstream from the curve a minimum distance approximately equal to the channel width (B), and downstream from the curve a distance equal to at least 1.5 channel widths, as shown in Figure 11-13. Where (R_C / B) is less than 3, these lengths should be extended using Figure 11A-2 as a guide.

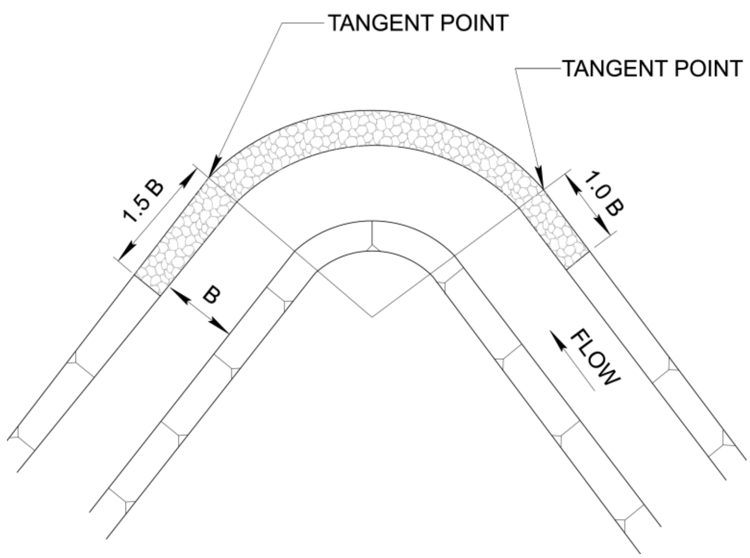


Figure 11-13
Longitudinal Extent of Revetment at a Channel Bend
Reference: Adapted from USDOT, FHWA, HEC-11 (1989)

The designer may find the above criteria difficult to apply on mildly curving bends or irregular, non-symmetric channels. In such cases, average values for the radius of curvature and channel width should be determined based on engineering judgment. It should be noted that this criteria is based on laboratory analysis of symmetric channel bends. Real-world conditions are rarely as simplistic. In actuality, many site-specific factors have a bearing on the actual length of stream bank that should be protected. The designer may find field reconnaissance to be a useful tool for the evaluation of the longitudinal extent of protection to be provided, particularly if the existing channel is actively eroding.

11.04.6.2.3 VERTICAL EXTENT OF PROTECTION

Revetments should extend from a height that provides adequate freeboard above the design flow elevation down to a depth below the channel bottom sufficient to provide toe protection.

The design freeboard is provided to account for factors such as superelevation in channel bends, hydraulic jumps, and flow irregularities due to transitions and flow junctions. In addition, unforeseen slope settlement, the accumulation of debris in the channel, and the growth of vegetation should be considered when setting freeboard heights. Although the amount of freeboard cannot be fixed by a single, widely applicable formula, the guidance provided in Section 11.04.5 will generally be considered adequate. However, the designer may adjust the required freeboard estimate based on any of the factors listed in the previous paragraph.

Undermining of the revetment toe can be one of the primary mechanisms of revetment failure. Thus, the toe of the revetment should be keyed into the streambed to a depth sufficient to prevent undermining. Where riprap is being used as revetment, the toe depth should be measured from the bottom of the riprap layer and should be equal to or greater than the minimum layer thickness for the class of riprap being placed. Machined Riprap (Class B) should be keyed to a depth of at least 2.5 feet while Machined Riprap (Class C) should be keyed to a depth of at least 3.5 feet.

Where a stream relocation project involves an alluvial channel, the designer should assume that the channel could meander across the floodplain stream cross section and eventually reach the toe of the protected slope. Thus, the depth of the keyed-in slope revetment should be based on the flow line of a pool segment in the relocated channel.

11.04.7 PERMIT REQUIREMENTS

The Design Division should coordinate with the Natural Resources Office of the Environmental Division as necessary to ensure that all needed permit applications for a stream relocation project are submitted. Detailed information on procedures and the permits which may be needed are provided in Section III of the Roadway Design Guidelines. Additional information may also be obtained from the Tennessee Environmental Procedures Manual.

11.04.8 RIGHT-OF-WAY AND EASEMENTS

All stream reaches relocated for TDOT roadway projects should be contained within right-of-way rather than in a permanent drainage easement. Once the alignment of the relocated channel has been determined, the designer should establish a right-of-way area sufficient to contain the relocated channel. The right-of-way area should extend a sufficient distance beyond the proposed tops of bank to allow equipment access necessary for the construction, monitoring, and maintenance of the channel.

This area should be shown on the plans as a proposed right-of-way. However, the designer should keep in mind that the relocation of the stream will have an impact on properties adjacent to the roadway. Thus, the final status of the acquisition will be determined by the Right-of-Way Division through negotiations with the affected property owners.

11.04.9 SAFETY AND MAINTENANCE CONSIDERATIONS

Where there is sufficient right-of-way, relocated streams should be located outside of the clear zone. Where this is not feasible, it may be necessary to acquire additional right-of-way or provide appropriate roadway safety measures, such guardrail, adjacent to the channel.

Permitting requirements will likely include a minimum period of 5 years during which the plantings and mitigation measures along the relocated reach will be monitored and maintained as needed. The designer should ensure that there will be adequate access to the site and sufficient space for vehicles to park.

11.04.10 CONSTRUCTION CONSIDERATIONS

In planning a stream relocation project, the designer should consider the means that would likely be employed by the contractor to manage the existing stream flow. In some settings it may be possible to construct most of the new channel in the dry while maintaining flow in the existing channel. The existing and new channels should be separated by undisturbed soil plugs until the new channel has been completed and the vegetation has been established. Once that has been accomplished, the plugs will be removed and flow from the existing channel will be diverted into the relocated channel. In some situations, it may be necessary to divert the flow. In either case, the designer should attempt to plan the layout of the project to accommodate the potential sequence of construction.

The need for construction of a temporary culvert crossing over the existing channel may be necessary. Details for design and construction of temporary crossings and flow diversions can be found in Chapter 10 of this Manual and on the Standard Drawings.

The construction of the relocated channel should also be coordinated with the phasing of the EPSC plan as discussed in Chapter 10.

11.04.11 SPECIAL CONSIDERATIONS FOR URBAN STREAMS

The natural stream design process can be extremely challenging in urban areas where the project reach can be unstable due to straightening, channelization, or changing hydrologic or sediment inflow conditions. Development on the floodplain surrounding the stream can result in increased runoff volumes and peak discharges as well as a declining watershed sediment yield. As a result, urban streams frequently present one or more of the following challenges:

- they are often highly channelized, and inherently unstable
- they can experience rapid bed and bank erosion
- opportunities for acquisition of easements may be limited due to high density development on either side of the stream
- the ecological stream values are often highly degraded
- the channels are often inadequate for significantly large floods and they may be associated with a large, but shallow floodplain
- they may face special permitting obstacles due to the presence of industrial or other pollutants in the stream

Many of these issues should be identified in the NEPA process, and the EB should contain information on these challenges when identified. However, the designer should not attempt a natural stream design for a channel relocation project in an urban area without performing a first-hand assessment of the conditions in the stream corridor.

As discussed in Section 11.04.2, an unstable urban stream should be evaluated in light of an appropriate channel evolution model. It may be that the stream would be subject to changes that could endanger public health and safety. In such cases, the designer should consider designing the proposed channel relocation to address some of the issues.

A two stage channel design, as described in *NEH 654* may be useful to address a number of these design challenges. However, such a solution would require a large amount of right-of-way, and thus is usually impractical due to site constraints in urban settings. The designer should consider whether it is more cost effective to purchase right-of-way and shift the roadway alignment away from the stream. In many cases, alluvial channel design would not be an option and the relocated channel would be designed using threshold methods.

11.04.12 SPECIAL CONSIDERATIONS FOR FEMA STUDIED REACHES

The term “studied streams” refers to streams for which a detailed flood insurance study has been completed. Detailed flood insurance studies include delineations for both the 100-year floodplain and the floodway. Relocating a stream reach will almost certainly change the location of the floodway and could potentially affect the delineated 100-year floodplain. To minimize the impact on flood insurance requirements in a local community, the designer should make an effort to maintain the relocated channel within the delineated floodplain.

Projects within a 100-year floodplain as delineated on a FEMA flood insurance map require coordination with the Hydraulics Section regarding the level of analysis necessary for the project. Where the flood insurance study for a relocated stream includes floodway delineation, re-delineation of the floodway will generally be the responsibility of the Hydraulics Section, which will then notify the local community that the floodway has been relocated and to suggest that local community maps may need to be revised through the FEMA Letter of Map Revision process.

SECTION 11.05 – DESIGN PROCEDURES

Because of the complexities often involved in natural stream design for channel relocation projects, it is not possible to provide a single step-by-step design procedure that can be applied in all cases. The specific procedure used to design a channel relocation will depend heavily on site specific conditions, especially whether the existing stream channel is threshold or alluvial. This section provides separate step-by-step procedures for threshold and alluvial channels; however, the designer should be aware that the design procedures provided may require some adjustment based on site specific conditions.

This section begins with some initial procedures which set the stage for the natural stream design process. It then provides generalized design procedures for threshold and alluvial streams. These generalized procedures provide a framework that is then filled out by detailed procedures for carrying out specific steps in the generalized procedures. These detailed procedures are included in the final part of this section. An overall view of the natural stream design process for channel relocation projects can be found in Figure 11A-1.

The procedures in this section are adequate for the design of a relocated channel that is equivalent to the existing channel, but not recommended for a stream enhancement project. Although stream enhancement is beyond the normal scope of a TDOT project, the Appendix includes several references which provide information on the design of enhancement projects, since much of the content in these references is relevant natural stream design for stream relocations.

11.05.1 INITIAL PLANNING

Prior to beginning a natural stream design, it will be necessary for the designer to make some initial assessments which will set the direction for the design procedure. These assessments (including hydraulic analysis of the existing stream) are necessary to determine whether the existing stream is considered stable and whether it should be classified as a threshold or an alluvial stream. A number of tasks are required to carry out these initial assessments, including a site visit and basic data collection as described in Section 11.03. Specific procedures for the hydraulic analysis are provided in Section 11.05.1.5.

Although these initial assessments will set the general direction of the design, it may be necessary to make adjustments to the design procedures as more site-specific information becomes available.

11.05.1.1 DETERMINING BEGIN AND END POINTS FOR THE RELOCATION PROJECT

A preliminary alignment for the relocated channel will typically be provided in the Environmental Boundaries (EB). This preliminary alignment will likely show curved alignments at the transition points between the existing stream and the relocated channel reach. To determine the beginning and ending points of the channel relocation project, the designer will need to evaluate and revise the curved preliminary alignments at these transition points and determine the length of any transitions which will be required between the existing and relocated reaches of the channel.

As shown in Figure 11-13, there is a length, L_p over which an increased shear stress would persist in the channel past the ends of the curved alignments at the tie-in points between the relocated channel and the existing channel. Transitions are typically required upstream and downstream of the relocated reach to account for this increased stress and to assure that the flow will be properly aligned to match smoothly back into the downstream channel. Sections 11.04.5 and 11.04.6 provide criteria for determining the required transition lengths upstream and downstream of these curved alignments. The total length of the relocation should be calculated based on the total length of the relocation reach, plus the lengths of the transitions. This total length should be used to determine the beginning and ending points for the channel relocation project.

The procedure for identifying the project starting and ending points should be as follows:

Step 1: Identify points at which the relocated channel will tie into the existing channel based on the preliminary alignment provided by the Environmental Division.

Step 2: Based on the project survey, determine B, the bottom width of the existing channel.

Step 3: Evaluate the radius of curvature (R_c) for the curved alignments at the tie-in points between the existing and proposed channel, based on the preliminary alignment in the EB. Based on the criteria in Section 11.04.5, it is preferable to keep the ratio of the radius of curvature to the channel bottom width (R_c / B) to a minimum value of 3. Thus, if this ratio for the preliminary alignment is too small, the curves should be revised if site conditions will allow.

Step 4: Where the ratio R_c / B is greater than or equal to 3.0, determine the upstream and downstream transition lengths based on the criteria in Section 11.04.6. Where the ratio is less than 3.0, Figure 11A-2 should be used by the designer to determine these lengths.

Step 5: The beginning and ending points for the stream relocation can be established based on the length of the preliminary alignment plus the lengths of the transitions.

11.05.1.2 DETERMINING EXISTING BED MATERIALS

Even though the data will be used for different purposes, this is an important step for both threshold and alluvial channels.

A preliminary alignment for the relocated channel should be determined during the Preliminary Plan development stage. Once this has been completed, the designer should request soil borings from the Materials and Test Division. The borings should be located at appropriate intervals along the proposed alignment as well as in the existing channel when possible. There should also be at least one boring upstream and one downstream beyond the limits of the relocated reach. The designer should be specific when requesting locations where borings are needed so that the Geotechnical Engineering Section can obtain the requested number of samples, and so that the samples are taken at the approximate locations desired.

The soil samples should be used to obtain a particle size distribution curve for each of the boring locations or the curve will be provided by the Geotechnical Engineering Section. A sample particle size distribution curve is shown below in Figure 11-14.

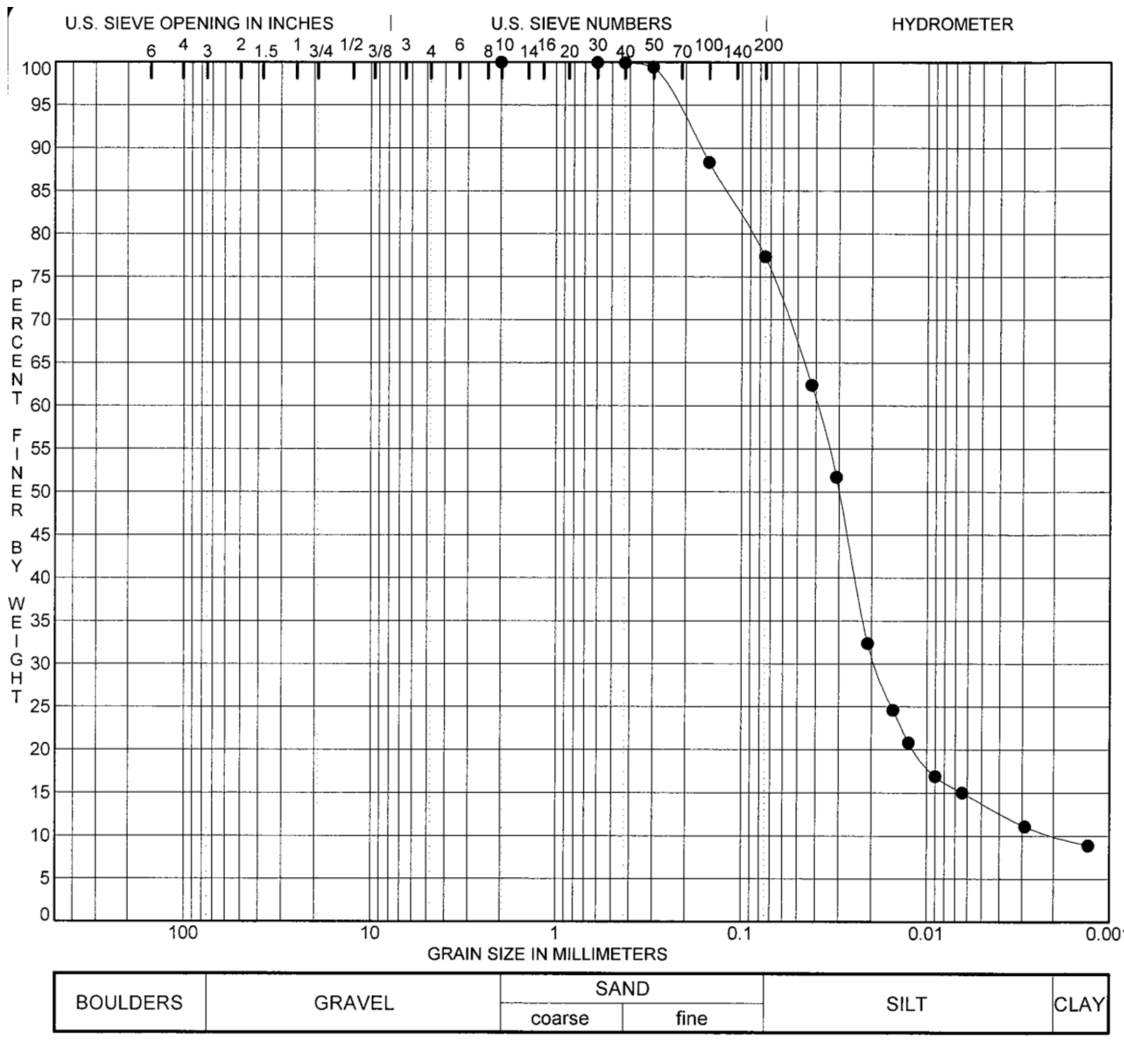


Figure 11-14
Example Sediment Particle Size Distribution Curve

11.05.1.3 DETERMINING EXISTING CHANNEL TYPE

The determination of whether a channel is threshold or alluvial is an important initial step in the natural stream design process since it will determine the procedure that will be used to design the relocated reach. As described in Section 11.03.1, the channel boundary material in a threshold channel will not be mobilized during the design storm event, which is typically the 50-year storm.

Often a simple visual inspection is sufficient for determining the channel type. If a channel bed is composed of fine-grained materials, or shows signs of lateral migration and bank erosion, it is likely to be an alluvial channel. Likewise, a channel that has developed entirely in bedrock will likely be a threshold channel.

However, visual inspection may not be sufficient for many other common situations in Tennessee. Streams which have bedrock on the bottom of the channel would not be threshold channels if the banks are composed of unconsolidated materials that are subject to erosion. Channels with coarse grained sediments such as cobbles and boulders should be considered alluvial if the channel material can be mobilized by the design storm. To evaluate the stability of these types of streams, the following procedure may be used by the designer:

Step 1: As a part of the hydraulic analysis of the existing channel, compute the maximum shear imposed on the channel bed during the design storm in both straight and curved reaches using the procedure provided in Section 5.06 of this Manual.

Step 2: Determine the permissible stress for the materials lining the channel based on the tables and other information found in the Appendix to Chapter 5.

Step 3: Compare the computed shear stress to the permissible shear stress. If the material in the channel boundary will be mobilized by the 50-year peak discharge, the designer should treat the stream as an alluvial stream; otherwise, it should be considered threshold.

11.05.1.4 ASSESSING EXISTING CHANNEL STABILITY

By definition, the stability of a threshold channel will be determined as a part of the hydraulic analysis described in the previous section. In contrast, the stability of an alluvial channel will be more difficult to determine, since evidence of erosion may not indicate that the channel is unstable. An alluvial stream is considered stable if the rate of the erosion of sediment from the channel is balanced with the rate of material deposition. Thus, signs of erosion should be expected in an alluvial stream. Further, the rate of erosion may not be a reliable indicator. Rapid changes in planform may be a part of the overall fluvial behavior of the stream and can occur in the context of sediment equilibrium. On the other hand, slow changes could appear benign, but may be the result of long-term instability.

Determining the stability of the existing channel is one of the most crucial steps in preparing to develop a natural stream design for an alluvial channel, and it is perhaps one of the most difficult steps as well. Because the assessment is based primarily on “reading” the evidence presented by a stream channel, an accurate determination of stability requires both experience and sound judgment.

The following steps should be taken in assessing the stability of a channel. The order in which they are presented is general, rather than step-by-step. Instead, the following steps indicate the types of activities which should be a part of assessing alluvial stream stability.

Step 1: As a part of the site inspection, the designer should evaluate the stream channel based on the list of physical indicators of instability listed in Section 11.03.4.5. This evaluation should be based on a weight of evidence approach. That is, multiple indicators need to be in agreement in order to conclude that the stream is either aggrading or degrading. For longer projects, it may be possible that one portion of the reach is degrading while another portion is aggrading. In general, the purpose of this step is to arrive at an understanding of the overall fluvial process that may be taking place.

Step 2: If it appears that the stream is unstable, the designer should examine the overall watershed for evidence of changes which could potentially impact the stability of the stream. A possible source of information for this watershed analysis would be historical aerial photography or topographic maps of the watershed. Changes that could cause this type of impact would include factors that could alter flood discharges or the supply of sediment into the channel. These could include:

- urbanization or other changes in the watershed land use
- construction projects near the stream
- construction of ponds or reservoirs in the watershed
- placement of a restrictive culvert on a local road
- dredging or channelization of the stream

The above steps will provide a general evaluation of the stability of the channel, based on a visual assessment of the fluvial processes which may be occurring. This evaluation should be sufficient to begin the natural stream design process for an alluvial channel relocation. As a part of this process, the stability of the stream should further be checked by means of a more detailed analysis based on a combination of hydraulic and sediment transport computations.

Possible approaches for addressing instability problems in a channel are provided in Section 11.04.2.

11.05.1.5 HYDRAULIC ANALYSIS OF THE EXISTING STREAM

Hydraulic analysis of the existing stream is necessary to establish a base line for flood elevations and shear stresses. This analysis should consist of using one of the computer programs listed in Section 5.07 to determine the water surface profiles for both the design discharge and the 100-year discharge. These profiles will provide a baseline for determining the impact of the proposed realignment on flood elevations, and may provide information that will be useful in assessing the stability of the existing channel. Features that may prove useful include velocity distribution computations at sensitive points in the study reach and the computation of shear stresses.

One of the important issues in modeling stream flows in the subcritical flow regime is that of determining the starting water surface elevation (sometimes called the boundary condition). In general, the guidance provided in Section 6.03.1 of this Manual should be sufficient for assessing the tailwater conditions at the site. When using a computer program to compute water surface profiles through the study reach, the designer should normally input the slope of the water surface that has been determined for the downstream end of the project reach. The program will then determine the starting water surface elevation using the slope-conveyance method as described in Section 5.03.4.

Another important issue in modeling stream flow is the selection of a Manning's roughness coefficient to be applied at each cross section. Because Manning's equation underlies most step-backwater computations, the n-value is a primary factor in determining the energy loss between each valley cross section. Changes in n-value may have a significant impact on the water surface elevations computed at each cross section. Thus, the designer should consider the n-values selected at each cross section, and the information used in the selection process should be well-documented. Table 5A-1 provides a guide for selecting n-values for man-made channels and natural streams. As an alternative to this table, the designer may choose to use Cowan's Method as described in Section 11.05.4.

Most hydraulic modeling software packages allow the designer to separately specify n-values for the channel and floodplains. Where the entire flow will be contained within the channel, a single n-value may be applied to the entire cross section. However, in areas where the design flow exceeds the channel capacity and spills out onto the adjacent floodplain, separate n-values should be defined for the channel and floodplain. This is true even where the floodplain and channel may be assigned the same n-value. In other words, the channel and floodplain should be assigned separate n-values even when those n-values are equal.

Where sufficient information exists, the hydraulic model of the existing stream should begin at a point downstream of the project reach, including any transitions which may be required. This will help to improve the accuracy of the elevations computed through the project reach. Specific guidance for determining the extents of the project reach is provided in earlier in this section.

11.05.2 DESIGN PROCEDURES FOR THRESHOLD CHANNELS

Once the supporting data have been collected as described in Section 11.03 and the initial steps described in Section 11.05.1 have been completed, the actual natural stream design process can be carried out for the relocated channel.

Because the boundary materials in a threshold channel should be immobile for the design discharge, the concept of channel-forming discharge does not apply to the design procedure, since natural fluvial processes do not affect the channel dimensions. Thus, the design process consists of determining cross sections, horizontal planform and vertical profile for the relocated channel, and performing a hydraulic analysis to assure the stability and hydraulic performance of the proposed stream design.

The general procedure for a threshold channel is as follows:

Step 1: Determine characteristics of the existing stream, including:

- bed-material size gradation
- Manning's n-value using Cowan's Method
- existing channel cross sections at several locations in order to determine the average channel width and depth as well as the variability in those dimensions
- length of the reach
- existing plan form, including the sinuosity ratio and the other meander characteristics (if any) listed in Section 11.03.4
- existing vertical profile

Step 2: Determine design discharges (see Section 11.04.3) and conduct a hydraulic analysis of the existing channel as described in the previous section, for both the design discharge (usually the 50-year storm) and the 100-year discharge. If the hydraulic analysis indicates that the bed will be mobilized for the design discharge, the designer should discontinue this procedure and proceed to the alluvial channel design procedure. Further, determine the flood elevations for the 100-year peak discharge, and note whether any existing structures are located within the 100-year floodplain.

Step 3: Determine the cross section, planform and vertical profile of the relocated channel, based on the criteria presented in Section 11.04.2. As much as possible, duplicate the physical parameters measured for the existing channel, including the variability in the channel depth and width.

Step 4: Perform a hydraulic analysis of the relocated channel for the design discharge and for the 100-year discharge. The designer should determine the following:

- whether the proposed channel materials will be stable for the design discharge
- whether the 100-year flood elevations have been increased at any location
- whether any structures that were previously not in the 100-year floodplain would be flooded by the relocated stream

In addition, the designer should evaluate the relocated channel for any areas where ineffective flow could occur. If wash load is available in the stream, the small particles could accumulate in these areas. The effect of this accumulation should be evaluated based on the hydraulic performance of the channel. In addition, the effect on habitat values in the channel should be coordinated with the Environmental Division.

If the proposed relocated stream does not meet all of the conditions listed above, the designer should return to Step 3, and make the necessary changes to the proposed geometry of the stream.

Step 5: Select appropriate mitigation measures from Section 11.08 to ensure that areas subjected to higher shear stresses (e.g. – the outside of a meander bend) would not be eroded in the design discharge. The selection of these measures should be coordinated with the Environmental Division. The Environmental Division may also recommend additional mitigation measures needed to duplicate the stream values available in the existing stream.

Step 6: If the mitigation measures selected in Step 5 will affect the hydraulic roughness or cross section of the channel, the designer should return to Step 4 to re-evaluate the hydraulic performance of the proposed channel.

11.05.3 DESIGN PROCEDURES FOR ALLUVIAL CHANNELS

Once the supporting data have been collected as described in Section 11.03 and the initial steps described in Section 11.05.1 have been completed, the actual natural stream design process can be carried out for the relocated channel. Because a stable alluvial channel is subject to fluvial processes which can alter its cross section or planform, the natural stream design process will require both hydraulic and sediment transport analyses. Although the procedure in this section is presented as a series of linear steps, the actual design process may turn out to be iterative, since the hydraulic and sediment transport characteristics of a channel are interrelated. Thus, an initial analysis of the channel may require the designer to make adjustments based the results of one analysis or another. In this manner, the process should typically progress from the preliminary design to the final result.

The general natural stream design procedure for alluvial channels is described in the following steps. Because this is a general procedure, it contains little detail as to how each step will be accomplished by the designer. Rather, detailed procedures for most of the steps listed below are provided in Section 11.05.4.

Step 1: Determine characteristics of the existing stream, including:

- bed-material size gradation
- Manning's n-value using Cowan's Method
- existing channel cross sections at several locations in order to determine the average channel width and depth as well as the variability in those dimensions
- length of the reach
- existing plan form, including the sinuosity ratio and the other meander characteristics listed in Section 11.03.4
- existing vertical profile

Step 2: Determine the discharge data needed to support the design, including both the 100-year peak flood discharge and the flow duration curve. Conduct a hydraulic analysis of the existing channel as described in Section 11.05.1.5 for the 100-year peak discharge. Note whether any existing structures are located within the existing 100-year floodplain.

Step 3: Determine sediment inflows for the project reach by calculating a sediment transport rating curve for the upstream supply reach; that is, the channel reach upstream of the channel relocation project limits. The sediment discharge rating curve may be computed based on a typical cross section in the supply reach by computing normal depth and using an appropriate sediment transport equation, as described in Section 11.03.2..

Step 4: Determine the bankfull discharge and effective discharge. Based on the results of these two procedures, estimate the channel forming discharge.

Step 5: Develop a stability curve based on the channel forming discharge and the sediment inflow rating curve developed in the previous steps. This involves calculating a family of slope-width-depth solutions for the channel cross section that satisfy normal depth calculations and provide the needed sediment transport capacity for the channel forming discharge.

Step 6: Check the slope and width of the existing channel against the stability curve developed in the previous step. If the slope and width do not reasonably match the curve, the designer should re-evaluate the stability of the existing channel. If the existing channel still appears to be stable, either check the data used to develop the stability curve, or adjust the width of the proposed channel to match the curve. This should provide the designer with a proposed channel geometry that is capable of transporting the inflowing sediment load through the project reach.

Step 7: Determine the cross section, planform and vertical profile of the relocated channel. In as much as possible, the design should duplicate the physical parameters measured for the existing channel, including sinuosity and the variability in the channel width and depth.

Step 8: Conduct a sediment budget analysis using the channel dimensions proposed for the relocated channel. Based on the criteria described in Section 11.04.2, the designer should conduct the analysis either by means of sediment rating curves or with the use of computer aided analysis. If the sediment budget analysis shows that either aggradation or degradation will occur, the designer should return to Step 8 with the appropriate changes in the channel cross section.

Step 9: Conduct a hydraulic analysis of the proposed relocated stream for the 100-year peak discharge. If the computed 100-year flood elevations for the relocated stream are greater than the elevations determined for the existing channel, the designer should modify the stream cross section to provide greater hydraulic conveyance and return to Step 8. Note that it also may be possible to modify the floodplain rather than the channel to provide the needed conveyance.

Step 10: Select appropriate mitigation measures from Section 11.08 to minimize the erosion of the relocated channel. Since a stable alluvial channel should be able to adjust its planform, the designer should make a distinction between in-channel measures and measures on the floodplain. Hard revetments or mitigation measures provided in Section 11.08 may be used near the edges of the floodplain to protect critical areas (e.g. – roadway embankments) from potential damage by future lateral migration of the channel. The erosion resistance of these measures should be checked using a 50-year design discharge. Measures installed within the channel itself may not need to be checked for erosion resistance, since it is assumed that the channel will migrate. However, these measures should offer sufficient resistance to allow the permanent vegetation to establish. The selection of these measures should be coordinated with the Environmental Division. The Environmental Division may also recommend additional mitigation measures needed to duplicate the stream values available in the existing stream.

Step 11: If the mitigation measures selected in Step 10 will affect the hydraulic roughness or cross section of the channel, the designer should return to Step 9 to re-evaluate the hydraulic performance of the proposed channel.

11.05.4 NATURAL STREAM DESIGN PROCEDURES

The previous two sections generalized natural stream design procedures for channel relocation projects in threshold and alluvial streams. Many of the individual steps in these generalized procedures are sufficiently complex, and they require their own detailed procedures. This section presents the detailed procedures needed to support the general framework provided in the previous sections.

11.05.4.1 ROUGHNESS COEFFICIENT DETERMINATION BY COWAN'S METHOD

When selecting Manning's n-values to be used in the hydraulic analysis of a stream, the designer has the option of estimating the value from Table 5A-1 or applying Cowan's equation (Equation 11-2), described in Section 11.03.4. Cowan's equation may prove useful; especially where the selection of n-value based on Table 5A-1 is not straightforward. The equation may be applied to any channel where the hydraulic radius is equal to 15 feet or less in the following manner:

Step 1: Select the base n-value, n_0, from Table 11A-1 in the Appendix. This value represents the effective Manning's n-value for the material comprising the channel bed, and would be the value used for a perfectly straight, smooth channel, free of obstructions or vegetation.

Step 2: Determine values for n_1, n_2, n_3 and n_4 from Table 11A-1. For each factor, match the description provided under the "Criteria" column to the conditions in the stream being analyzed. A more complete description of each of these criteria is provided in Ven T. Chow's *Open Channel Hydraulics*. It should be remembered that these factors are additive; that is, each value represents an additional amount to be added to the base n-value determined in Step 1. Caution should be exercised by the designer so as not to "double count" any of the factors when selecting these values. For example, severe sloughing of the channel banks considered in selecting a value due to irregularity should not be considered as representing a variation in the channel cross section.

Step 3: Compute a value for the sinuosity using Equation 11-6, as described in Section 11.05.4.2.

Step 4: Based on the computed value for sinuosity, select a value for m_5 from Table 11A-1 and compute a value for Manning's n-value from Equation 11-2.

11.05.4.2 COMPUTING SINUOSITY

Computing a value for the sinuosity (as defined in Section 11.03.4) of a stream may be accomplished using the project survey, supplemented by either topographic mapping or aerial photography if needed. This procedure is illustrated in Figure 11-15, and is as follows:

Step 1: Trace a line along the centerline of the stream valley from the beginning of the project reach to the end, measuring its length L_v. If the overall valley (as opposed to the channel) follows a curved alignment, L_v should be based on a line that generally follows the valley curvature.

Step 2: Measure the length of the channel, L_{chan}, between the same two valley points following any meanders that may exist. Where the channel follows a meandering path through the valley, the value of L_{chan} will be greater than L_v.

Step 3: Compute the sinuosity of the stream using Equation 11-6 as:

$$Sin = \frac{L_{chan}}{L_v} \tag{11-6}$$

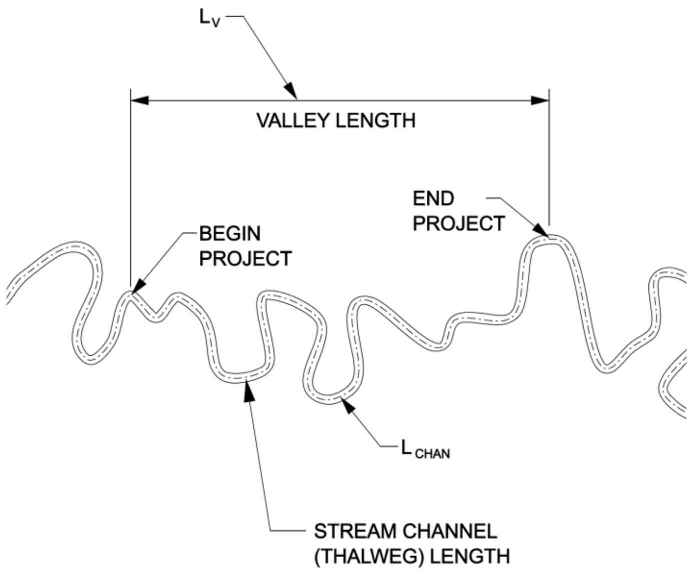


Figure 11-15
Measuring Valley and Stream Length for Sinuosity Computation

11.05.4.3 MEASURING MEANDER CHARACTERISTICS

As discussed in Section 11.03.4, meander characteristics can be defined in terms of a number parameters that are illustrated in Figure 11-7. Measuring these parameters for the existing stream may perhaps be most efficiently accomplished by using tools available in most computer-aided drafting software and working directly with the CADD files for the project survey data. If additional information is needed, it can be obtained from either topographic mapping or aerial photography.

Longer project reaches may include multiple meanders. Where this is the case, the procedure in this section should be used by the designer to measure the parameters of each meander. The results should be used to determine the average, minimum, and maximum values for each of the meander characteristics discussed in this section. The variation in these parameters should then be duplicated in the planform of the relocated channel to the extent that site constraints will allow.

The recommended procedure for the designer should be as follows:

Step 1: Using either hand or computer-aided drafting techniques, fit a circle to each of the curves in the meandering planform and measure the radius of each circle (R_c) as shown in Figure 11-16a. It is generally sufficient to fit these circles visually. As needed, compute the average, minimum, and maximum radius values.

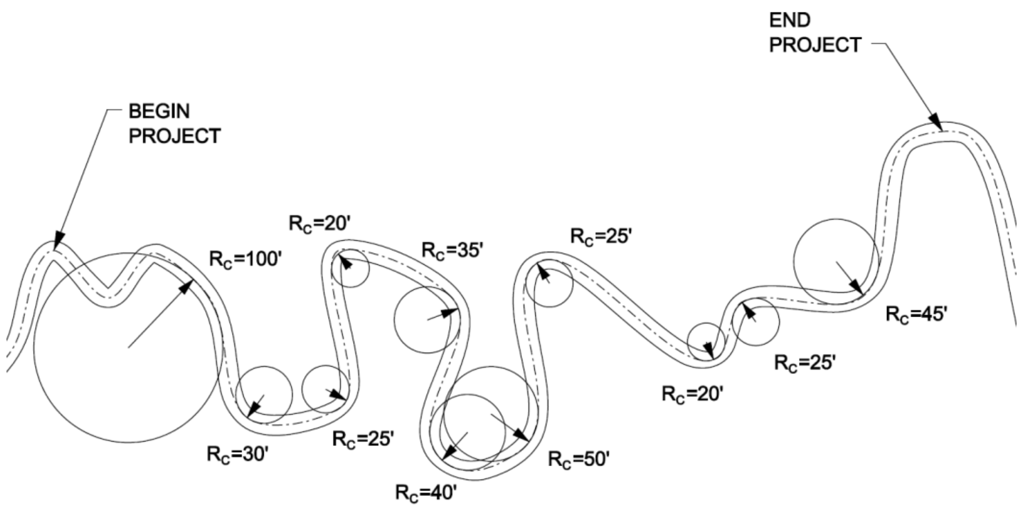


Figure 11-16a
Measuring Radius of Curvature for a Meandering Reach

Step 2: Visually determine and mark the two points at which the channel alignment begins to deviate from the circles which were drawn in Step 1. Determine the arc angle (θ) between these points with respect to the center of the circle as shown in Figure 11-16b. As needed, compute the average, minimum, and maximum values of these arc angles.

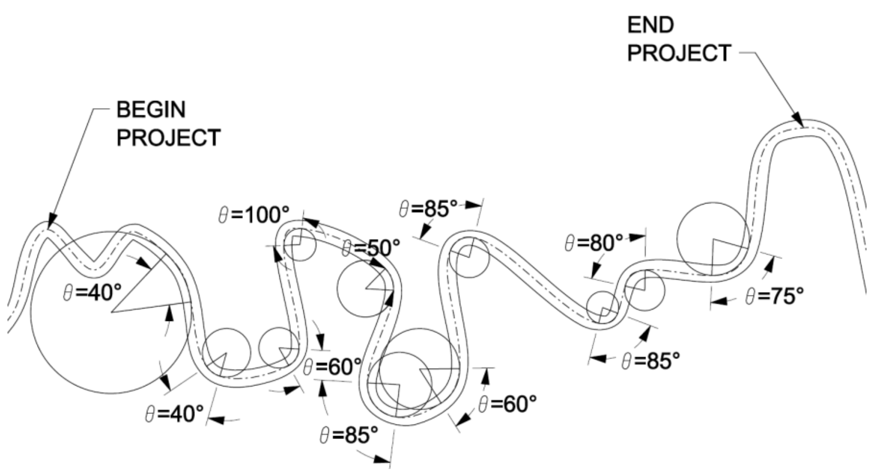


Figure 11-16b
Measuring Radius of Arc Angles for a Meandering Reach

Step 3: Visually determine and mark the deflection points between adjacent meander bends. Where there are straight reaches between the meanders, mark the approximate midpoints of these reaches. Beginning at one end of the project reach, measure the meander wavelength (L) as the straight-line distances between every other point along the channel, as shown in Figure 11-16c. As needed, compute the average minimum and maximum values of the meander wavelengths.

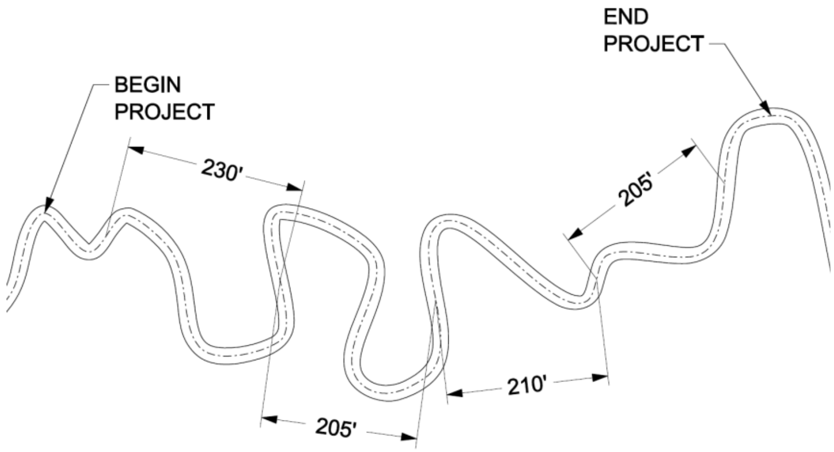


Figure 11-16c
Measuring Radius of Meander Wavelength for a Meandering Reach

Step 4: Using the deflection points marked in Step 3, compute the meander arc length (M_L) as the distances along the channel flow line between every other point, as shown in Figure 11-16d. As needed, compute the average, minimum, and maximum values of the meander arc lengths.

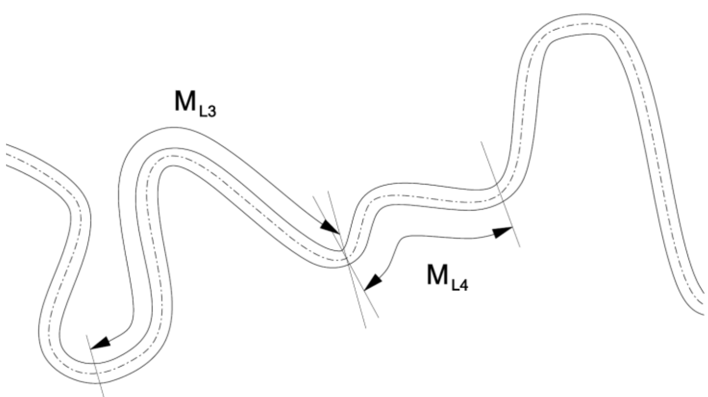


Figure 11-16d
Measuring Radius of Arc Length for a Meandering Reach

Step 5: As shown in Figure 11-16e, the meander amplitude (M_A) is measured as the distance between the channel flow lines at the furthest points of adjacent meander bends. Again, the designer should compute the average, minimum, and maximum values for this parameter.

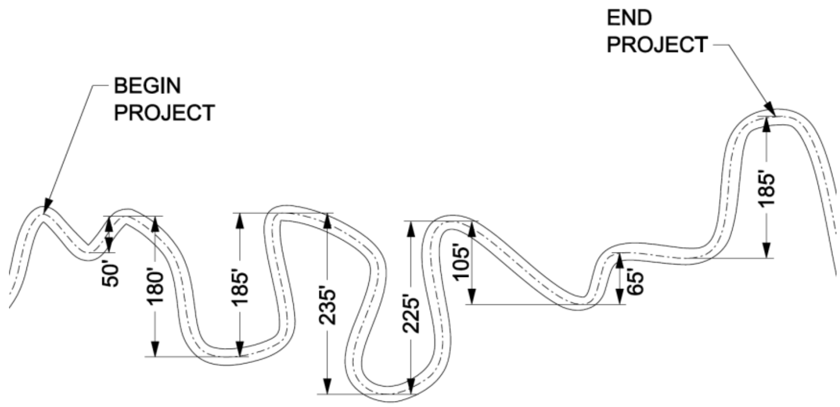


Figure 11-16e
Measuring Radius of Meander Amplitude for a Meandering Reach

11.05.4.4 ESTIMATING A FLOW DURATION CURVE

As described in Section 11.04.3, a flow duration curve indicates the percentage of time that a given discharge value will be exceeded at a given site. Determining a flow duration curve requires that flow duration information from nearby gauged sites be transferred to the project site, which will most likely be un-gauged.

It is critical that the watershed characteristics for the stream gauging site be as similar as possible to those for the project site. Since flow duration is dependent on watershed conditions, the accuracy of this procedure is directly related to the similarity of the selected gauged sites to the project site in terms of slope, geology, and land use. If possible, it is desirable for the ratio of the drainage area at the project site to the drainage areas at the gauging stations be between 0.5 and 2.0.

The procedure for estimating the flow duration at a site is as follows:

Step 1: Based on data from the USGS Publication *Flow Duration and Low Flows of Tennessee Streams Through 1992,* or a similar publication, select a group of presently active or historical stream gauging stations that are near the project site and have watershed characteristics similar to the project site. At least four sites should be selected, when possible.

Step 2: Record the flow duration statistics for each of the gauging stations selected from the publication used in Step 1.

Step 3: The duration statistics will be presented as a set of flow classes based on the percent of time that a given discharge is exceeded, from 99.5% to 0.5% of the time. These exceedance flows will usually be directly proportional to the drainage area. Thus, for each of the flow classes, the designer should construct a plot of discharge versus drainage area using the data from all of the gauging stations identified in Step 1. Then, draw a straight line through the data for each flow class.

Step 4: Based on the drainage area at the project site, use the graphs constructed in Step 3 to determine a discharge for each flow class.

11.05.4.5 ESTIMATING SEDIMENT FLOWS

Computing a sediment discharge for an alluvial stream should be considered a two step process. The first step involves a hydraulic analysis and the second step uses the results of the hydraulic analysis to estimate the quantity of sediment that would be transported. The hydraulic analysis generally involves determining an effective roughness factor (such as Manning's n-value) and then using this roughness factor to compute the value for hydraulic radius that is associated with the sediment. This hydraulic radius should then be used by the designer in a sediment transport equation to compute the total sediment load within the reach.

Sediment transport is a complex process. There has been a considerable amount of research in this area, yielding a wide variety of sediment transport equations, but none that will cover all circumstances found in nature. For the purposes of most natural stream designs, the designer should chose one of the following two equations:

- The **Brownlie Sediment Transport Equation** should be used for sand bed streams with particle sizes up to 1.4 mm
- The **Meyer-Peter and Muller Equation** should be used for streams with beds composed of gravel or coarser particles, with sizes of 0.4 mm and larger

Often, the particle size distribution for a stream includes both sand and gravel sized particles. In this situation, using both sediment transport equations, the anticipated sediment flow should be computed and the larger value used for design.

The procedures in this section may be used on TDOT projects to compute a sediment discharge (Q_S) in tons/day for a given discharge. However, the alluvial stream design process usually requires the computation of rating curves of sediment transport versus discharge. Thus, these procedures will usually be carried out multiple times for a range of discharges.

This analysis can also be performed using the SIAM module included in the computer program HEC-RAS, beginning with version 4.0 of the software.

11.05.4.5.1 BROWNLIE SEDIMENT TRANSPORT FUNCTION

The roughness and sediment transport equations developed by Brownlie are recommended for sand-bed streams because they account for bed-form roughness. Brownlie derived two separate roughness equations to account for the various sand bed forms and designated them for upper and lower regime flows. Upper regime flow occurs with bed forms such as plane bed, antidunes or chutes, and pools, which do not provide significant form resistance. Thus, it is characterized by relatively high velocities and high sediment transport. Lower regime flow occurs on dunes or ripples, which provide significant form resistance. Thus, it is characterized by relatively low velocity and low sediment transport.

The following procedure may be used by the designer to compute sediment discharge using the Brownlie Equations:

Step 1: Examine the project geotechnical report to determine the median sediment particle size (D_{50}) as well as particles sizes for the 16^{th} and 84^{th} percentile particle sizes (D_{16}

and D_{84}). The geotechnical report should also provide the specific gravity of the sediment (γ_s). If the specific gravity is not provided, γ_s may be assumed to be 170 lb/ft^3.

This information can then be used to compute the bed material gradation coefficient (σ):

$$\sigma = \left(\frac{D_{84}}{D_{16}} \right)^{0.5} \tag{11-7}$$

Step 2: Assuming a depth of flow in the channel (d), compute the cross sectional area (A). Using the Continuity Equation (Equation 5-3), compute the average flow velocity (V) based on the given discharge. For an initial trial, the depth may be estimated by using the valley slope and a Manning's n-value based on engineering judgment.

This hydraulic analysis, combined with the soils information determined in Step 1 is needed to compute the sediment transport, beginning with selecting the flow regime. The selection of the flow regime also requires the calculation of a dimensionless parameter related to the unit flow in the channel (q_*):

$$q_* = \frac{Vd}{\sqrt{gD_{50}}} \tag{11-8}$$

Where: g = acceleration due to gravity, (32.2 ft/sec^2)

Step 3: Determine whether the flow would be in the high or low regime. In order to determine if upper or lower regime flow exists, Brownlie defined a grain Froude number (F_g) and a variable F_g'. These variables are computed as follows:

$$F_g = \frac{V}{\sqrt{gD_{50}\left(\frac{\gamma_s - \gamma}{\gamma} \right)}} \tag{11-9}$$

Where: V = velocity of the flow, (ft/s)
g = acceleration due to gravity, (32.2 ft/sec^2)
D_{50} = median particle diameter of the sediment, (ft)
γ_s = specific gravity of the sediment, (lb/ft^3)
γ = specific gravity of water, 62.4 (lb/ft^3)

$$F_g' = \frac{1.74}{S^{0.3333}} \tag{11-10}$$

Where: S = slope, (ft/ft)

According to Brownlie, upper regime flow occurs when the slope (S) is greater than 0.006 ft/ft or if F_g is greater than $1.25F_g'$. Lower regime flow occurs if F_g is less than $0.8F_g'$. Between these limits there exists a transition zone. For practical calculations, the point at which $F_g = F_g'$ may be used to distinguish between upper and lower regime flow.

Step 4: Based on the results of Step 2, compute the hydraulic radius associated with the bed form (R_b). For upper regime flow:

$$R_b = 0.2836 D_{50}\, q_*^{0.6248} S^{-0.2877} \sigma^{0.0813} \qquad (11\text{-}11)$$

And, for lower regime flow:

$$R_b = 0.3742 D_{50}\, q_*^{0.6539} S^{-0.2542} \sigma^{0.1050} \qquad (11\text{-}12)$$

Where: The variables are as defined in the previous steps and D_{50} is in feet.

Step 5: The designer should then check the flow depth assumed in Step 2 by computing the hydraulic radius associated with the sides of the channel (R_S) and computing a revised cross sectional flow area. The hydraulic radius of the channel sides may be computed as:

$$R_s = \left(\frac{V n_S}{1.468 S^{0.5}} \right)^{1.5} \qquad (11\text{-}13)$$

Where: V = the average flow velocity, (ft/s)
n_S = Manning's roughness coefficient for the channel sides, (dimensionless)
S = slope, (ft/ft)

Based on the cross sectional data, the designer should then estimate the total width on the bottom of the cross section across which sediment transport is assumed to be taking place. For this analysis, this total width is used to determine the wetted perimeter of the channel bed (P_b). The lengths of the two sides of the channel between the bed and the water surface should be added together to determine the wetted perimeter of the channel side slopes (P_s). This information can then be used to compute the cross sectional area of the flow as:

$$A = R_b P_b + R_s P_s \qquad (11\text{-}14)$$

Where: R_b = hydraulic radius associated with the channel bottom, (ft)
P_b = wetted perimeter of the channel bottom, (ft)
R_S = hydraulic radius associated with the channel sides, (ft)
P_S = wetted perimeter of the channel sides, (ft)

If the flow area computed by this equation does not match the flow area determined in Step 2, the designer should revise the depth assumption as needed and return to Step 2. Otherwise, continue with Step 6.

Step 6: Compute sediment concentration in the flow (C). Before computing the sediment concentration, it is first necessary to solve four separate equations to obtain dimensionless parameters needed for solving the final sediment concentration equation. These four equations must be solved in specific order (Equations 11-15 through 11-18), since the results from each equation are used as inputs to the next subsequent equation.

The first equation computes a dimensionless form of hydraulic radius related to the roughness of the channel materials (R_g) as follows:

$$R_g = \frac{\sqrt{gD_{50}^3}}{v} \qquad (11\text{-}15)$$

Where: g = acceleration due to gravity, (32.2 ft/sec^2)
D_{50} = median particle diameter of the sediment, (ft)
v = kinematic viscosity of water, (approximately 1.0x10^{-5} ft^2/sec)

Using R_g, the second equation computes a dimensionless parameter (Y) as follows:

$$Y = \left(\sqrt{\frac{\gamma_s - \gamma}{\gamma}} R_g\right)^{-0.6} \qquad (11\text{-}16)$$

Where: R_g = parameter computed by Equation 11-15, (dimensionless)
γ_s = specific gravity of the sediment, (lb/ft^3)
γ = specific gravity of water, (62.4 lb/ft^3)

The third equation computes a dimensionless shear parameter related to the critical shear stress for the channel boundary materials (τ_{*0}) as follows:

$$\tau_{*0} = 0.22Y + 0.06(10)^{-7.7Y} \qquad (11\text{-}17)$$

This dimensionless shear parameter (τ_{*0}) is then used to compute a Froude number related to the flow condition at the critical shear stress (F_{go}) as follows:

$$F_{go} = \frac{4.596\,\tau_{*0}^{0.5293}}{S^{0.1405}\sigma^{0.1606}} \qquad (11\text{-}18)$$

Where: S = slope, (ft/ft)
σ = bed material gradation coefficient, (from Equation 11-7)

Once these four equations have been completed, the sediment concentration load in the flow (C), in parts per million can be computed as:

$$C = 9{,}022\left(F_g - F_{go}\right)^{1.978} S^{0.6601}\left(\frac{R_b}{D_{50}}\right)^{-0.3301} \qquad (11\text{-}19)$$

Where: F_g = sediment grain Froude number, computed in Step 2
S = slope, (ft/ft)
D_{50} = median particle diameter of the sediment, (ft)
R_b = hydraulic radius associated with the bed form, (ft)

Step 7: Convert the sediment discharge from a concentration in ppm (C) to a load in tons/day (Q_s) as follows:

$$Q_s = \gamma_s CBdV \tag{11-20}$$

Where: γ_s = specific gravity of the sediment, (lb/ft^3)
C = sediment concentration, (ppm)
B = width of the channel transporting sediment, (ft)
d = depth in the channel, (ft)
V = flow velocity, (ft/sec)

This equation will yield a value for Q_s in lbs/sec. This result can then be converted to tons/day by multiplying by 43.2.

11.05.4.5.2 MEYER-PETER AND MULLER SEDIMENT TRANSPORT FUNCTION

The Meyer-Peter and Muller sediment transport equation is appropriate for gravel bed streams because the associated equations for computing hydraulic roughness can account for the decrease in roughness which occurs with increasing water depth. Like the Brownlie equations, it treats the channel bottom separately from the channel sides by computing separate values for roughness and hydraulic radius. However, this method goes a step further by separately considering each of the influences that contribute to the roughness of the channel bottom. The roughness equations will compute a conceptual roughness value that represents only the roughness associated with the coarseness of the materials on the channel bottom. The other contributions to the total roughness of the channel should be added by engineering judgment, based on the factors used in Cowan's Equation described in Section 11.03.4.

For a given discharge, the Meyer-Peter and Muller equation sediment transport equation can be used to compute the sediment load as follows:

Step 1: Assume a depth of flow in the channel (d). For an initial trial, the depth may be estimated by using the valley slope and a Manning's n-value based on engineering judgment. Based on the assumed depth, compute:

- cross sectional area (A) of the flow
- average flow velocity (V) based on the Continuity Equation (Equation 5-3), using given discharge
- maximum shear stress on the bottom of the channel (τ_{max}), using Equation 5-10
- the shear velocity associated with the maximum shear stress (U_*')

The shear velocity may be computed as:

$$U_*' = \sqrt{gds} \tag{11-21}$$

Where: d = depth of flow in the channel, (ft)
S = slope of the channel, (ft/ft)
g = acceleration due to gravity, (32.2 ft/sec^2)

Step 2: Based on the depth assumed in Step 1, the designer should determine separate hydraulic radius and roughness values for the bottom and sides of the channel. This is accomplished by first computing the hydraulic radius and roughness values that are associated only with the grain roughness of the coarse materials on the channel bottom. This hydraulic radius (R_b') can be computed from Equation 11-22 as:

$$\frac{V}{U_*^{'}} = 5.66 \log\left(3.80 \frac{R_b^{'}}{D_{84}}\right) \qquad (11\text{-}22)$$

Where: V = average flow velocity, (ft/sec)
U_*' = shear velocity computed in Step 1, (ft/sec)
R_b' = hydraulic radius associated with grain roughness, (ft)
D_{84} = grain size for which 84 percent of the bed material is finer, (ft)

The Manning's roughness coefficient associated with the grain roughness of the channel bottom particles, (n_b') can be computed as follows:

$$n_b^{'} = \frac{1.486\left(R_b^{'\,0.1667}\right)}{g 5.66 \log\left(3.80 \frac{R_b^{'}}{D_{84}}\right)} \qquad (11\text{-}23)$$

Where: R_b′ = hydraulic radius associated with grain roughness, (ft)
g = acceleration due to gravity, (32.2 ft/sec^2)
D_{84} = grain size for which 84 percent of the bed material is finer, (ft)

As described above, the n-value equated by using Equation 11-23 accounts only for the grain roughness of the materials on the channel bottom. The overall roughness of the channel bottom (n_b) may be computed by re-writing Equation 11-3 as:

$$n_b = \left(n_b^{'} + n_1 + n_2 + n_3 + n_4\right) m_5 \qquad (11\text{-}24)$$

Where: n_b' = base n-value for the coarse bed materials
n_1 = coefficient for the degree of channel irregularity
n_2 = coefficient for variations in the channel cross section
n_3 = coefficient for relative effect of channel obstructions
n_4 = coefficient for channel vegetation
m_5 = correction factor for the degree of meandering

The computed value for n_b can then be used to compute the hydraulic radius associated with the channel bottom (R_b) as follows

$$R_b = \left(\frac{V\, n_b}{1.486\, S^{0.5}}\right)^{1.5} \qquad (11\text{-}25)$$

Where: V = average flow velocity, (ft/sec)
S = slope, (ft/ft)
n_b = Manning's n-value associated with the channel bottom, (dimensionless)

Based on engineering judgment, the designer should select a Manning's n-value for the sides of the channel (n_s). The Cowan method may be used to compute this n-value, as described above. Once this n-value has been determined by the designer, the hydraulic radius associated with the channel side slopes (R_s) may be compute as follows:

$$R_s = \left(\frac{V\, n_s}{1.486\, S^{0.5}} \right)^{1.5} \qquad (11\text{-}26)$$

Where: V = average flow velocity, (ft/sec)
S = slope, (ft/ft)
n_s = Manning's n-value associated with the channel sides, (dimensionless)

Step 3: Based on the cross sectional data, estimate the total width on the bottom of the cross section across which sediment transport is assumed to be taking place. This total width should be assumed equal to the wetted perimeter of the channel bed (P_b). The lengths of the two sides of the channel between the bed and the assumed water surface should be added together to determine the wetted perimeter of the channel side slopes (P_s). This information can then be used to compute the cross sectional area of the flow as:

$$A = R_b P_b + R_s P_s \qquad (11\text{-}27)$$

Where: R_b = hydraulic radius associated with the channel bottom, (ft)
P_b = wetted perimeter of the channel bottom, (ft)
R_s = hydraulic radius associated with the channel sides, (ft)
P_s = wetted perimeter of the channel sides, (ft)

If the flow area computed by this equation does not match the flow area determined in Step 1, the designer should revise the depth assumption as needed and return to Step 1; otherwise, continue with Step 4.

Step 4: One of the key inputs to the Meyer-Peter and Muller sediment transport equation is the median diameter (D_m) of the sediments on the channel bottom. The information needed to compute this parameter should be contained in the grain size analysis conducted as a part of the geotechnical investigation. The grain size analysis should define a set of grain size classes and indicate the fraction of the total sample that is within each grain size classification. The median diameter may then be computed as:

$$D_m = \sum_{i=1}^{n} f_i\, D_i \qquad (11\text{-}28)$$

Where: n = total number of sediment size classifications
f_i = fraction of the sediment sample in size classification *i*
D_i = mean particle diameter of the particles in size classification *i*, (ft)

Step 5: The Meyer-Peter and Muller sediment transport equation yields a value for sediment transport per unit width of the channel bottom (q_S). That is, it computes the transport in terms of weight per time for a 1-foot wide swath of the total bottom width. For the sake of convenience, the equation is computed by defining three variables (A, B, and C) which are used to compute the actual sediment transport. The first parameter (A) may be computed as:

$$A = \left(\frac{n_b'}{n_b} \right)^{1.5} \gamma R_b S \tag{11-29}$$

Where: n_b' = base n-value for the coarse bed materials
n_b = Manning's n-value associated with the channel bottom, (dimensionless)
γ = specific gravity of water, (62.4 lb/ft^3)
R_b = hydraulic radius associated with the channel bottom, (ft)
S = slope, expressed as a decimal, (ft/ft)

The next parameter (B) may be computed as:

$$B = 0.047 (\gamma_s - \gamma) D_m \tag{11-30}$$

Where: γ = specific gravity of water, (62.4 lb/ft^3)
γ_S = specific gravity of the sediment, 170 lb/ft^3 (if no other value is provided)
D_m = median diameter of the sediments computed in Step 4, (ft)

The third parameter (C) may be computed as:

$$C = 0.25 \left(\frac{\gamma}{g} \right)^{0.333} \left(\frac{\gamma_s - \gamma}{\gamma_s} \right)^{0.667} \tag{11-31}$$

Where: γ = specific gravity of water, (62.4 lb/ft^3)
γ_S = specific gravity of the sediment, (lb/ft^3)
g = acceleration due to gravity, (32.2 ft/sec^2)

Once these three parameters have been computed, the sediment transport per unit width (q_S) may be computed as:

$$q_s = \left(\frac{A - B}{C} \right)^{1.5} \tag{11-32}$$

Where: q_S = sediment transport per unit width, (lb/sec-ft)

Step 6: Compute the total sediment transport by multiplying the per-unit width value computed in Step 5 by the bottom width of the channel (B). The bottom width should be assumed to be the width across the channel bottom over which sediment transport will occur. Thus, the total sediment transport (Q_S) may be computed as:

$$Q_s = q_s \ B \tag{11-33}$$

Where: Q_s = total sediment transport, (lb/sec)

It should be noted that this equation uses the horizontal width across the channel bottom (B) as opposed to the wetted perimeter (P_b). Additionally, it assumes that the sediment transport rate will be constant across the entire width of the channel. The results of Equation 11-33 can be converted to tons per day by multiplying the result by 43.2.

11.05.4.6 ESTIMATING CHANNEL FORMING DISCHARGE

Channel forming discharge is required only for the relocation of an alluvial stream. As discussed in Section 11.04.3, channel forming discharge should be evaluated based on a comparison between the bankfull discharge and the effective discharge. Thus, the procedure for estimating the channel forming discharge involves computing both the bankfull and effective discharges as follows:

Step 1: Obtain cross sections at several locations along the existing channel. If a clear pool and riffle structure exists in the stream, use the cross sections at the upstream ends of the riffles.

Step 2: Based on photography or an actual field check, examine each of the cross sections taken in Step 1 to determine the height of any of the indicators of bankfull flow listed in Section 11.04.3. Where possible, this determination should be based on two or more indicators.

Step 3: For each cross section, prepare a rating curve of top width versus depth. Look for deflection points in these rating curves and compare the elevations at which these deflections occur to the height of the bankfull flow indicators found in Step 2. From this comparison, determine the depth of the bankfull flow at each cross section.

Step 4: If a hydraulic model has been developed for the existing channel, run a series of discharges by trial and error until a profile is computed that most closely matches the bankfull flow depths determined in Step 3. If a hydraulic model is unavailable, compute a discharge at each cross section using Manning's Equation based on the slope of the channel through the project reach. The average of the discharges computed in this manner should be considered the bankfull discharge.

Step 5: Once the bankfull discharge has been determined, the next step should be to determine the effective discharge. This process should begin by estimating a flow duration curve as described earlier in this section. This procedure will provide a discharge value for a series of flow classes based on the percent of time that each discharge value is exceeded at the project site.

Step 6: Compute a sediment rating curve for each of the cross sections taken in Step 1. This can be accomplished by computing the total sediment transport at each cross section for each of the flow duration curve discharge values determined in Step 5.

Step 7: Using the results from Steps 5 and 6, construct a bar graph as depicted in Figure 11-17 for each of the cross sections in the analysis. This graph will have dual Y-axes. One Y-axis will represent the percentage of time that a given discharge is exceeded, and the other Y-axis will represent the corresponding sediment discharge in tons per day. The X-axis of this graph should represent increasing discharge. For each discharge along the X-axis, the percent exceedance is multiplied by the sediment transport value. The point at which the product of these two factors is maximized is the effective discharge. The effective discharges determined for the cross sections in the project reach should be averaged to determine the final effective discharge.

The peak of the effective discharge curve shown in Figure 11-17 indicates the fraction of discharge that transports the majority of material; and thus, does the most work in forming the channel.

Step 8: The designer should then compare the values determined for bankfull discharge and effective discharge and decide on a final channel forming discharge value based on engineering judgment.

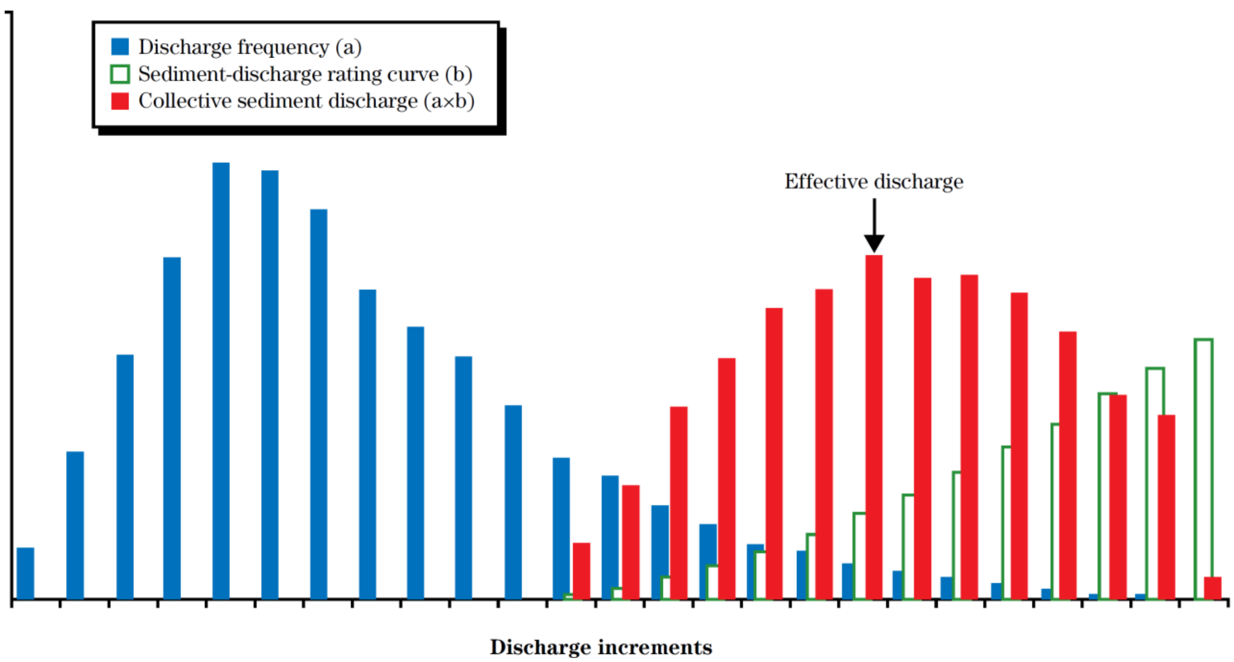


Figure 11-17
Relationship Between Sediment Transport, Frequency, and Effective Discharge
Reference: USDA, NRCS, NEH Part 654 (2007)

11.05.4.7 DEVELOPING A STABILITY CURVE FOR AN ALLUVIAL CHANNEL

The normal procedure for a stream relocation project would be to duplicate the physical parameters of the existing stream as closely as possible. If the existing channel is stable, this approach should theoretically guarantee the stability of the relocated channel. However, in many real-world situations, the existing stream may not be stable, or it may not be possible to exactly duplicate the length or slope of the existing stream. In these situations, it is important for the designer to determine a slope and cross section for the relocated channel such that the relocated channel would remain stable for the current conditions in the project reach.

A stability curve can be utilized to estimate a channel width and slope for the relocated stream that will fit the constraints imposed by the project site without being subject to aggradation or degradation. A stability curve has the channel width on the X-axis and the stream slope on the Y-axis, and the plotted line represents a range of possible combinations of width and slope that would provide a stable condition. A channel for which the combination of width and slope would plot above the line would be subject to degradation, while a combination of width and slope below the line would result in aggradation. A stability curve is constructed for a given design discharge, depending on the purpose of the calculation. For most alluvial stream designs, this should be the channel forming discharge.

The following procedure can be used to construct a stability curve for an alluvial channel:

Step 1: Based on the purpose of the analysis, determine the discharge to be used to construct the curve. This will most often be the channel forming discharge.

Step 2: Select a cross section in the existing stream upstream of the project reach and use the procedure provided in Section 11.05.4.5 to compute the sediment transport (Q_S) that would be generated by the selected discharge.

Step 3: Assume a channel width and slope for the relocated reach. Compute the sediment transport in the relocated channel for the assumed slope and channel width. If the sediment transport in the relocated channel is greater than the sediment transport in the existing upstream cross section, the channel will be subject to degradation and the proposed slope should be reduced. Conversely, if the sediment transport in the relocated channel is less than the upstream value, the slope should be increased. Adjust the slope as needed and repeat this process until the sediment transport computed for the relocated channel matches the sediment transport at the upstream cross section.

Step 4: Assume a new channel width and repeat Step 3. This process should be carried out for a range of channel widths to construct a curve. The completed curve should have a minimum point as shown in Figure 11-18.

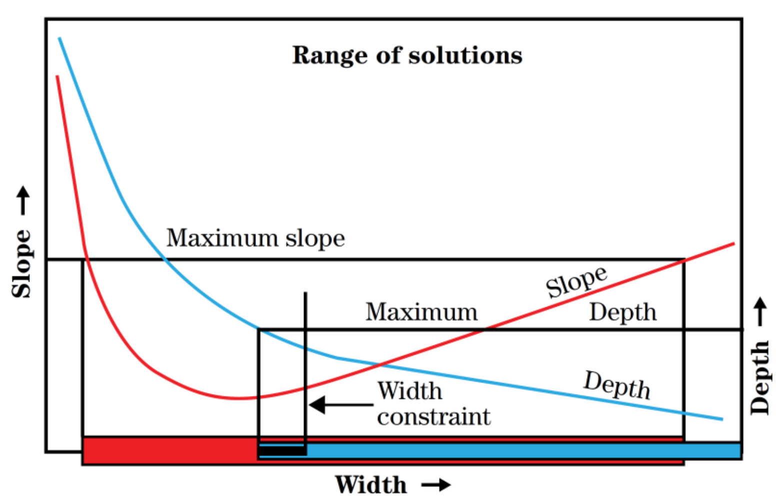


Figure 11-18
Theoretical Stability Curve Illustrated
Reference: USDA, NRCS, NEH Part 654 (2007)

These curves can also be constructed using the SIAM module included in HEC-RAS version 4.0 and higher.

11.05.4.8 SEDIMENT IMPACT ANALYSIS

The procedure in the previous section is useful for the stability design of a stream relocation project, but is based on a single discharge. Once the proposed alignment and cross section of the relocated channel have been established, the stability of the new channel should be assessed for the full range of discharges which can be expected to occur at the site. This assessment is called a sediment impact analysis.

Sediment impact analysis may be carried out by means of either rating curves or computer analysis. The rating curve method should be adequate for the majority of TDOT projects. However, Section 11.04.2 provides criteria for determining when a computer software analysis may be justified. Procedures for both methods are as follows:

Rating curve method:

Step 1: If a flow duration curve has not already been determined for the project site, one should be estimated based on the procedure provided earlier in Section 11.05.4.4. In order to construct a sediment rating curve for a given location on the stream, the sediment transport should be computed for each of the discharges on the flow duration curve using the procedures provided earlier. This will allow for the development of a rating curve of sediment transport versus discharge. These sediment rating curves should be developed for the reach upstream of the project (the supply reach) as well as for the project reach itself.

Step 2: Superimpose the curve(s) developed for the relocated reach onto the curve(s) developed for the upstream supply reach, as shown in Figure 11-9. If the two curves match reasonably well, then the relocated stream should be stable for the expected sediment inflows and the analysis is complete.

If the two curves deviate from each other, the potential for some type of instability is indicated and corrective action should be taken. If the rating curve for the project reach is below the upstream rating curve, aggradation would occur in the relocated reach. Conversely, if the rating curve for the relocated reach is above the upstream curve, degradation could be expected. If instability is indicated, the procedure should continue with Step 3.

Step 3: Compare the two rating curves to determine the discharge at which the two curves begin to deviate. Based on the hydraulic analysis of the relocated channel, determine the flow depth which corresponds to this discharge, and alter the width of the relocated channel above (or in some cases below) this depth to make the needed adjustments to the sediment transport capacity of the relocated stream. Then, go back to Step 1 with the modified channel cross section.

Computer method:

Computer-aided sediment transport analysis can be difficult for the novice designer. The quality (and validity) of the results will depend much on the quality and accuracy of the input data. However, it is often difficult to obtain accurate soils data due to limited project budget and the natural variability of soils across a project site. Modeling results are also affected by the values selected for various parameters which control the computations, such as the time step. For these reasons, the best results will be obtained where data is available for calibration of the model in advance. In addition, it is best for this type of modeling to be conducted by experienced individuals.

One of the basic data inputs to any sediment transport modeling computer program is the flow rates which occur in a stream. The discharge data for a sediment impact analysis should be reflective of the actual daily stream flows which occur at the project site and cover a sufficient length of time to provide a general assessment of the stability of the relocated stream reach. In general, a year of flow data would likely be adequate for this purpose. The procedure for obtaining this data for the project site will be similar to the procedure recommended earlier in this section for determining a flow duration curve. However, instead of using flow duration statistics for nearby gauging stations, the procedure would be carried out for daily stream flows. This data can be downloaded from the website of the USGS Tennessee Water Science Center by accessing the historical stream flow data.

A detailed procedure for conducting computer-aided sediment impact analysis is beyond the scope of this Manual. For more information on how to conduct the analysis, the designer should refer to the user’s manual and documentation of the software being used. In particular, the *HEC-RAS Reference Manual* (March 2008) provides the basic information needed to conduct a sediment impact analysis using the USACE program HEC-RAS.

SECTION 11.06 – THE NATURAL STREAM DESIGN PLAN

11.06.1 NATURAL STREAM DESIGN PLAN DEVELOPMENT PROCESS

The natural stream design process for stream relocation should begin early in the development of a roadway project and continue until well after the construction of the roadway has been completed. The need for a stream relocation project is usually identified in the early planning stages of the project as it goes through the NEPA process. The NEPA process usually results in a document known as the Environmental Boundaries (EB). The EB forms the basis of the detailed design of the stream relocation project, which is included in the overall plan set for the roadway project. Although design of the relocation should begin during the Preliminary Plans stage, the EB may not be finalized until the Right-of-Way Plans stage. Thus, the design process may require some coordination with the Environmental Division. Once the construction of the roadway has been completed, the natural stream design process continues for a period of years as the success of the relocation project is monitored and maintenance performed as needed.

A natural stream design usually involves consideration of a wide variety of influences on the habitat values of a stream, including hydraulics, sediment transport, vegetation, etc. Because of this, a well-designed project will require the designer to gain input from a number of different divisions within TDOT. The Design Division will have the lead role in preparing the natural stream design plan sheets, and it will be based on coordination with other Divisions or Sections within TDOT.

It is strongly recommended that the designer conduct a field check at the proposed relocation site prior to completing a detailed natural stream design. In addition, it may be necessary for the designer to be present during the construction process to ensure that the proposed mitigation measures are being installed as intended.

This section discusses the steps which the Design Division should to carry out during development of the stream relocation plan.

11.06.1.1 THE ENVIRONMENTAL BOUNDARIES DOCUMENT

During the NEPA process, a final alignment for the proposed roadway will be selected, and the potential impacts of that alignment on ecological resources will be identified. One of the results this process is the Environmental Boundaries document which contains the Ecology Report, Mitigation Memorandum, and Environmental Commitments. These documents provide detailed information on the impacts that the proposed construction may have on various habitats present in the project area, as well as specific steps that should be taken to minimize, avoid, or mitigate these impacts.

The EB document is provided to the Design Division from the Environmental Division and should form the basis for developing the project specific objectives and goals related to the stream relocation. The objectives should be specific, realistic, achievable, and feasible. They should also be based on the goal of providing the needed stream functions and habitat in the relocated reach. The objectives should:

- meet the requirements specified in the EB document
- clearly identify the desired project outcome

- define the goals of the stream design (e.g. – mimic existing boulders, reconstruct 150 LF of channel, recreate fish habitat, etc…)
- define the scope and limits of the work
- provide an approach to collecting the remaining necessary field data
- evaluate mitigation alternatives, including the risks associated with each

Once the project design objectives are established, the designer should be able to identify the remaining data collection efforts and develop the final design. The objectives of the design and the approach should be in written format and should be placed in the project documentation folder.

11.06.1.2 DESIGN OF THE RELOCATED STREAM

One of the primary roles of the designer in the stream relocation design process is to select a planform (i.e. alignment), profile, and cross section for the relocated channel that will pass the incoming sediment load without either accumulating additional sediment or being eroded. Because of the relationships between the channel configuration, vegetation, and the sediments on the channel bottom, a significant amount of coordination may be required between the Design Division and the other TDOT divisions which may have design input.

During the preliminary plan development phase of the natural stream design, the designer should provide the Environmental Division with a set of draft plans showing the proposed channel configuration. This will allow the Environmental Division to comment on the proposed design before it is finalized.

11.06.1.3 STREAM MITIGATION PRACTICES

As discussed in Section 11.04.6, stream mitigation practices can be placed in the relocated channel to re-establish the stream bed profile, prevent erosion or encourage the re-establishment of vegetation. Some of the needed mitigation measures will be specified by the Environmental Division through the EB and possible other environmental commitments. The designer should place these measures into the relocated channel at appropriate locations as well as select additional measures as needed to protect the stability of the relocated reach.

During the right-of-way plan development stage, the designer should provide the Environmental Division with a set of draft plans showing the proposed stream mitigation measures. This will allow the Environmental Division to comment on the proposed design before it is finalized.

11.06.1.4 PLANTING SCHEDULE AND PLANT LIST

During the right-of-way plan development stage, the designer should forward a set of plans to the Environmental Division for their use in developing the plant list and planting schedule. Along with the stream relocation sheets, the forwarded plans should include the present and proposed layout sheets for the roadway in the vicinity of the stream relocation. In addition, the plans should show the proposed right-of-way and any utilities present in the stream relocation area.

The Environmental Division will typically select the vegetation needed to complete the natural stream design. Usually, this will include all of the vegetation to be planted as a part of the stream relocation project. This should also include vegetation that will be placed in conjunction with coconut (coir) rolls or other vegetated mitigation practices (i.e. gabions, MSE walls, riprap, etc.).

During the development of the construction plans, the designer should coordinate with the Environmental Division to ensure that the following items are included in the plans:

- any special notes required for the specific stream relocation
- site-specific construction notes where required including any calendar or time of year constraints for planting specified vegetation
- planting schedule and plant table including any seed mixes
- limits and extent of each measure shown in the proposed layout
- special vegetation related details (i.e., tree tie-down details, spacing details, etc…)
- estimated quantities for each vegetative measure

The designer should insert the mitigation measures noted above into the overall plan set at the appropriate locations. The designer should also verify any quantities that have been provided by the Environmental Division. In addition, the details of the vegetation design should be reviewed to ensure that they are compatible with the other elements of the stream relocation and roadway designs. In coordination with the Environmental Division, the designer may revise the Planting Schedule as needed to ensure that it is compatible with the overall project design. Details of what is to be shown on each sheet of the stream relocation plans are provided in the following section.

11.06.1.5 PERMITS

The Environmental Division, Natural Resources Office, Permits Section, will typically file permit applications and coordinate with the appropriate regulatory agencies to acquire the permits needed for a project. Once the right-of-way plans have been completed, the designer should forward a set of plans to the Environmental Division to initiate the permit application process. The Environmental Division will typically review these plans and may request additional information and sketches or modifications to the plans to accommodate regulatory requirements. The plans forwarded to the Environmental Division should include the sheets for the stream relocation design, as well as the EPSC plan sheets.

Once the required permits have been secured, the Environmental Division will typically distribute copies of the approved permits to the Design Division. These permits will often contain specific conditions or limitations.

11.06.2 PLAN REQUIREMENTS FOR NATURAL STREAM DESIGN

The final result of natural stream design should be a set of stream relocation plans sufficient for the contractor to bid and construct the relocated stream. The Stream Relocation Plans should be grouped together as a separate section of the roadway plan set, immediately before the Traffic Control Plans. As with other aspects of the roadway design, Stream Relocation Plans will become progressively more complete as the roadway design advances through the various plan development phases. This section outlines the data that should be included on the Stream Relocation Plan sheets at each of these phases.

Stream relocation plans are based on a centerline alignment for the relocated channel, which will have its own stationing, independent of roadway alignment for the associated project. Thus, it is important to provide a means of locating the proposed stream centerline. This is usually accomplished by providing a station and offset for the beginning and ending points of the relocation, referenced to the roadway alignment. However, the locations of these points could also be based on the project coordinate system. In either case, the relocation plans must be “tied” to the roadway plans, preferably the mainline or side road centerline stations.

11.06.2.1 DEVELOPMENT OF THE STREAM RELOCATION PLAN

Plans for stream relocation become progressively more complete as the design for the overall project goes through the various stages of plan development. The information to be shown on the stream relocation plans at each stage of plan development may be summarized as follows:

Preliminary Plans should include the plan and profile of the proposed relocated channel.

Right-of-Way Plans should include the proposed design features such as the cross sections and mitigation measures. Each mitigation measure in the proposed design should be identified by its station on the relocated channel alignment. At this stage, the plans should also include a Stream Relocation Notes sheet, stream design tables, and detail sheets for any non-standard mitigation measures.

Construction Plans add the Planting and Seeding Schedules and quantity tabulations to the design information developed for the previous plan phases, as well as any needed additional Stream Relocation Notes and special details. In addition, the natural stream design should be adjusted as needed to accommodate any conditions that were imposed by the permit approvals.

11.06.2.2 RELOCATION PLAN INFORMATION BY PLAN SHEET

Stream relocation plans should be grouped together in the overall project plans, and shall be located in the plan set just before the Traffic Control Plans. The typical set of stream relocation plans should include the following sheets:

The ***Stream Relocation Notes Sheet*** includes the General Notes for all projects and any Special Notes developed for each specific relocation project.

The ***Stream Relocation Quantities Sheet*** includes tables listing the specific quantities for the stream relocation portion of the project.

The Stream Relocation Quantities table should include:

- pay item number
- item description
- units and quantity

This table lists the quantities for plant materials as well as for structural stream measures, and should be organized by pay item number as shown in Figure 11-19. Any footnotes which may be required should be placed below the table in list form similar to the Estimated Roadway Quantities footnotes.

STREAM MITIGATION QUANTITIES			
ITEM NO.	**DESCRIPTION**	**UNIT**	**QUANTITY**
203-08	CHANNEL EXCAVATION (UNCLASSIFIED)	C.Y.	8,500
209-03.31	STREAM MITIGATION - COCONUT FIBER ROLLS	L.F.	486
209-03.32	STREAM MITIGATION - BOULDER CLUSTERS	EACH	4
209-03.38	STREAM MITIGATION - J-HOOK	EACH	2
209-03.39	STREAM MITIGATION - W-WEIR	EACH	2
209-03.45	STREAM MITIGATION - LIVE FASCINES (WILLOW)	L.F.	1220
209-03.64	STREAM MITIGATION - FELLED TREE (24" DIA.)	EACH	3
209-08.02	TEMPORARY SILT FENCE (WITH BACKING)	L.F.	530
209-08.08	ENHANCED ROCK CHECK DAM	EACH	2
209-65.01	TEMPORARY STREAM DIVERSION (PUMP AROUND)	EACH	1
801-01.07	TEMPORARY SEEDING (WITH MULCH)	UNIT	2
801-01.07	TEMPORARY SEEDING (WITH MULCH)	UNIT	2
801-02	SEEDING (WITHOUT MULCH)	UNIT	7
802-01.04	TREES (ACER RUBRUM) (1.5 - 2" CAL. B&B)	EACH	12
802-02.30	CUTTINGS: SALIX NIGRA (18IN-24IN LENGTH)	EACH	281
802-02.31	CUTTINGS: SALIX SERICEA (18IN-24IN LENGTH)	EACH	281
802-12.26	PLANTANUS OCCIDENTALIS (SYCAMORE SEEDLING B.R.)	EACH	12
801-03	WATER (SEEDING & SODDING)	M.G.	1
805-12.03	EROSION CONTROL BLANKET (TYPE III)	S.Y.	760

Figure 11-19
Example Tabulation of Quantities for Stream Relocation
(Values in Table Shown for Example Only)

This sheet should also include any Cross Drain and/or Side Drain Tables that will list the small structures (if any) that are to be constructed in conjunction with the relocated stream. The tables to be used on this sheet will be as shown in Table 6A-2 through Table 6A-5 of this Manual.

Finally, the Stream Relocation Quantities sheet should contain a reference to the bridge plans for any structures with a span greater than 20 feet which may cross the relocated stream.

The ***Stream Relocation Plan and Profile Sheets*** are split such that the top half of the sheet shows a plan view of the proposed stream relocation and the bottom half shows the proposed profile. The plan view should include:

- centerline alignment of the proposed relocated channel, including the locations of the beginning and ending points (stations), channel stationing, and curve data
- proposed roadway centerline station and offset labeled at the beginning and ending stations of the proposed relocated channel
- existing features such as roads, drainage structures, trees, etc…

- proposed roadway centerline and roadway stationing
- proposed structures such as riffle structures, J-hooks, riprap, culverts, etc…
- existing and proposed right-of-way, along with any temporary easements needed for construction and post-construction monitoring
- bench marks or other survey monuments
- existing utilities

If the relocated stream is to be crossed by a bridge, the size and type of the bridge should be noted in the plan view, along with a reference to the applicable bridge plans.

The profile should include:

- existing ground along the proposed channel centerline alignment
- proposed ground along the proposed channel centerline (channel flow line), with tie-ins to the existing ground at the ends of the project
- channel stationing at the proposed alignment beginning and ending points
- proposed roadway centerline station and offset labeled at the beginning and ending stations of the proposed relocated channel
- top of bank profile
- labels with stationing for all of the channel bottom profile features such as riffles, pools, weirs, J-hooks, etc.
- riffles should be labeled by type (log or rock) and stations should be shown for the beginning and ending points of each riffle

The ***Planting Schedule Sheets*** should include a minimum of two sheets for each project. The first sheet (or set of sheets) will apply to grasses, grass mixtures, and other seeded vegetation. This sheet should show the plan view of the proposed channel relocation including the following:

- centerline alignment of the proposed relocated channel with channel stationing
- existing features such as roads, drainage structures, trees, and contours
- proposed roadway centerline station and offset labeled at the beginning and ending stations of the proposed relocated channel
- proposed roadway centerline and roadway stationing
- proposed structures such as riprap, pipe culverts, bridges, etc…
- hatched areas showing the different seeding zones indentified

Each seeding zone will have a unique combination of grasses and other types of seed blends for the area to be covered (i.e. stream bank, floodplain, upland areas, etc.) and will be represented on the plan view by a different style of hatching for each zone. The designer should provide a legend of the zone hatchings on this sheet for reference.

This first sheet should also contain a table of estimated seeding quantities which is divided into sections for each seeding zone identified, as shown in Figure 11-20. Each section of the table will include a line for the location to be seeded (indicates the seeding zone), separate lines for each type of seed or proposed seed mixture for the specific zone, and an additional line to specify the total quantity of seed designated for each zone.

Entries on the Estimated Seeding Quantities table should also include:

- pay item number
- item description
- application rate and area to be seeded
- percent distribution (should total 100% for each zone)
- total quantity (total weight in pounds)

ESTIMATED SEEDING QUANTITIES					
ITEM NO.	DESCRIPTION	APPLICATION RATE (LB./ACRE)	AREA (ACRES)	DISTRIBUTION (PERCENT)	QUANTITY (LB.)
ZONE 1 - STREAMBANK					
801-01.06	SEEDING (SPECIAL MIXTURE)	40	0.25	50	5.00
801-01.35	GRASS SEED MIX (RIPZN/FLPL) W/MULCH	40	0.25	25	2.50
801-01.36	SPECIAL WETLAND SEED MIXTURE	20	0.25	25	1.25
ZONE 1 TOTAL			0.25	100	8.75
ZONE 2 - BANKFULL BENCH (FLOODPLAIN)					
801-01.08	SEEDING (SPECIAL MIXTURE) WITH MULCH	40	0.62	25	6.20
801-01.35	GRASS SEED MIX (RIPZN/FLPL) W/MULCH	40	0.62	75	18.60
ZONE 2 TOTAL			0.62	100	24.80
ZONE 3 - UPLAND AREAS					
801-01.04	SEEDING (WILDFLOWER MIXTURE)	30	1.12	32	10.75
801-01.35	GRASS SEED MIX (RIPZN/FLPL) W/MULCH	40	1.12	68	30.46
ZONE 3 TOTAL			1.12	100	41.22
ZONE 3A - UPLAND AREAS (BETWEEN HAUL ROAD AND MAINLINE)					
801-01.01	SEEDING (SERICEA LESPEDEZA)	40	1.50	100	60.00
ZONE 3A TOTAL			1.50	100	60.00
ZONE 4 - HAUL ROAD/TEMPORARY ACCESS					
801-01.06	SEEDING (SPECIAL MIXTURE)	40	0.32	25	3.20
801-02	SEEDING (WITHOUT MULCH)	40	0.32	75	9.60
ZONE 4 TOTAL			0.32	100	12.80
TOTALS			3.81		147.57

Figure 11-20
Example Seeding Quantities Table
(Values in Table Shown for Example Only)

The second sheet (or set of sheets) of the Planting Schedule will include the details for planting trees, live stakes, stems, shrubs, or other types of vegetation that are not generally seeded. This sheet will contain the Planting Table, non-standard planting details, and installation notes for the specified plant materials.

As shown in Figure 11-21, the Planting Table should be divided into sections for each planting zone, which should correspond to the zones listed in the Seeding Table. The header line for each planting zone should include a brief description indicating the location of the zone. Beneath each zone header, there should be a separate line for each type of tree or bush to be planted. Entries for this table include:

- pay item number
- pay item description
- common name of plant

- spacing
- total number of stems per acre
- location specific area in acres
- percentage (describes the proportion of each plant material, should total 100% for each planting zone)
- total quantity of stems for each zone

The Planting Method entries are used to describe the type of planting (i.e. – live stakes bare root planting, etc.) as well as the sizes of the material to be planted.

PLANTING TABLE (PLANTING AREA 3.81 ACRES)

ITEM NO.	DESCRIPTION	COMMON NAME	SPACING (FT)	STEMS/ACRE	AREA (ACRES)	DISTRIBUTION (PERCENT)	QUANTITY (STEMS)
ZONE 1 - STREAMBANK							
802-02.30	CUTTINGS: SALIX NIGRA (18IN-24IN LENGTH)	BLACK WILLOW	3 X 3	4502	0.25	24.00	281
802-02.31	CUTTINGS: SALIX SERICEA (18IN-24IN LENGTH)	SILKY WILLOW	3 X 3		0.25	24.00	281
802-02.32	CUTTINGS: CORNUS AMOMUM (18IN-24IN LENGTH)	SILKY DOGWOOD	3 X 3		0.25	24.00	281
802-02.33	CUTTINGS: SAMBUCUS CANADENSIS (18IN-24IN LENGTH)	ELDERBERRY	3 X 3		0.25	24.00	281
802-12.07	BETULA NIGRA (RIVER BIRCH SEEDLING B.R.)	RIVER BIRCH	8 X 8	188	0.25	1.33	16
802-12.26	PLATANUS OCCIDENTALIS (SYCAMORE SEEDLING B.R.)	SYCAMORE	8 X 8		0.25	1.33	16
802-12.37	QUERCUS PALUSTRIS (PIN OAK SEEDLING B.R.)	PIN OAK	8 X 8		0.25	1.33	16
	ZONE 1 TOTAL				0.25	100	1172
ZONE 2 - BANKFULL BENCH (FLOODPLAIN)							
802-12.17	JUGLANS NIGRA (BLACK WALNUT SEEDLING B.R.)	BLACK WALNUT	8 X 8	4502	0.62	12.00	399
802-12.18	LIQUIDAMBER STYRACIFLUA (SWEETGUM SEEDLING B.R.)	SWEET GUM	8 X 8		0.62	12.00	399
802-12.19	LIRIODENDRON TULIPIFERA (TULIP POPLAR SEEDLING B.R.)	TULIP TREE	8 X 8		0.62	12.00	399
802-12.26	PLATANUS OCCIDENTALIS (SYCAMORE SEEDLING B.R.)	SYCAMORE	8 X 8		0.62	12.00	399
802-12.37	QUERCUS PALUSTRIS (PIN OAK SEEDLING B.R.)	PIN OAK	8 X 8		0.62	12.00	399
802-12.44	ULMUS AMERICANA (AMERICAN ELM SEEDLING B.R.)	ANERICAN HORNBEAM	8 X 8		0.62	12.00	399
802-13.54	CORNUS AMOMUM (SILKY DOGWOOD SDLNG BARE ROOT)	SILKY DOGWOOD	8 X 8		0.62	12.00	399
802-01.04	TREES (ACER RUBRUM) (1.5 - 2" CAL. B&B)	RED MAPLE	12 X 12	10	0.62	4.00	10
802-01.07	TREES (LIQUIDAMBER STYRACIFLUA) (1.5 - 2" CAL. B&B)	SWEET GUM	AS DIRECTED	10	0.62	4.00	10
802-11.17	JUGLANS NIGRA (BLACK WALNUT 2-5 FT CNTNR GRWN)	BLACK WALNUT	AS DIRECTED	4	0.62	4.00	4
802-11.39	QUERCUS RUBRA (NORTHERN RED OAK 2-5 FT CNTNR GRWN	NORTHERN RED OAK	75 X 75	4	0.62	4.00	4
	ZONE 2 TOTAL				0.62	100	2821
ZONE 3 - UPLAND AREAS							
802-12.04	ACER SACCHARUM (SUGAR MAPLE SEEDLING B.R.)	SUGAR MAPLE	8 X 8	188	1.12	15.5	35
802-12.11	CERCIS CANADENSIS (REDBUD SEEDLING B.R.)	REDBUD	8 X 8		1.12	15.5	35
802-12.12	CORNUS FLORIDA (FLOWERING DOGWOOD SEEDLING B.R.)	FLOWERING DOGWOOD	8 X 8		1.12	15.5	35
802-12.14	DIOSPYROS VIRGINIANA (PERSIMMON SEEDLING B.R.)	PERSIMMON	8 X 8		1.12	15.5	35
802-12.15	FAGUS GRANDIFOLIA (BEECH SEEDLING B.R.)	AMERICAN BEECH	8 X 8		1.12	15.5	35
802-12.19	LIRIODENDRON TULIPIFERA (TULIP POPLAR SEEDLING B.R.)	TULIP TREE	8 X 8		1.12	15.5	35
802-01.06	TREES (ACER SACCHARUM) (1.5 - 2" CAL. B&B)	SUGAR MAPLE	AS DIRECTED	8	1.12	3	8.00
802-11.29	QUERCUS ALBA (WHITE OAK 2-5 FT CNTNR GRWN)	WHITE OAK	75 X 75	8	1.12	3	8.00
802-11.12	CORNUS FLORIDA (FLOWERING DOGWOOD 2-5 FT CNTNR GR	FLOWERING DOGWOOD	AS DIRECTED	10	1.12	1	10.00
	ZONE 3 TOTAL				1.12	100	236
ZONE 3A - UPLAND AREAS (BETWEEN HAUL ROAD AND MAINLINE)							
802-03.01	SHRUBS (SALIX HUMILLS)	PRAIRIE WILLOW	10 X 10	20	1.50	100	20.00
	ZONE 3A TOTAL				1.50	100	20
ZONE 4 - HAUL ROAD/TEMPORARY ACCESS							
802-03.01	SHRUBS (SALIX HUMILLS)	PRAIRIE WILLOW	10 X 10	188	0.32	50	30
802-12.11	CERCIS CANADENSIS (REDBUD SEEDLING B.R.)	REDBUD	8 X 8		0.32	50	30
	ZONE 4 TOTAL				0.32	100	60
TOTALS					3.81		4309

Figure 11-21
Example Planting Table
(Values in Table Shown for Example Only)

The ***Stream Design Data Sheet*** contains at least two tables which provide detailed information on the proposed stream design. The first table is the Stream Profile Data table which provides flow line and top of bank elevations at each of the break points in the flow line profile. These break points occur at the transitions between the elements of a pool and riffle stream structure. The table should thus include an entry for each of the following points in the flow line:

- begin riffle
- end riffle / begin pool
- mid-pool
- end pool / begin riffle
- tie to existing flow line
- scour pool
- step

As shown in Figure 11-22, the Stream Profile Data table should include:

- channel station
- bankfull elevation (top of bank)
- channel invert elevation
- description (selected from the list above-or others)

STREAM PROFILE DATA			
STATION	**BANKFULL ELEVATION**	**CHANNEL INVERT**	**DESCRIPTION**
5+42.34	929.61	926.65	TIE TO EXISTING
5+50.31	929.53	927.36	START RIFFLE
5+70.00	929.35	926.98	END RIFFLE / START RUN
5+81.29	929.25	926.41	END RUN / START POOL
5+95.60	929.12	924.65	MID POOL
6+21.13	928.88	925.95	END POOL / START GLIDE
6+45.82	928.65	926.53	END GLIDE / START RIFFLE
6+85.29	928.29	925.89	END RIFFLE / START RUN
6+92.09	928.23	925.31	SCOUR POOL
6+98.05	928.17	925.40	STEP
6+04.97	928.11	924.83	SCOUR POOL
6+11.47	928.05	925.00	STEP
6+20.67	927.95	924.47	TIE TO EXISTING

Figure 11-22
Example Stream Profile Data Table
(Values in Table Shown for Example Only)

The second table on this sheet is the Stream Mitigation Data Table which identifies the locations for each of the structural mitigation measures used in the relocated stream. This table should include:

- control point channel station

- control point offset
- flow elevation at the channel forming discharge
- channel bottom elevation
- depth of scour (if applicable)
- description (indicates type of measure used, e.g. J-hook, root wad, etc.)
- design data

The control point location, as indicated on the Standard Drawings, is the point that will be used in the field to stake the location of the mitigation measure. The station and offset for these control points must be shown in the Stream Mitigation Data table so that the measure can be constructed in the field at the correct location. The designer should provide the structure control point based on their placement of the structure in their design files.

The last column in the Stream Mitigation Data Table is the Design Data. Specific information needed to properly construct a measure, such as minimum stone size or the required tensile strength of an anchor for a rack structure should be shown in this column. Different information will be required for different mitigation measures, and the specific information to be listed for each type of measure is described in the Planning and Design Criteria provided in Sections 11.08.1 and 11.08.2.

Any footnotes that may be required to provide additional guidance should normally be placed below the table in list form similar to the Estimated Roadway Quantities footnotes.

Figure 11-23 shows an example of the Stream Mitigation Data Table.

The ***Stream Relocation Detail Sheets*** should be included in the plan set only if non-standard structural measures are being included in the natural stream design. These sheets should provide drawings of the measures sufficient for construction along with any required installation notes.

The plan set should include a separate set of ***Stream Relocation Cross Section Sheets*** even if the relocated stream can be shown on the roadway cross sections. These cross sections should be placed at regular intervals along the relocated channel centerline alignment based as well as at any crossings. The cross sections should be located based on the channel centerline stationing and show:

- existing and proposed ground
- flow line and top of bank elevations for the cross section
- the cross sectional area of cut and fill
- labels indicating whether the cross section is located in a pool, riffle, run, or glide

STREAM MITIGATION DATA

STATION	OFFSET (FEET)	CHANNEL FORMING FLOW ELEV.	CHANNEL BOTTOM ELEV.	SCOUR DEPTH (FEET)	DESCRIPTION	DESIGN DATA
2+05	0	873.65	869.92	1.23	ROCK CROSS VANE	MIN. STONE DIAMETER = 9 IN
2+58	-6.8	871.23	867.53		ROOT WAD	MIN. LOG DIAMETER = 15 IN
2+67	-7.2	871.05	867.22		ROOT WAD	MIN. LOG DIAMETER = 15 IN
2+76	-6.9	870.92	867.25		ROOT WAD	MIN. LOG DIAMETER = 15 IN
2+85	-7.1	870.85	867.00		ROOT WAD	MIN. LOG DIAMETER = 15 IN
2+94	-6.7	870.79	866.97		ROOT WAD	MIN. LOG DIAMETER = 15 IN
3+17	0	869.52	865.67		BEGIN ROCK RIFFLE	D50 = 4 IN
3+30	0	869.47	865.43		END ROCK RIFFLE	
3+56	0	868.85	864.83	0.85	"VEE" LOG DROP	MIN. LOG DIAMETER = 18 IN, POINT UPSTREAM
3+60	-7.9	868.81	864.79		BEGIN VEGETATED RIPRAP	CLASS B
3+75	-8.1	868.77	864.75		END VEGETATED RIPRAP	
4+01	9.2	868.14	863.51	1.91	RACK STRUCTURE	MIN. DIA = 15 IN, ANCHOR STRENGTH = 2800 LBS
4+23	8.7	867.81	863.13	2.05	RACK STRUCTURE	MIN. DIA = 15 IN, ANCHOR STRENGTH = 2800 LBS
4+45	0	867.21	862.62	2.15	J-HOOK	MIN. STONE DIAMETER = 12 IN
4+70	0	866.89	861.88	2.15	J-HOOK	MIN. STONE DIAMETER = 12 IN
5+00	0	866.43	861.56	2.15	J-HOOK	MIN. STONE DIAMETER = 12 IN
5+18	-9.5	865.78	861.92		BEGIN LONGITUDINAL STONE TOE	CLASS B, SEE STREAM MITIGATION DETAILS
5+25	-1.2	865.74	861.83	0.75	BOULDER CLUSTER	MIN. STONE DIAMETER = 14 IN
5+37	2.7	865.55	861.48	0.75	BOULDER CLUSTER	MIN. STONE DIAMETER = 14 IN
5+48	-2.6	865.21	861.12	0.75	BOULDER CLUSTER	MIN. STONE DIAMETER = 14 IN
5+53	-9.8	865.00	860.95		END LONGITUDINAL STONE TOE	

Figure 11-23
Example Stream Mitigation Data Table
(Values in Table Shown for Example Only)

11.06.2.3 EPSC PLANS FOR STREAM RELOCATION

Sheets for Erosion Prevention and Sediment Control should not be included in the plan sheets for a stream relocation project. Rather, the EPSC measures for the stream relocation should be incorporated into the EPSC plans for the overall project.

As described in Section 10.06.2, the EPSC plan for a roadway construction project will have a minimum of two stages. The first is termed the clearing and grubbing stage and covers the initial part of the project when the clearing and large scale earth moving activities for rough grading occur. Typically, the construction of the proposed relocated channel will be included in this stage. Where this is the case, the designer should ensure that the EPSC plans for the first stage include a method for flow diversion during construction of the relocated channel.

In some cases, site-specific conditions or other factors may require that the relocated channel be constructed prior to the start of roadway construction activities. In such cases, it would be possible to place the EPSC measures for the stream relocation project into a separate sub-stage so that these activities could be carried out independently from the larger project.

The second stage is termed the final construction stage (when a two-stage plan is allowed) and covers the construction of the project from rough grading to the finish. Usually, temporary and permanent seeding are not shown in the project EPSC plans, since the contractor will carry out these activities as required in the project specifications. However, the stream relocation plans will include areas which are to receive special seeding and planting as specified by the Planting Schedule. Thus, the EPSC plans should clearly indicate which areas are to be seeded per the project specifications and which areas are to receive special plantings for the stream relocation. In addition, these areas should be provided with notes referring to the stream relocation planting schedule.

SECTION 11.07 – ACCEPTABLE SOFTWARE

Table 11-3 lists software packages that may be used for natural stream design for TDOT stream relocation projects. Although all of the software systems listed in this section offer the capabilities needed to support a natural stream design project, TDOT does not specifically recommend the use of any commercial software package. Rather, it is anticipated that HEC-RAS, which is in the Public Domain, will be the most commonly used computer program.

The computer programs listed in this section should be used for natural stream design unless special circumstances on the project or in the watershed require the use of another software package. The TDOT design manager should approve the use of any software other than what is listed in this section.

Natural Stream Design Software	Uses
HEC-RAS	Hydraulic analysis, stable alluvial channel design, sediment transport analysis
B.A.G.S.	Bedload transport analysis for gravel-bed streams based on six equations, Excel based, export to other programs
WinXSPRO	Sediment transport rates, specific to high gradient streams, geometry estimates
RIVERMorph™	Data storage, natural stream design, stream gauge analysis, etc.

Table 11-3
Natural Stream Design Computer Software

11.07.1 HEC-RAS

HEC-RAS was developed by the U.S. Army Corps of Engineers for performing one-dimensional steady or unsteady flow analysis of open channel flow. The public domain program offers the capability of computing the sediment transport capacity for a specific cross section. Beginning with version 4.0, HEC-RAS offers the capability of a full sediment transport analysis through a reach using the methodologies developed for the previous program HEC-6. HEC-RAS should be used for the analysis of relocated natural streams.

11.07.2 B.A.G.S.

Bedload Assessment in Gravel-bedded Streams (BAGS) is public domain software developed by the U.S. Forest Service’s Stream Systems Technology Center for computing bedload transport. The program is an Excel based spreadsheet model that predicts bedload transport capacities on the basis of available field data (i.e. surveyed cross sections and material grain size distributions) and stores the output as tabulated values on separate spreadsheets. The values can be retained for additional analysis or even exported to other programs to produce visualizations and plots of the results. Options within BAGS allow the designer to select from six transport relations (models) specifically developed for gravel-bed streams. The program can compute the transport rates for a single discharge or series of discharges depending on availability of data.

Each of the six available models for computing bedload transport rates require the designer to input site specific parameters including:

- discharge measurements
- average slope of the study reach
- grain size distribution (or estimate thereof) of the bed material
- measured channel cross section or bankfull width at a minimum

The designer should evaluate the results from the BAGS model to verify that the computed transport rates are within the realm of "reasonable" for the studied reach. Bedload transport models can be sensitive to estimates of available grain sizes and shear stress; therefore, small differences in estimating these two inputs can result in very large differences in computed results. With any transport analysis, the designer should consider if the study reach or watershed is even appropriate for transport analysis, if the bed material sampled is truly representative of the reach, and if the shear stress estimates of the boundary material are reasonable. The use of the BAGS model should be avoided in highly sinuous channels and streams with sharp changes in grade. Additionally, the program is not applicable to mountain streams or bedrock channels where sediment supply is not driven by the natural fluvial process.

11.07.3 WINXSPRO

WinXSPRO was developed by the U.S. Forest Service's Stream Systems Technology Center for computing stream channel cross section data for geometric, hydraulic, and sediment transport parameters, is available in the public domain, and can be run in as stand-alone application. WinXSPRO was specifically developed for use in high-gradient streams (gradient > 0.01) and supports four alternative resistance equations for computing boundary roughness and resistance to flow. Cross section input data may be obtained from project cross-section surveys.

WinXSPRO allows the user to subdivide the channel cross section into multiple sub-sections and additionally has the ability to vary water-surface slopes with discharge to reflect natural conditions. Analysis options include developing stage-discharge relationships, evaluating changes in channel cross sectional area, and computing sediment transport rates. The designer can use the estimated stream-channel geometry cross section hydraulic characteristics and sediment transport output to assist with the natural stream design and monitoring, in-stream flow analysis, the restoration of adjacent riparian areas, and the placement of in-stream mitigation measures (structures).

11.07.4 RIVERMORPH™

RIVERmorph™ is a commercially available software package that is designed to support the design of stream enhancement projects. It employs a database-oriented approach to store, query, and share geomorphic data on a stream and offers a wide variety of tools that can be used to automate the design calculations for a natural stream design project. These tools can assist with reducing survey data, establishing the channel bottom profile, assessing the stability of an alluvial stream, and analysis of discharges recorded at stream gauging stations. RIVERMorph™ also interfaces with the HEC-RAS as well as with HEC-HMS, the Corps of Engineers hydrology software package.

SECTION 11.08 – MITIGATION PRACTICES FOR NATURAL STREAM DESIGNS

This section contains guidelines and criteria for applying a number of commonly used natural stream design mitigation practices on typical stream relocation projects. While this section provides guidance for many best management practices for stream relocation and stabilization activities, it should not be considered an “all inclusive” list. Other measures and standards of practice may be required for any given stream relocation. Site specific considerations or regulatory agency requirements often play a significant role.

Each mitigation practice (section) includes the following information:

- Definition and Purpose
- Appropriate Applications
- Limitations
- Planning and Design Criteria
- Example Application

The example application for each mitigation practice provides a brief example for applying the practice to a stream relocation project and calculating quantities for the pay item(s). However, it will be included only for commonly used mitigation practices.

The mitigation practices in this section are grouped by their primary intended function of a stream relocation project. These two primary functional classifications are:

- Hydraulic Control Mitigation Practices
- Stabilization Mitigation Practices

For simplification, the mitigation practices are presented in the following sections as separate practices. Page numbering at the bottom of each page within Section 11.08 indicates whether the mitigation practice is used for hydraulic control (HC) or stabilization (SB) purposes. The designer should be aware that it is not uncommon for multiple practices to be combined into one integrated technique to provide for the stability of the relocated channel bed and banks or to adequately reconstruct the existing habitat. Since the combination of measures is considered endless for some relocation projects, the designer should evaluate each site on a case-by-case basis as to which measures, or combination of measures, are appropriate for use.

11.08.1 HYDRAULIC CONTROL MITIGATION PRACTICES

This section describes best management practices for in-stream mitigation structures that may be used on TDOT stream relocation projects where natural stream design and construction methods are utilized. The measures presented in this section have been classed as hydraulic control measures since they are typically deployed within the flowing waters of the stream where mitigation practices are needed. These measures are generally not considered suitable for use above the toe of the stream bank. They are primarily used for hydraulic control, grade control, flow deflection, and habitat preservation with the flowing waters of the stream.

11.08.1.1 BOULDER CLUSTERS

Boulder Clusters Placed in Stream
Location: Columbia County, Washington

11.08.1.1.1 DEFINITION AND PURPOSE

Boulder clusters are a permanent in-stream mitigation practice consisting of a single or a group of large immobile rocks strategically arranged in a stream to recreate or improve habitat by producing small scour pools and areas of reduced velocity.

Boulder clusters are generally used to provide permanent habitat for aquatic animals and as in-stream hydraulic improvement structures. When properly spaced, boulder clusters produce turbulence, thereby creating small scour pools and eddies which can be used as fish resting areas. This turbulence diffuses sunlight to provide cover for aquatic life. Boulder clusters can also be used to restore meanders and small pools in channelized reaches and can be used in protecting eroding stream banks by deflecting flow away from the banks. Proper placement of boulder clusters can restore and maintain channel form, thus reducing erosion and sedimentation.

11.08.1.1.2 APPROPRIATE APPLICATIONS

Boulder clusters are generally considered a low-risk mitigation practice for streams provided that they do not block a large portion of the bankfull flow area. On TDOT stream relocation projects, boulder clusters should only be used where existing boulders are present in the reach or adjacent reaches. The use of clusters is applicable to stream relocation projects that include stream stability or habitat preservation as a goal. Boulder clusters may be used in most stream habitat types (i.e. riffles, runs, open pools, etc…), but are most effective when used under the following conditions:

- wide to moderately wide shallow streams
- streams with gravel or rubble (cobble) stream beds
- stream reaches where less than 20 percent of the length could be classified as a pool
- high velocity (supercritical) streams

11.08.1.1.3 LIMITATIONS

The use of boulder clusters should be avoided in streams that do not already show the presence of existing boulders within flowing waters. TDOT's policy is to recreate the habitat of the stream being relocated, but not to enhance it. In addition, the following limitations should be considered by the designer prior to utilizing boulder clusters for a stream relocation project:

- This measure is not recommended for use in streams with sand beds or beds of small gravel (for example, streams in west Tennessee). They should only be used in streams with course gravel or larger substrate.
- This measure is not recommended for unstable streams experiencing either aggradation or degradation.
- The average flow velocity of the stream should be greater than 2 feet per second as sub-critical flow regimes will not allow the desired scour pools to develop.
- Placement of boulders may require the use of heavy equipment, thus causing a significant amount of disturbance to achieve project construction.
- This measure is not suitable for streams with highly erodible stream bank material or streams with a high natural bed load sediment discharge.
- Boulder clusters are not recommended for streams with steep gradients or bedrock channels.

In addition to the limitations provided above, the designer should consider the expected debris load in the channel. Minor amounts of small debris collected on the boulders can be beneficial to in-stream habitat when it becomes lodged against boulder clusters. However, if larger debris collects on the clusters, it may cause negative backwater effects on the upstream channel resulting in sediment deposition, localized flooding, and bank scour. Avoid using boulder clusters in areas where large debris loads are expected.

11.08.1.1.4 PLANNING AND DESIGN CRITERIA

The primary benefits of a boulder cluster are achieved as the stream flow impacts the stone and must flow either over or around it. This creates turbulence which adds oxygen to the water and scours a hole in the channel bottom at the downstream face of the rock. This scour hole provides cover for fish and serves as a mini-pool to preserve aquatic life during periods of low flow. Thus, boulder clusters assist in creating a more diverse habitat for aquatic life. They can also help dissipate high-energy flows and improve the appearance of a channel.

Boulder clusters as described in this section are best utilized in small to moderately wide streams or modified channels that have a uniform shape and little canopy cover. They are useful where erosive forces should be reduced, where habitat should be enhanced, and where the appearance of a channel could be restored to a more natural condition.

The placement of boulder clusters is critical for optimal results. The objective is to place each boulder so that high stream flows will tumble over the boulder, creating an eddy effect that will cause a small hole to form downstream of the rock.

Selecting rocks of an appropriate size is critical to ensuring that they will resist movement during high stream flows. Where possible, the boulders present in the existing stream should be transferred to the relocated channel. Otherwise boulders of the same size as those in the existing stream should be supplied. As an approximate check, the proposed boulder size can be evaluated by using the two equations presented below. The rock sizes determined by these two equations should be compared and the larger size utilized.

$$W_b = \frac{0.00002 V_b^6 \, SG}{0.207 \left(SG - 1\right)^3} \qquad \text{(11HC-1)}$$

Where: W_b = weight of the boulder, (lbs)
V_b = adjusted velocity at the boulder (1.33 times V), (ft/sec)
V = average channel flow velocity, (ft/sec)
SG = specific gravity of the rock, (usually 2.65, dimensionless)

Because Equation 11HC-1 yields the weight of the stone, it will be necessary for the designer to compute the equivalent volume in ft^3 using the specific gravity, and then estimating an approximate dimension based on an assumption of the shape of the boulder.

While Equation 11HC-1 utilizes velocity to estimate the required stone size, Equation 11HC-2 utilizes the depth and friction slope which are components of computing the shear stress:

$$D_s = \frac{32 \, d \, S_f}{SG - 1} \qquad \text{(11HC-2)}$$

Where: D_s = diameter of the boulder, (ft)
d = flow depth, (ft)
S_f = friction slope, (ft/ft)
SG = specific gravity of the rock, (usually 2.65, dimensionless)

In general, the largest dimension of a single boulder should not be greater than one-fifth the width of the channel. However, in smaller channels with gradients of more than 5 percent, an individual boulder may be up to one-third of the channel width. Where possible, the top of the boulder should be lower than the flow level at the channel forming discharge.

Boulder cluster configurations should be shown on the Stream Relocation Plans. The Stream Mitigation Data Table should provide station and offset data to define the location of each cluster. Enter the minimum required boulder diameter into the Design Data column of the table. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Boulder clusters shall be paid for under the following item number:

- Item Number 209-03.32, Stream Mitigation-Boulder Clusters, per Each

11.08.1.1.5 EXAMPLE APPLICATION

Given: Boulder clusters have been proposed as a mitigation measure for the relocation of a threshold stream with the following characteristics:

- Q50 = 450 cfs
- Slope = 1.25%
- Channel bottom width = 12 feet

- Channel side slopes = 1.5H:1V
- Length of reach = 1500 feet

Find: Determine the required boulder size and compute the required quantities for this hydraulic control measure.

Solution: Based on hydraulic analysis of the proposed channel cross section it is determined that the depth of flow, d, is equal to 3.71 feet and the average flow velocity, V, is equal to 6.92 ft/sec. Based on this data, Equations 11HC-1 and 11HC-2 can both be used to estimate the required boulder size. The larger result from these two equations will then be used to specify the required boulder size.

To apply Equation 11HC-1, it is first necessary to estimate the flow velocity at the boulder as 1.33 times the average velocity, or:

$$V_b = 1.33V = 1.33(6.92) = 9.20 \text{ ft/sec}$$

Since the specific gravity of the stone is equal to 2.65, the equation can be solved as:

$$W_b = \frac{0.00002 V_b^6 \, SG}{0.207\,(SG-1)^3} = \frac{0.00002\,(9.20^6)(2.65)}{0.207\,(2.65-1)^3} = 34.6 \text{ pounds}$$

To compare this result to the result of Equation 11HC-2, it is first necessary to convert the weight of the stone into an equivalent diameter. Based on the definition of specific gravity, the specific weight of the stone, γ_S, may be computed as:

$$\gamma_s = SG(\gamma_w) = 2.65(62.2) = 164.8 \text{ lb/ft}^3$$

The average volume of the stone, Vol_S, can then be computed as:

$$Vol_s = \frac{W_b}{\gamma_s} = \frac{36.4}{164.8} = 0.21 \text{ ft}^3$$

If the individual stones are considered to be roughly spherical in shape, the diameter of the stone, D_S, may be computed from:

$$D_s = 2\left(\frac{0.75 Vol_s}{\pi}\right)^{1/3} = 2\left(\frac{0.75[0.21]}{\pi}\right)^{1/3} = 0.74 \text{ feet}$$

Rounded to the nearest inch, this result is equal to 9 inches. The result of Equation 11HC-1 is then compared to the result of Equation 11HC-2:

$$D_s = \frac{32\, d\, S_f}{SG-1} = \frac{32(3.71)(0.0125)}{(2.65-1)} = 0.90 \text{ feet}$$

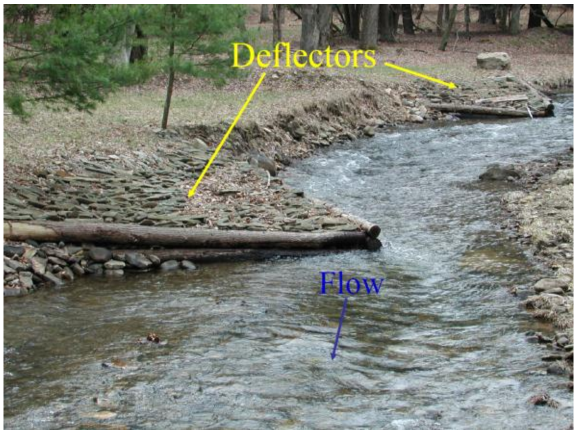
Rounded to the nearest inch, this result is equal to 11 inches. Since the required stone size is typically selected based on the larger of the results from these two equations, the stone size should be 11 inches. However, examination of boulders found in a nearby stream reach indicates that the smallest stable stone size in the stream reach is approximately 13 inches. Thus, the required stone size is determined to be 13 inches.

The pay item for boulder clusters is:

<u>Item Number 209-03.32, Stream Mitigation-Boulder Clusters, per Each</u>

Based on the inspection of the nearby stream reach, it is determined that an appropriate average spacing between boulder clusters would be approximately 150 feet. Since the relocated channel will be 1500 feet long, it will be necessary to include 11 clusters in the project design.

11.08.1.2 LOG DEFLECTORS AND VANES



Typical Log Deflectors
Reference: WA Dept. of Fish & Wildlife

11.08.1.2.1 DEFINITION AND PURPOSE

Log deflectors and vanes are rigid structures that extend from the bank into the stream to reduce the width to depth ratio of the bankfull channel. They act by directing normal flows towards the center of the channel, thus causing an increase in flow velocity. This results in scour that can serve a number of different purposes, including:

- assisting in the development of meander patterns
- deepening and narrowing wide channels
- creating scour pools
- increasing flow velocities
- removing silt from spawning gravels and habitat areas critical for macroinvertebrates
- enhancing pool-riffle ratios

Log deflectors and vanes are cost effective and simple to construct and can assist in creating a meandering thalweg for relocated channels that would otherwise be wide, shallow, and sluggish. The pools and scour holes they create can improve habitat by maintaining clean substrates which attract aquatic insects and spawning fish. The mid-channel pools created by these structures can also provide resting and feeding areas for juvenile and adult fish. In addition, log deflectors may be used to direct flows away from an eroding bank.

Structures that are placed into a channel to deflect flow may be known by a variety of names, and the term “deflector” is often applied to a number of different configurations. For the purposes of TDOT projects, a triangular log structure projecting from the stream bank will be identified as a log deflector. Structures which utilize a single log will be identified as log vanes. Technical manuals or information from other sources may use a different terminology. When referring to these manuals, it is important to verify the actual structural configuration that is being described.

11.08.1.2.2 APPROPRIATE APPLICATIONS

Log deflectors and vanes may be utilized in a stream relocation project to replace the horizontal and vertical complexity and in-stream habitat which may have existed in the original stream channel. They can assist in recreating an existing pool and riffle structure as well as re-establishing a meandering thalweg along the channel bottom. In addition, vegetated riprap may be utilized within the triangular structure of a log deflector to provide shade along the stream bank.

Log deflectors and vanes are best applied in channels which have a relatively large width to depth ratio, and where backwater from downstream structures would not affect the flow velocities at the site. Log vanes are better suited than log deflectors for locations subject to large amounts of bedload sediment transport.

The applicability of log deflectors or vanes to a given stream reach should be evaluated based on the slope of the stream and the channel lining materials. As a general rule, the effectiveness of this type of log structure is related to the velocities that would occur at normal flow. Thus, as the slope of the stream increases, the depth of scour and the size of the particle that may be mobilized also increases. Where the valley slope is between 2% and 4%, these measures may be applied in stream reaches with channel lining materials that consist of boulders, cobbles, or gravel. However, where the substrate is dominated by small gravel or sand and silt, it will likely be necessary to employ additional bank stabilization measures to prevent excessive scour. Where the slope of the stream is less than 2 percent, log deflectors will typically be effective only in streams with relatively fine-grained channel lining materials. Although it may be possible to apply this measure in streams where the channel lining materials consist of boulders or large cobbles, its effectiveness would be reduced.

The location and spacing of an installation of log deflectors or vanes should be determined based on the configuration of the channel and the intended purpose of the measure. The predominant types of configuration are as follows:

- **Alternating structures** are used to create meanders or a narrower thalweg within the low flow channel. Structures are placed on alternating banks at a spacing which would recreate the meander characteristics of the existing stream. If the existing meander characteristics are not known, the spacing may be set at 5 to 7 times the channel width at the channel forming discharge level.

- **Opposite structures** are constructed on opposite banks directly across from each other. This creates a flow restriction which facilitates gravel deposition upstream due to backwater effects as well as a scour hole downstream. This method is well suited to wide, shallow stream reaches where flow velocities would otherwise be insufficient to create a pool and riffle structure. Using this type of installation to constrict the channel can thus assist in improving spawning habitat for fish. Where opposite structures are placed in series, they should be spaced according to the criteria provided in Section 11.08.1.4 for the design of step pools.

- **Stream bank protection structures** typically consist of multiple structures intended to control stream bank erosion on the outside of meander bends. Log deflectors are preferred for this type of installation and careful consideration should be given to the deflector spacing. Because the height of a log deflector is usually limited, this method is best suited for areas characterized by shallow channels and flat overbanks. The effectiveness of this measure to provide stabilization for other stream bank configurations is likely to be limited.

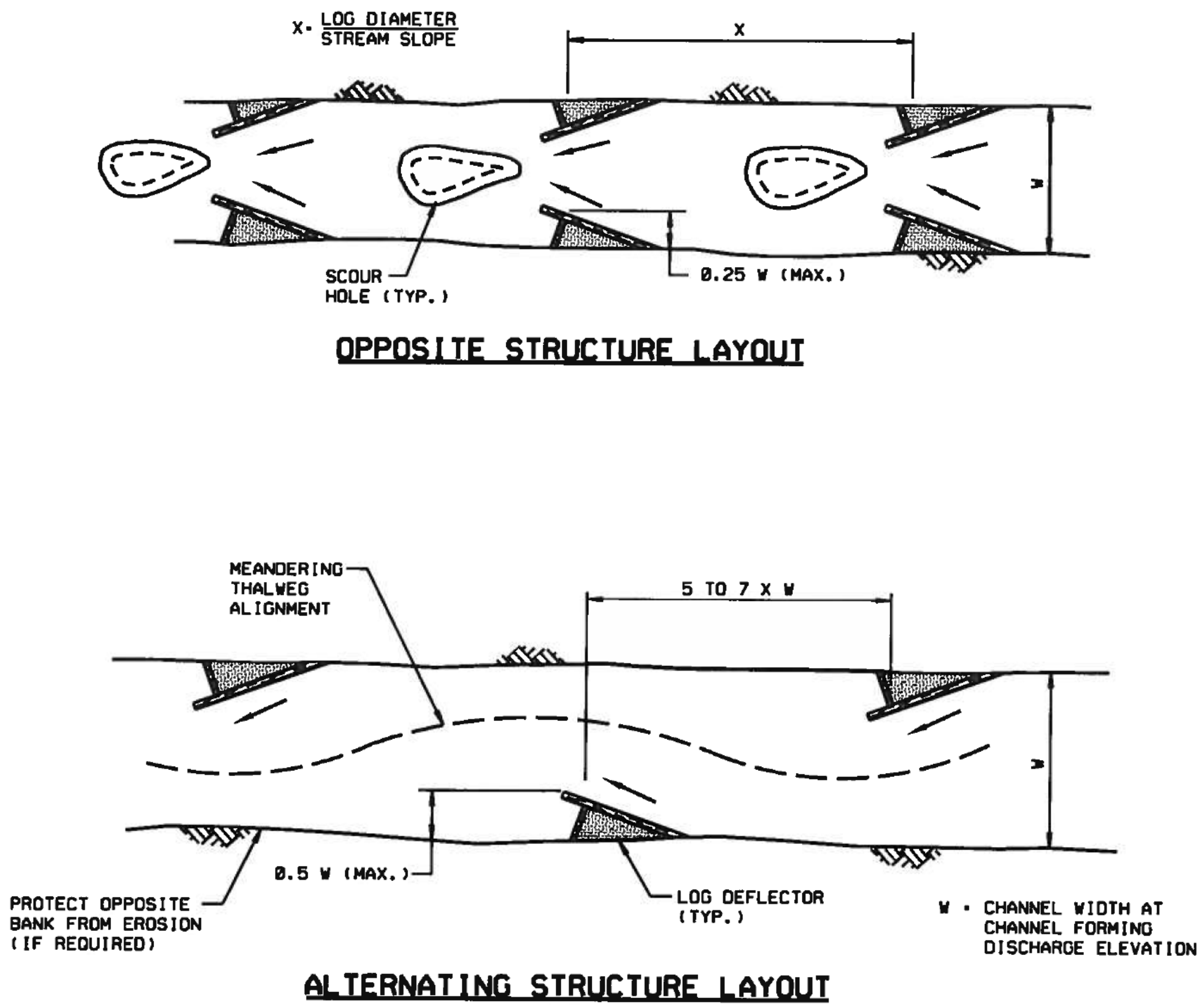


Figure 11HC-1
Configuration Types for Log Deflector Installation

11.08.1.2.3 LIMITATIONS

Log deflectors and vanes typically have limited lengths; thus, they may not be appropriate where the channel width surpasses 30 feet.

Since log deflectors and vanes are designed to create scour pools to enhance in-stream habitat, they should only be applied in alluvial channels. Since minimal bed scouring occurs in a threshold channel (for example a stream where the bottom consists of bedrock), these measures would be ineffective. Further, since these measures rely on the flow velocity to be effective, they should not be applied in reaches characterized by pools or other factors that tend to create backwater.

Stream bed substrate should be carefully considered before specifying log deflectors or vanes for a particular location. These measures are typically not well-suited for streams with highly erodible substrates due to the high risk of undermining caused by excessive scour as erosion continues to occur around the installation. Log structures placed on opposite banks may be particularly subject to excessive erosion due to the degree of constriction they create. These measures should also not be applied in streams with slopes in excess of 4%, regardless of the channel substrate material.

Log deflectors and vanes should not be utilized on unstable streams experiencing either aggradation or degradation. In addition, they should be applied with caution on streams which carry large loads of either debris or sediment.

Log deflectors and vanes are temporary structures with a typical life expectancy of approximately 5 years. Because of this, the design should incorporate vegetated riprap or other live plant material to take over the function of the installation as the logs decay.

11.08.1.2.4 PLANNING AND DESIGN CRITERIA

Because hydraulic parameters such as velocity and shear are difficult to determine for low flow conditions, it is usually not possible to conduct a detailed design for a log deflector or vane. Thus, the locations and dimensions of a set of these structures will usually be determined using engineering judgment based on the criteria presented in this Section. Achieving an effective design will require a clear understanding of the channel characteristics and the overall nature of the watercourse including factors such as debris loads, the variability of discharges in the stream, and sediment transport.

The arrangement of log deflectors or vanes in a given installation should be determined based on the purpose of the measures and the channel structure that they are intended to create. A number of alternate arrangements are described in the criteria provided in the Appropriate Applications section. A log deflector will be effective only where there is sufficient flow velocity to scour the channel substrate. Thus, this measure should not be located in areas such as the inside of a meander bend where the flow velocities would tend to be low.

A log deflector or vane should be designed to deflect flows only up to the level of the channel forming discharge. This can be accomplished by limiting the height of the installation to a level at or below this elevation. The length of the proposed structure should also be carefully evaluated as described below. Installations that are too large may create aggravated erosion or channel instability problems in other parts of the channel, especially on the opposite channel bank. Thus, the placement of any measure of this type should be carefully studied to determine whether additional erosion prevention measures would be required.

To prevent undermining, half of the height of the logs should be embedded into the channel bed. Where significant scour is anticipated, the apex of the deflector (the tip of the vane) may be supported with large footer rocks entrenched beneath, and slightly downstream, of the end of the structure.

It is also important to design the log structure to withstand the forces that will be imposed on it during periods of high flow. Movement of the logs within the stream bed due to these forces can cause failure of the structure. To ensure the required stability, the logs should be sized as described below and be trenched into the channel bank a minimum length of 5 to 6 feet. The trenches should be backfilled and compacted to help hold the logs in place. The ends of the logs that are in the channel should be secured by means of ¾ inch rebar driven into the channel bed to a depth of 3 feet below the approximate scour depth.

The log structure should be constructed with locally available untreated logs in good condition at least 8 to 10 inches in diameter. Where logs of this size are not readily available, smaller logs may be pinned together to form larger structures. The pins should consist of ½ inch diameter (minimum) rebar which are long enough to extend a minimum of 3 feet into the channel bottom. The rebar should be driven until the upper 4 inches remains and this remaining length should be bent in the downstream direction to ensure that the logs remain securely anchored to each other.

Although log deflectors and vanes are considered to be temporary, a few steps can be taken to maximize the functional life of the structure. Where feasible, the logs should be taken from decay-resistant species such as cedar, white oak, etc. In addition, the structures can be designed to remain submerged even during low flows, which will help reduce the rate at which they decay.

Design considerations which apply specifically to log deflectors are as follows:

A typical log deflector will be constructed in a triangular configuration with an apex angle of 90 degrees and an angle between the upstream log and the stream bank of not greater than 40 degrees. Angles greater than 40 degrees may cause erosion of the opposite bank and disproportionately increase the forces exerted against the structure by the flow. Thus, this angle should be carefully evaluated where a log deflector is to be installed on the outside of a meander bend. However, this angle is more critical where the average flow velocity is greater than 5 to 6 feet per second.

Two other factors that determine the effect of a log deflector are the height of the structure and the deflector length, L_d. The deflector length is the distance from the channel bank to the apex of the triangular structure. These two factors determine the degree of obstruction that the deflector will impose on the low-flow channel, and this is directly related to the depth of scour that will occur. In small to medium sized channels where a single deflector is installed, the deflector length should be no more than 50% of the channel width. In a similar manner, the lengths of opposite deflectors should be no more than 25% of the channel width so that half of the channel will remain unobstructed. In larger channels, the deflector length should be less than 50% of the channel width. The height of the structure should be limited so that no more than 6 inches of the deflector is above the normal flow elevation. Exceeding these criteria may result in excessive scour of the channel bed or possible erosion damage in other parts of the channel.

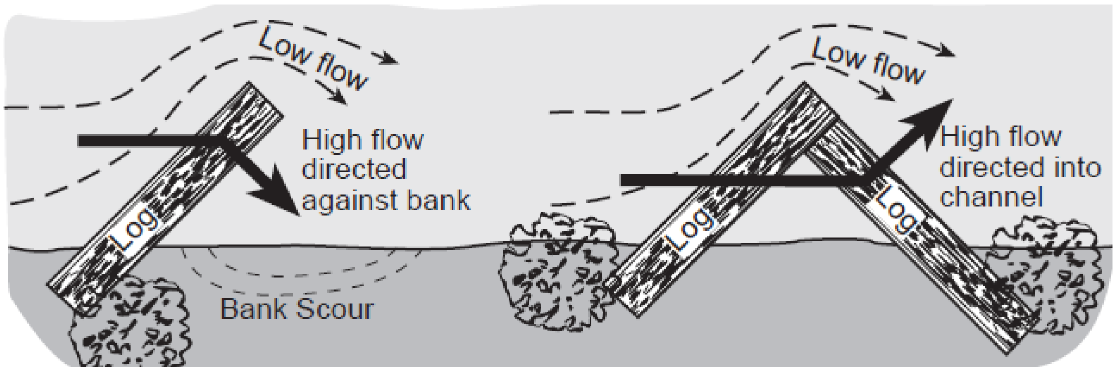


Figure 11HC-2
Flow Patterns Created by Log Deflector Installation
Reference: Ohio Stream Management Guide (2007)

Although the main purpose of a log deflector is to cause scour on the channel bed, it may cause unintended erosion in other parts of the channel. Thus, it is important to consider where erosion may potentially occur and provide appropriate erosion prevention measures. As discussed above, during low flow conditions, log deflectors may tend to direct the flow toward the opposite bank. Where this is anticipated to be an issue, the bank opposite the deflector should be protected against scouring with coir rolls, a longitudinal stone toe, or other suitable measures. Scour of the stream bank can also occur due to turbulence upstream and downstream of the deflector. Thus, the stream bank in these areas should be protected by placing riprap or large stone with Geotextile Fabric (Type III) (Erosion Control). Depending on average flow velocity and bank configuration, this protection should extend in each direction a distance equal to two times the deflector length, L_d.

During periods of higher discharge, the flow patterns at a log deflector will be different than at low flow stages as shown in Figure 11HC-2. When a deflector is overtopped, the flow will tend to be turned toward a direction perpendicular to the edge of each log face. At the downstream edge of the deflector, the current will tend to be turned back toward the center of the channel, and thus avoid damage to the stream bank. However, at the upstream side, the flow will tend to be directed into the stream bank. This effect can be avoided by sloping the deflector away from the bankfull elevation at the bank, down to the elevation of normal low flow at the tip.

The triangular frame of a deflector should be tightly packed with appropriately sized riprap or native stone. The class of machined riprap should be selected based on the design discharge (usually the Q_{50}) and the velocity criteria presented in Section 5.04.7. Live plantings can be incorporated into the stone. These live plantings can help prevent stream bank erosion and provide shade to help moderate the temperature regime in the stream.

Design considerations which apply specifically to log vanes are as follows:

Log vanes should be placed pointing downstream at angle of 20° to 30° from the channel bank as shown in Figure 11HC-3. At the point where a vane ties into the bank, its crest should be at the level of the channel forming flow. From that point, it should slope at rate of 3%

to 7% to the tip, which should be partially embedded in the channel bottom so that it is submerged even at low flows.

As a general rule, the larger the channel, the shorter a vane should be relative to the overall channel width. Where the channel is less than 20 feet wide, the vane may extend into the channel as much as one half of its width. In larger streams, log vanes should occupy no more than one third of the channel width.

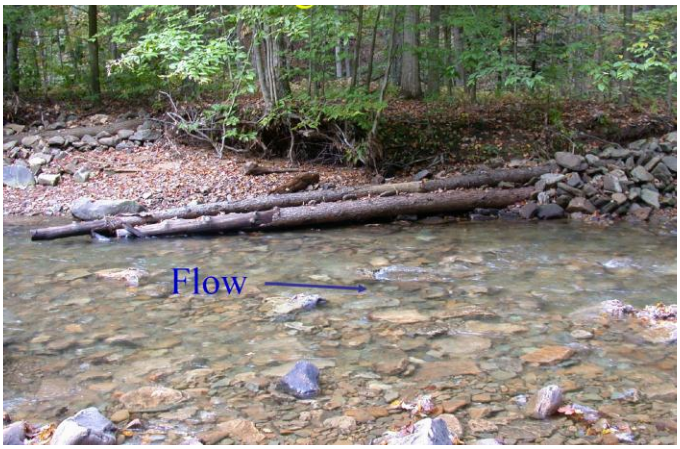


Figure 11HC-3
Multi-Log Vane Deflector
Reference: Washington Department of Fish and Wildlife

As discussed above for deflectors, log vanes may tend to deflect low flows into the opposite channel bank. Where this is anticipated, appropriate measures should be applied to protect the bank opposite the vane. During periods of higher flow, a log vane will tend to turn the flow direction towards the adjacent bank, potentially causing erosion in this area. Additional measures, such as rootwads or large stone should be placed in this area to minimize the potential for erosion damage.

Log deflectors and vanes should be shown on the Stream Relocation Plan by providing specific station and offset values at both ends of each of the logs in the structure. Notes or a table should be placed in the drawing to specify the elevations of the logs. Where a log deflector is proposed, an additional note should be provided to specify the class of machined riprap required.

The Stream Relocation Plans should clearly communicate to the contractor the intended lines and grades for each log vane or deflector. The Stream Relocation Plans should show the appropriate symbol for the structure being specified. The Stream Mitigation Data Table should provide station and offset data for the control points used to define the location of each structure. In general, the control point will be located at the point where the deflector log intersects the channel bank. The table should also show the flow elevation at the channel forming discharge, intended channel bottom elevation and anticipated scour hole depth. For both types of structure, enter the minimum required log diameter and deflector length, L_d, into the Design Data column of the table. Where a log deflector is specified, the table should also indicate the required class of machined riprap. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Log Deflectors and Log Vanes shall be paid for under the following item numbers:

- Item Number 209-03.33, Stream Mitigation-Log Structures and Deflectors, per LF
- Item Number 209-03.34, Stream Mitigation-Log Vanes, per LF

11.08.1.2.5 EXAMPLE APPLICATION

Given: It has been determined that a natural stream design will be required to mitigate the relocation of approximately 2000 feet of an alluvial stream which has channel bed materials composed of sand and gravel. Although, the existing stream is fairly wide, the channel bottom is characterized by a significant amount of complexity introduced by fallen trees, rocks, and other obstructions along the channel banks. Based on an evaluation of the existing stream, it has been determined that log deflectors will be an appropriate means of ensuring that the relocated stream will exhibit the same complexity.

The basic design parameters for the relocated channel are as follows:

- Channel forming discharge ≈ 25 cfs
- Q50 = 625 cfs
- Slope = 0.7%
- Channel bottom width = 16 feet
- Channel side slopes = 2H:1V
- Manning's n-value = 0.045

Find: Determine the basic design and required quantities for this measure.

Solution: Based on an evaluation of the existing channel, it is determined that the log deflectors should be placed in an alternating arrangement, at an average spacing of 85 feet between the deflectors on opposing sides of the channel. Further, it is determined that the average deflector length, L_d, should be approximately 6 feet.

Hydraulic analysis of the channel indicates that the flow depth at the channel forming discharge is 0.7 feet, or about 8 inches. Since approximately half of the diameter of the logs is to be keyed into the channel bottom, the required log diameter is 16 inches. Hydraulic analysis for the 50-year discharge yields an average flow velocity of 5.79 ft/sec in the channel. Because the stone will be contained by the logs used to construct the vane, it would be possible to fill the area between the logs with Machined Riprap (Class A-1). However, because the logs are a temporary measure, Class B riprap will be used for the deflectors to ensure that a somewhat more permanent installation will remain once the logs have rotted.

The pay item for log deflectors is:

Item Number 209-03.33, Stream Mitigation-Log Structures and Deflectors, per LF

As described in the Planning and Design Criteria, the upstream log of the deflector will form an angle of approximately 30° with the channel bank. Since the angle at the apex of the deflector is 90°, the downstream log will intersect the bank at an angle of 60°. Thus, the length of the structure along the bank may be computed as:

$$L = (\cos 30° + \cos 60°)L_D = (0.87 + 0.50)6 = 8.2 \text{ feet}$$

Since the deflector length, L_D, is 6 feet, the total length of the erosion prevention measures downstream of the wood structure should be 12 feet, which results in an overall length of 20.2 feet, which is rounded to 20 feet. Based on an average spacing of 85 feet between alternating structures, 24 deflector structures would be needed over the entire 2000-foot project reach. Thus, the final quantity for the log deflectors would be 480 LF.

11.08.1.3 LOG DROP

Double Log Drop Structure
Location: SR-15, Wayne County, TN (2011)

11.08.1.3.1 DEFINITION AND PURPOSE

Log drops are low profile in-stream structures that utilize logs to create an abrupt drop in the channel profile. Although a variety of configurations are possible, these structures usually span the entire channel width and thus tend to scour the channel bottom downstream of the drop while creating a shallow pool on the upstream side. Depending on the configuration of the structure, log drops can be used either alone or in series to serve a number of different purposes including:

- energy dissipation
- maintaining the elevation of the stream bed
- directing stream flows away from erodible channel banks
- creating variation in the structure of stream bed
- assisting in the passage of fish and other aquatic organisms

Log drops can assist in stabilizing stream beds by providing a hard non-erodible point in the profile. They also can act to redistribute and dissipate the energy of stream flows in order to help control flow velocity in a high gradient stream.

This measure can also help increase habitat complexity by breaking up long glides or riffles into a series of step pools. This creates surface turbulence, plunge pools, velocity chutes, and hiding areas, which all improve habitat for fish and other aquatic organisms by providing locations to hide, rest and spawn.

11.08.1.3.2 APPROPRIATE APPLICATIONS

For TDOT stream relocation projects, log drops should be used only to duplicate a similar structure or function that may be present in the existing stream reach to be relocated. Log drops can be built either singly or in series. When built in series, they can function as step pools, or help to create a pool and riffle structure in the channel.

In general, log drops may be applied in small to medium-sized stable alluvial channels. Channel stability is important because the sediment build up in an aggrading stream will tend to bury the scour pools, rendering the measure ineffective. On the other hand, degradation of the channel bed can undermine the log structures, causing the failure of the measure. In addition, log drops should not be applied in channels which carry large amounts of sediment.

Log drops may be utilized in channels with slopes ranging from 1% to 3%. Streams with gradients less than 1% are often not characterized by a pool and riffle structure, and it would not be appropriate to artificially create this type of structure by constructing a series of scour pools. Usually the length of the scour pool will increase as the slope of the stream increases. Since the allowable height of a log drop is limited, the length of the scour pools will begin to exceed the required spacing of the drop structures for slopes greater than 3%. In this situation, the energy at a given drop structure will not be able to dissipate completely before the flow reaches the next downstream structure. This reduces the effectiveness of the installation as a velocity control measure.

Log drops are most suitably applied in channels characterized by gravel and cobble materials. It is difficult to securely anchor a log installation on a bedrock channel and highly erodible materials such as sand and silt greatly increase the likelihood that the structure will fail due to erosion.

A number of different log drop configurations are possible, and the configuration to be utilized will depend on the function that the structure is intended to serve. The simplest configuration is a horizontal straight weir as illustrated in the photograph at the beginning of this section. This configuration is effective for dissipating energy to control flow velocity, however, it tends to create a channel cross section that is flat and uniform. The scour pool created by this configuration tends to begin at the base of the structure and span the entire channel. This configuration also provides less of an opportunity for the passage of fish or other aquatic organisms.

A log drop may also be placed in a horizontal “vee” shape to generate more variation in the cross section of the scour pool. A “vee” shaped alignment takes advantage of the fact that a weir tends to turn flow in a direction perpendicular to its alignment. Thus, where the apex of the “vee” points in the upstream direction, the flow will be focused toward the center of the channel. This will result in a longer pool with a better defined thalweg. Where the apex of the “vee” points in the downstream direction, scour pools will tend to form on both sides of the channel. Either of these configurations is useful for improving habitat while still dissipating energy and helping to control the flow velocity.

As illustrated in Figure 11HC-4, a “K” weir log drop consists of a horizontal log on which two other logs have been placed at an angle. During periods of low flow, this structure will create a scour pool at the center of the channel. However, when the stream discharge has increased sufficiently to overtop the structure, the situation will be reversed with scour pools forming at the sides of the channel. Although this structure will still provide control of flow velocities, it is more suitably applied as a measure to improve conditions for the passage of fish or other aquatic organisms.

Figure 11HC-4
Typical "K" Weir Installation
Reference: Washington Dept. of Fish and Wildlife,
2004 Stream Habitat Restoration Guidelines, Final Draft

11.08.1.3.3 LIMITATIONS

Like any untreated wooden structure in a stream environment, a log drop structure is subject to rot, especially where the wood is exposed to cyclic wetting and drying. Thus, this measure should be considered to be temporary.

Log drops should not be applied in actively meandering streams, due to the risk that channel migration at the structure may cause erosion around the side of the log structure, resulting in the failure of the measure. For the same reason, log drops should not be placed in curved reaches of a stream. In a curved channel alignment, most of the bank erosion occurs along the outside edge where the velocities are greatest. Thus, it is likely that a log drop structure located on a bend would experience undercutting and bank erosion problems which would lead to failure of the structure. Log drops should be applied only in straight reaches where the channel alignment is expected to remain relatively fixed.

Log drop structures typically lie low in the stream channel and thus rarely result in a significant decrease in the channel cross sectional area. Thus, these structures usually cause backwater effects only during periods of low or moderate flow. Although these structures do not usually present a significant backwater effect for high flows, a series of drop structures may collectively increase the hydraulic roughness of the channel, causing an increase in flood elevations. Thus, the effective roughness of a proposed log drop installation should be checked during design.

Log drops should be applied with caution in streams which carry a high debris load as debris may become trapped on the structure. This debris may increase the degree of backwater created during high flow events, or even redirect the flow causing bank erosion and the failure of the structure.

This measure should be applied only where logs of the appropriate tree species are readily available. Further, these logs should be of sufficient length to construct the proposed type of drop structure.

While log drops can be used to improve the aquatic habitat, misapplication of these structures can have the opposite effect. A drop structure is essentially a hard, immovable point in the stream profile. Thus, it could prevent the channel from moving laterally or adjusting vertically to respond to changing watershed conditions. These processes are important for the creation of new habitat as well as the maintenance of existing habitat values. In addition, the height and width of the drop must be limited to prevent the structure from becoming a barrier to the passage of fish or other aquatic organisms. The maximum allowable height between the downstream pool level and the top of the log is usually limited to a foot or less. This can be exceeded if the channel incises over time, or if the next downstream structure fails.

11.08.1.3.4 PLANNING AND DESIGN CRITERIA

A variety of configurations and purposes are available for log drop structures. Normally, the first step in designing a log drop will be to identify its intended purpose so that its planform configuration can be selected. For TDOT projects, there are four basic types of planform configurations: a straight weir, a diagonal weir, a “vee” weir and a “K” weir.

As described in the Appropriate Applications section, a straight horizontal weir is normally used to dissipate energy or control flow velocity where the slope of the stream is relatively steep. Because these structures tend to spread flow and energy evenly across the channel, they encourage a relatively flat cross-section upstream, and form a wide, shallow scour pool that spans the entire channel. Because these structures provide a minimum degree of bed form complexity, they are not recommended where the existing stream offers a significant degree of aquatic habitat. Where a limited amount of concentrated flow is desired, these structures can be provided with a small notch.

Where a horizontal weir is placed perpendicular to the channel, it can contribute to bank erosion by directing energy towards the sides of the channel. However, this effect can be controlled to a degree by changing the weir orientation in the channel and placing it at a slope. This is typically accomplished by orienting a straight weir diagonally across the channel. Because flow over a weir tends to be turned in a direction perpendicular to the weir alignment, this method can be used to direct flow away from sensitive areas on the banks. A diagonal weir should also be placed at a 5% slope such that the upstream end is lower than the downstream end. This arrangement will concentrate flow on one side of the channel while causing sediment to collect at the higher end of the log.

A “vee” shaped planform can be used either to concentrate flows toward the center of the channel or to spread them towards the outside. As described in the Appropriate Applications section, where the “vee” is pointing upstream, the flow will tend to be concentrated through the apex to create longer and deeper, but narrower scour pools than would form with a straight weir. This arrangement is also more structurally sound, since it utilizes the strength inherent in a triangular form to transfer the loads imposed by the thrust of stream flow and bedload into the banks.

Installations where the apex of the “vee” is pointing downstream are more effective at dissipating energy because they tend to direct flow to the outside of the channel. Thus, this arrangement will spread scour over a wider area and create shallower pools. In streams where fish are present, this arrangement can also be used to collect gravel to create spawning habitat. However, this arrangement can potentially cause erosion on adjacent stream banks and should be applied in combination with appropriate erosion prevention measures on the stream banks. This arrangement should also be applied with caution on streams with steep slopes since the forces imposed by the stream flow and bedload may separate the ends of the logs at the apex. In such situations, it may be necessary secure the ends of the logs by providing wooden piles to resist the movement of the logs.

As the angle of the apex of the “vee” decreases (i.e. – the point gets sharper), the effects of the resulting flow redirection become greater. Where the apex points upstream, this would cause more flow to be directed to the center of the channel, increasing the depth of the scour pool and increasing the risk of undermining the structure. Conversely, decreasing the angle where the apex points downstream would tend to direct more flow into the channel banks, increasing the risk of erosion. To minimize these risks while still providing effective flow redirections, it is recommended that the apex angle of the “vee” range from 100° to 120°.

A “vee” log drop can be symmetrical or asymmetrical, depending upon the thalweg alignment as it approaches the structure and the desired thalweg alignment immediately downstream. Typically, the apex is located within the center third of the channel. A meandering thalweg can provide additional channel complexity and should be taken into account in positioning the apex.

As shown in Figure 11HC-4, a “K” weir consists of a base log on which two other logs have been placed at an angle. The upper two logs are placed at a 5H:1V slope and the ends of the logs are secured to the base log to ensure the structural stability of the structure. The base log should be placed at the desired elevation of the thalweg. At the bank line, where the upper ends of the logs are trenched into the bank the top of the structure should not exceed the elevation of the ordinary high water mark.

Because of its configuration, a “K” weir may be more likely to trap debris. Thus, this measure should be used with caution on streams which carry a high debris load.

The hydraulic performance of a “K” weir is somewhat more complicated than for a horizontal weir. During periods of low flow, all of the flow should be funneled through the gap between the upper logs. As the discharge in the channel increases, the angle and slope of the upper logs initially will continue to concentrate flows toward the center but will increasingly direct water toward the banks as the discharge continues to rise. Thus, a “K” weir will tend to maintain a deep scour pool at the center of the channel during low flow periods, but transfer the scour pools to the outside of the channel during high flow events. “K” weirs can also create significantly higher levels of backwater than a level weir. The potential effects of this backwater can include gravel accumulation and increased risk of upstream flooding.

In the design of this measure it is important to carefully consider all of the potential effects on the hydraulics of the channel. Typically, the designer should consider the median discharge (i.e. – the 50% exceedance flow) at the site as well as the 50-year design discharge. The gap between the upper logs should be sufficiently wide to pass the median discharge without overtopping the upper logs while the backwater effects should be considered for the design discharge. In addition, it may be necessary to employ the procedure described below to estimate the scour pool depth along the sides of the channel in order to evaluate the potential for erosion on the channel banks for increasing discharges. The median discharge can be determined as described in Section 11.04.3 while the 50-year discharge may be determined using procedures provided in Chapter 4 of this Manual.

Once a suitable configuration has been determined, the designer should consider the allowable drop height at each structure. The height of a structure can have a significant impact on the passage of fish or other aquatic organisms. Thus, the maximum allowable drop height should generally be limited to 12 inches. Where the passage of wildlife is not an issue, the drop height may be selected based on the depth of the scour pool that would be created. To prevent undermining, the depth of the scour pool should not exceed the depth of the lowest log in the structure. However, where a series of drop structures is utilized, the top of the downstream log should be placed at an elevation equal to or higher than bottom of the upstream log.

As noted above, the depth of the scour pool is affected by the drop height of the structure. As a general rule, the drop structure should be designed such that the bottom of the scour pool is above the bottom of the lowest log in the installation. In some situations it is possible that these criteria will place an undue restriction on the allowable drop height. Where this is the case, the scour pool may be lined with aggregate that is properly sized to minimize mobilization and displacement in large flow events. For larger structures, this may require the use of riprap.

The depth of a scour pool formed by a vertical drop (d_S) may be estimated using Equation 11HC-3:

$$d_s = 1.32 H_t^{0.225} q^{0.54} - TW \quad \text{(11HC-3)}$$

Where: d_S = depth of the scour pool below the un-scoured channel bottom, (ft)
H_t = drop height, (ft)
q = unit discharge on the weir, computed as q = Q/L, (ft^3/sec/ft)
Q = discharge, (ft^3/sec)
L = weir length, (ft)
TW = tail water depth above the un-scoured channel bottom, (ft)

It is recommended that the depth of the scour pool be computed for the median discharge (i.e. – the 50% exceedance flow) as described in Section 11.04.3.

Where a series of log drops are to be utilized, they should be spaced to maintain the slope of the existing reach to be relocated, based on the allowable drop height. Thus using Equation 11HC-4:

$$X_d = \frac{H_t}{S_0} \quad \text{(11HC-4)}$$

Where: X_d = log drop structure spacing, (ft)
H_t = drop height, (ft)
S_0 = slope of the existing channel, (ft /ft)

The location of each log drop in a relocated channel should be determined based on the desired spacing. Log drops should be located in straight channel reaches within non-riffle areas where the bank height is at least 18 inches. Since drop structures affect the velocity, flow hydraulics, and sediment transport characteristics in the vicinity of the structure, consideration should be given to the possible impacts on other nearby structures. In particular, a log drop located downstream of a culvert outlet should be far enough downstream to prevent the accumulation of sediment or other debris in the culvert barrel. Upstream of a culvert, the log drop should be located sufficiently far away that the scour pool created by the structure will not extend to the culvert inlet and potentially undermine the pipe.

For most log drop structures it is important to provide armor on the channel banks near the structure to prevent erosion during high flow conditions. Generally, armor should be placed at least 3 feet upstream of the structure, and sufficiently far downstream to reach the beginning of the scour pool tailout. Although riprap is most commonly used for this purpose, other materials such as large natural stones or coir rolls, may be utilized as well. Armor placed downstream of the structure should extend to the anticipated depth of scour to prevent undermining as the hole develops. However, in order to minimize the disruption caused by excavation, it may also be possible to provide an additional quantity of riprap at the toe of the protection as launchable material. Riprap and large rock used for this purpose should be placed on geotextile fabric to prevent the piping of bank material. Where a “vee” weir with the apex pointing downstream is utilized, it may be possible to utilize rootwads to protect the bank. Although some undermining may occur, the rootwads would provide protection for the mid and upper bank as well as cover for fish or other organisms that would use the pool to feed, hide or rest.

The logs used to construct the drop structure should be keyed into the bank a distance sufficient to prevent the flanking of the structure. This is most likely to occur when the structure or the next upstream structure directs flow towards the bank, or when the downstream scour pool extends sufficiently far to undermine the bank toe and the ends of the logs are exposed, causing the failure of the structure. Generally, the logs should extend into the banks for a distance equal to 0.4 times the width of the channel bottom, but not less than 5 feet. However, this length may need to be increased in actively meandering streams that have a high probability of shifts in the channel alignment.

Another important aspect of log drop design is to minimize the occurrence of subsurface flow through the structure. Where a substantial portion, if not all of the low flows passes underneath the structure, passage of fish or other aquatic organisms can be impeded, or the material under the logs can be piped causing the structure to be undermined. Sealing of the structure is most often achieved by installing a well-graded mix of compacted sediment (including at least 10 to 15 percent fines) on the upstream side. Geotextile Fabric (Type III) (Erosion Control) should be placed between the structure and the added sediment mix to prevent piping. This fabric should extend from the top of the drop structure, down its upstream face to a depth at least two feet below the streambed, and upstream at least five feet. The sides of the fabric along the banks should be at least as high as the top of the weir and should extend into the key trenches to completely seal the structure. Where extra tensile strength is required, the geotextile fabric may be provided with wire backing.

To maximize the service life of a log drop, the drop should be constructed using a slowly decaying tree species. In general, conifers such as cedar offer superior rot resistance as compared to deciduous species. However, the choice of species used will also depend on the local availability of logs with a sufficient diameter. The life expectancy of an installation can greatly increased where the log remains submerged year round.

The minimum recommended log diameter is 16 inches.

By their nature, log drops may require maintenance and should be monitored regularly. Thus, an effort should be made to provide adequate access to a log drop installation.

The Stream Relocation Plans should clearly communicate to the contractor the intended lines and grades for each type of log drop structure. The Stream Relocation Plan and Profile Sheets in the Stream Relocation Plans should show the configuration, and alignment for each log drop structure. The Stream Mitigation Data Table should provide the apex elevation and estimated scour depth for each structure as well as the station for the control point used to define the location of each structure. In general, the control point will be located at the point where the proposed stream alignment crosses the log drop structure. The information entered into the Design Data column of the table will vary according to the type of log drop structure:

- for horizontal or diagonal log drops, as well as “K” weirs, enter the minimum required log diameter.
- for “vee” log drops, enter the minimum required log diameter and either “point upstream” or “point downstream,” depending on the intended configuration in relation to the direction of stream flow. If an asymmetrical “vee” weir is proposed, also include an offset for the location of the apex.

An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Log drops shall be paid for under the following item number:

- Item Number 209-03.35, Stream Mitigation-Log Drop Structure, per LF

11.08.1.3.5 EXAMPLE APPLICATION

Given: A short reach of a small gravel bed stream is located adjacent to a proposed roadway widening project. Due to site constraints, it will not be possible to adjust the roadway alignment to avoid impacts to the stream and it has been determined that a natural stream design will be needed to mitigate these impacts.

Inspection of the site indicates that the channel bank materials consist of silty sand and gravel. There is significant concern for the erosion resistance of these materials during the time that vegetation is establishing on the banks of the relocated channel. Thus, it is decided to utilize “vee” shaped log drops with the apexes pointed upstream in order to help minimize flow velocity and direct the force of the flow towards the center of the channel. In addition, these structures will help to encourage the formation of a pool and riffle channel structure.

The channel of the stream has a bottom width of approximately 6 feet and 1.5H:1V side slopes. In its existing condition, it has a straight alignment and a slope of 1.5% over a length of 200 feet. Based on analysis of the records at nearby stream gauging stations, it is estimated that the median discharge at the site is 3.2 cfs.

Find: Determine the design, spacing and required quantities for the proposed log drops.

Solution: The spacing between log drops should be determined by considering both the slope of the stream and the length of the scour pool. Since both of these parameters are related to the drop height, the design of a set of log drops involves determining a log diameter such that the spacing based on Equation 11HC-4 is sufficiently long to contain the length of the scour pool that will develop.

As an initial trial, a log diameter of 18 inches is assumed. It is also assumed that half of the height of the log will be embedded into the channel bottom so that the drop height, H_t, will be 9 inches or 0.75 feet. Based on Equation 11HC-4 the spacing, X_d, can be computed as:

$$X_d = \frac{H_t}{S_0} = \frac{0.75}{0.015} = 50 \text{ feet}$$

It is also decided to provide an angle of 120° at the apex of the "vee." This will result in an angle of 30° between each log and a line perpendicular to the channel. Since the width of the channel bottom is 6 feet, the total weir length, L, in each installation can be computed as:

$$L = \frac{6}{\cos(30°)} = 8.5 \text{ feet}$$

The unit discharge, q, can be then be computed as:

$$q = \frac{Q}{L} = \frac{3.2}{8.5} = 0.38 \text{ ft}^2\text{/sec}$$

To determine the tailwater depth, TW, a uniform flow computation is performed on the trapezoidal ditch cross section based on a Manning's n-value of 0.050. This analysis results in a depth of 0.31 feet. Thus, the scour hole depth can be computed as:

$$d_s = 1.32 H_t^{0.225} q^{0.54} - TW = 1.32\left(0.75^{0.225}\right)\left(0.38^{0.54}\right) - 0.31 = 0.42 \text{ feet}$$

It is judged that the length of scour hole created by a scour hole of the depth computed above will be significantly less than 50 feet, which was the spacing computed based on the slope of the stream. Thus, a log diameter of 18 inches will be adequate for this site.

The pay item for log deflectors is:

<u>Item Number 209-03.35, Stream Mitigation-Log Drop Structure, per LF</u>

It was determined above that the total weir length for each log drop installation will be 8.5 feet. To anchor the proposed logs, it will be necessary to embed an additional 5 foot length of log into each bank of the channel. Thus the total length for each installation will be 18.5 feet. Based on a spacing of 50 feet, there should be 4 installations in the relocated reach. Thus, the final quantity for this item will be 74 LF.

11.08.1.4 STEP POOL

Step Pool System
Location: Warren Creek, Ovanda, Montana

11.08.1.4.1 DEFINITION AND PURPOSE

Step pools result from a naturally-occurring channel bed morphology commonly found in relatively steep mountainous streams. The channel bed materials are usually coarse grained cobbles and boulders and the channels themselves would be classified as threshold channels for the purposes of natural stream design. Step pools are characterized by an accumulation of cobbles and boulders into organized ribs that span the channel. These ribs form an alternating series of rough weirs and pools which results in a stepped longitudinal stream profile. Step pools generally function to control the grade and flow velocity of a steep stream by allowing the flow to step down over a series of drops. Under low flow conditions, the flow becomes supercritical as it passes over each step and drops into the next pool, dissipating its energy in a roller eddy. This alternating sequence of supercritical flow over the steps and subcritical flow through the pools controls the velocity of the flow and provides aquatic habitat by introducing complexity into the flow and aerating the water.

As mitigation measures for a TDOT stream relocation project, step pools should consist of rows of boulders and other coarse materials placed in a series of rows to reproduce the natural step pool morphology of an existing stream reach to be relocated.

11.08.1.4.2 APPROPRIATE APPLICATIONS

Constructed step pools should be utilized only where the existing stream to be relocated is characterized by step pool morphology. This measure would typically be used as grade control structure for confined steep threshold channels with slopes greater than 3%. Where the channel slope is greater than 6.5%, the channel morphology tends to be characterized by short steps known as cascades. In either configuration, the vertical drops provide habitat value for aquatic organisms while dissipating energy.

11.08.1.4.3 LIMITATIONS

The mechanics of the processes which form step pools in natural systems is the subject of ongoing research and there are few reliable analytical methods available for step pool design. Thus, constructed step pools should not be utilized where they are not a characteristic of the existing channel. Typically this will exclude streams with channel substrates that contain large percentages of sand, silt, or clay.

Due to the limited amount of design information that is available, the designer should exercise appropriate judgment to ensure that the stone specified for a step will be appropriately sized to remain stable under the design flood conditions.

Where step pools are utilized, heavy equipment and skilled operators may be required to place the rock correctly within the stream. Thus, the selected site should offer adequate access for heavy equipment.

11.08.1.4.4 PLANNING AND DESIGN CRITERIA

The design of a system of step pools should be based on duplicating the natural step pool morphology in the existing stream reach to be relocated. Because of the lack of analytical formulas for predicting step pool geometry for given bed materials and flow conditions, the designer should exercise caution when detailing step pool systems.

It may be possible to evaluate a proposed system of step pools by comparing it to information available on the morphology of natural step pool systems. It is generally known that, as the channel slope increases, the step height increases while the pool length decreases. The natural spacing between the steps typically adjusts to achieve the maximum flow resistance. Thus, for channel slopes between 3% and 6.5%, the pool length is typically equal to 1 to 4 times the channel width, while the pool length for channels with slopes greater than 6.5% can be from 0.5 to 1 times the channel width. A general check can also be performed by computing the mean steepness of the channel using Equation 11HC-5:

$$S_c = \frac{H/L}{S_0} \qquad \text{(11HC-5)}$$

Where: S_c = channel steepness factor, (dimensionless)
H = average step height for the system, (ft)
L = average pool length for the system, (ft)
S_0 = average slope of the channel, (ft/ft)

For a natural system, the channel steepness factor will typically have a value ranging from 1 to 2, although it may be possible for this parameter to be greater than 2 for streams with slopes greater than 7.5%.

Where the existing stream reach exhibits characteristics that do not meet these criteria for pool length and channel steepness, the designer should carefully evaluate whether the processes occurring in existing stream reflect a stable condition.

As shown in Figure 11HC-5, the steps in a typical constructed step pool system consist of a row of weir boulders (or logs) placed on one or more courses of footer rocks. The weir rocks are typically staggered with respect to the footer rocks so that the weir boulders are supported on two or more footer rocks.

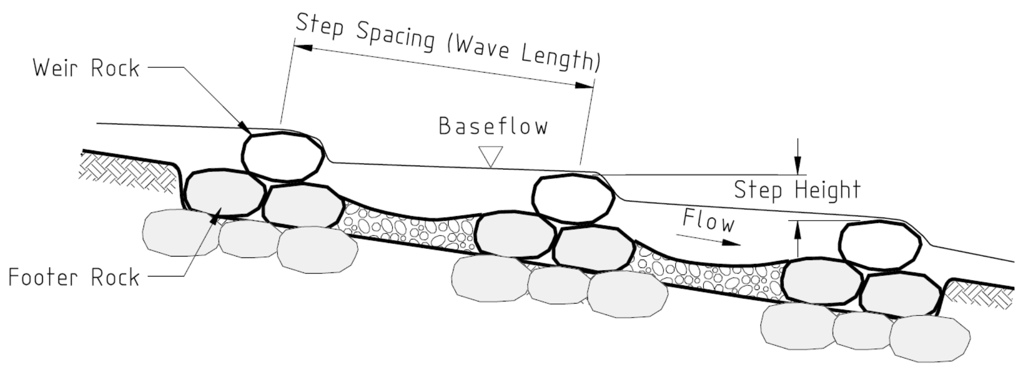


Figure 11HC-5
Profile of Typical Constructed Step Pool System
Reference: Virginia DCR (2004)

Where the foundation of a step is not set on bedrock, its integrity should be ensured by checking the maximum depth of the downstream scour pool and sealing the structure to prevent the piping of smaller material. The maximum scour depth may be computed by Equation 11HC-3, which is presented in the previous section. However, to account for variations in the elevation of the top of the weir, the unit discharge, q, should be based on half of the actual length of the weir. The bottom of the footer rocks should then be placed at an elevation below the maximum scour depth.

Where a significant portion of channel bed material is fine enough to pass the between the rocks in a step structure, it should be sealed to prevent settlement or failure due to piping. This can be accomplished by wrapping the base of the foundation with Geotextile Fabric (Type III) (Erosion Control) and placing a layer of properly sized coarse aggregate, and/or riprap on the upstream side of the structure.

The boulders used to form the weir should be properly sized to be stable for the design discharge, which is typically the 50-year event. Where possible, the stones which form the steps in the existing channel should be utilized to construct the steps in the relocated channel. Typically the step structure will be composed of two or more anchor boulders with smaller boulders interspersed between them. Where the size of the anchor boulders cannot be determined from the existing channel, a diameter of 3 feet may be used in most cases.

The number of steps in a given channel reach should be determined based on the slope of the stream and the allowable drop height. The allowable drop height may also be limited by the need to provide passage for fish or other aquatic organisms. Typically, the drop height should be limited to 12 inches where fish passage is a concern. However, many natural step pools have step height of 1 to 2 feet.

Where steps are constructed in channels with erodible banks, the structures should be extended a minimum of 2 feet into each bank and riprap or other hard armor should be placed on the banks upstream and downstream of the structure to provide protection against erosion.

Step pool systems should be shown on the Stream Relocation Plans by providing stations, offsets and elevations for both the ends and the center of each step. The stations and offsets should be referenced to the centerline alignment for the relocated channel. The Plan should also include notes to indicate the minimum required stone size.

The Stream Relocation Plans should clearly communicate to the contractor the intended lines and grades for each step pool by placing the appropriate symbol on the alignment for the relocated stream and indicating in the Stream Mitigation Data Table the station for the control points used to define the location of each step. In general, the control point will be located at the point where the proposed stream alignment crosses the step pool structure. The table should also show the intended channel bottom elevation and anticipated scour depth. Enter the minimum required boulder diameter into the Design Data column of the table. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Step pools shall be paid for under the following item number:

- Item Number 209-03.36, Stream Mitigation-Step Pool, per Each

11.08.1.4.5 EXAMPLE APPLICATION

Given: An existing 375-foot reach of stream in Sevier County has previously been impacted by a roadway widening project. As a part of the mitigation for the previous impact, it has been proposed to use step pools to restore a more natural channel bottom profile to the stream. Survey data for the project indicates that the average slope of the stream is approximately 4.5%.

Find: Determine the height, spacing and required quantities for the proposed step pools.

Solution: Since specific guidelines for the design of step pools are not generally available, the design of the proposed step pool system will be based on an examination of nearby similar streams as well as an un-impacted reach immediately upstream of the project site. Examination of the nearby stream reaches indicates an average step height, H, of 1.2 feet, and an average pool length, L, of 16 feet. Equation 11HC-5 can be used to compute a steepness factor, S_c, corresponding to the observed step pool data:

$$S_c = \frac{H/L}{S_0} = \frac{1.2/16}{0.045} = 1.67$$

Since the computed value for the steepness factor seems to be reasonable for the project site, the observed pool data will be used to determine the design of the step pools in the project reach.

Hydraulic analysis of the stream indicates that the flow velocity for the 50-year peak discharge will be approximately 10.5 ft/sec. Based on the criteria provided in Table 11HC-1, it is determined that the minimum boulder size for the step pool structure should be 28 inches.

The pay item for step pools is:

Item Number 209-03.36, Stream Mitigation-Step Pool, per Each

Given an average spacing of 16 feet over a reach length of 375 feet, the final quantity for step pools will be 24.

11.08.1.5 ROCK VANES

Cross Vane in Reconstructed Stream
Location: SR-15, Wayne County, TN (2011)

11.08.1.5.1 DEFINITION AND PURPOSE

Rock vanes may be constructed in four different configurations. A straight rock vane consists of a single line of rocks placed at an angle to the bank. A rock cross vane is a “U”-shaped rock structure consisting of two arms which are angled upstream and are connected to a central apex which is perpendicular to the flow. The arms are sloped downward from the banks to the center of the stream so that the apex is at or slightly above the bed elevation. A rock “W” weir is another possible configuration consisting of two cross vanes placed side by side. This configuration is typically applied in wider streams. A third possible configuration is a “J”-hook, which is also similar to a cross vane but typically extends across only two thirds of the channel forming flow width.

This measure differs from a step pool in that its purpose is primarily re-directive; that is, it acts to concentrate flow in the center of the channel, while step pools act primarily to control flow velocity and maintain the grade of a steep stream. Rock vanes may also be applied in streams with flatter slopes and finer channel substrate materials.

Rock vanes may be utilized to accomplish a number of purposes, including:

- controlling the grade of the channel bed
- narrowing the channel bottom width
- redirecting flow velocity away from erodible banks
- maintaining the sediment transport capacity of the channel

The drop and flow constriction created by a rock vane tend to create a scour pool immediately downstream of the cross vane apex. This pool and the associated complexity introduced into the flow pattern can provide modest enhancement to the aquatic habitat.

11.08.1.5.2 APPROPRIATE APPLICATIONS

Due to their configuration, rock cross vanes and “”W weirs tend to create backwater conditions upstream of the structure while focusing the force of the flow towards the center of the channel downstream. This minimizes the flow velocities and shear forces on the channel banks while creating scour pools and narrower channel bottom widths at the center of the channel. “J” hooks act in a similar manner, but redirect from away from only one bank. Rock vanes may be utilized in a TDOT channel relocation project to prevent damage to potentially erodible channel banks. Straight rock vanes may be used to redirect flows from the bank while minimizing the scour that would occur on the channel bottom.

Rock vanes can also assist in reproducing the existing aquatic habitat values in a relocated stream reach, particularly where vegetative cover can be established on the channel banks. When constructed and spaced properly, rock vanes can recreate the natural pattern of pools and riffles that may exist in the channel to be relocated. They also create areas of low flow velocity which can provide cover and resting areas during periods of both high and low flow. The flow complexities introduced by these measures can also result in increased opportunities for feeding by the aquatic organisms in the stream. Further, the gravel deposits which form in the tail out or glide portions of the downstream pool can provide spawning areas.

Rock vanes are most appropriately used in streams with moderate to high slopes (0.005 ft/ft and greater) and channel substrate materials ranging from moderately erodible sand or clay to cobbles and boulders. They are also of value where the channel banks are highly erodible or very steep. Because they tend to concentrate higher velocity flows at the center of the channel, they are also suitable for streams with large amounts of bedload sediment transport.

Straight rock vanes and rock cross vanes may be applied in streams with channel widths up to 50 feet while “W” weirs may be applied where the channel width exceeds 40 feet. “J” hooks as seen in Figure 11HC-5, may be applied to streams of any width, and on wider streams may extend into the channel a distance less than two thirds of the width at the channel forming flow. In addition, straight rock vanes and “J” hooks may be applied on streams where a cross vane would impede the passage of aquatic organisms or boat traffic.

Figure 11HC-5
Typical J-Hook Rock Vane in Gravel Bed Stream
Reference: U.S. EPA, Essentials of Stream Restoration (2005)

Rock vanes are primarily intended for application on streams with a sustained base flow. This measure may be of limited value on ephemeral or intermittent streams or streams where the flows are flashy in nature.

Figure 11HC-6
Typical Straight Rock Vane in a Gravel Bed Stream
Location: SR-15, Furnace Branch, Wayne County, TN (2011)

11.08.1.5.3 LIMITATIONS

Rock vanes should be applied only where they would be useful to recreate an existing pool and riffle structure in a relocated stream channel.

Because rock vanes are designed to create a scour pool on the downstream side of the structure, they would be of limited value for streams with bedrock channels. Conversely, this measure should not be utilized in channels characterized by highly erodible substrate materials such as silt or fine sand. There is a possibility that the depth of the downstream scour hole could become excessive, resulting in the failure of the structure. Further, they should not be applied in actively degrading channels or where a significant head cut is migrating upstream. Rock vanes are ineffective at mitigating either of these conditions and the instability of the channel would most likely lead to the failure of these measures.

Rock vanes should be applied with caution in streams with sand and clay beds. Additional foundation design will likely be required to ensure that the large rocks that make up the structure will not sink or subside. This setting may also create difficulties for the proper construction and placement of the measure.

Where rock vanes are utilized, heavy equipment and skilled operators may be required to place the rock correctly within the stream. Thus, the selected site should offer adequate access for heavy equipment as well as adequate room to stockpile materials.

These measures may also be difficult to apply in small streams due to the large rock sizes required.

11.08.1.5.4 PLANNING AND DESIGN CRITERIA

Rock vanes should be carefully designed to ensure that they will meet their intended purposes. As shown in Figure 11HC-7, rock cross vanes consist of two arms connected to a vane at the apex that is oriented perpendicular to the flow direction in the stream while the apex end of a "J" hook is curved (see Figure 11HC-8). The arms are placed at an angle of 20° to 30° with respect to the stream bank, and each occupies approximately ⅓ of the channel width at the channel forming discharge. The apex takes up the remaining ⅓ of the channel width. A straight rock vane is essentially equivalent to one arm of a rock cross vane.

The design of a rock vane will require a determination of the flow depth at the channel forming discharge, as described in Section 11.04.3. The ends of the arms should tie into the bank at a level equal to the flow level of the channel forming discharge and then slope downward toward the center of the channel at a rate of 3 to 7 percent to tie into the apex of the structure at the desired thalweg elevation.

Where rock vanes are used in series, it will be necessary to determine the maximum allowable drop between successive vanes. This maximum allowable drop should be coordinated with the Environmental Division in order to ensure adequate passage for fish and other aquatic organisms. In the absence of a specific environmental requirement, the drop height may be determined based on the spacing criteria provided below and the desired slope of the relocated channel. However, to ensure the structural stability of the measure, the drop should generally not be allowed to exceed 1 foot.

The spacing between successive vanes should be determined based on the riffle and pool structure of the existing relocation reach. The locations of the upstream ends of each pool should be determined based on the criteria provided in Section 11.04.2, and rock vanes may be applied at the beginning of each desired pool location to recreate the natural riffle-pool structure of the stream. As described in Section 11.04.2, the pool spacing should not be constant; rather, it should vary based on the natural variation in spacing observed in the existing stream reach.

The vane spacing can be checked by using Equation 11HC-6 as a rule of thumb:

$$P_s = 8.25 W_{CF}\left(S_0{}^{-0.98}\right) \qquad \text{(11HC-6)}$$

Where: P_S = average spacing between successive vanes, (ft)
W_{CF} = channel top width at the channel forming discharge, (ft)
S_0 = average slope of the channel, (%)

This relationship was derived based on data from natural streams and rivers, but gives unrealistic values for slopes less than 1% or greater than 2%. An additional factor to consider is that the vanes should be spaced far enough apart that the backwater from the downstream vane does not submerge the upstream vane.

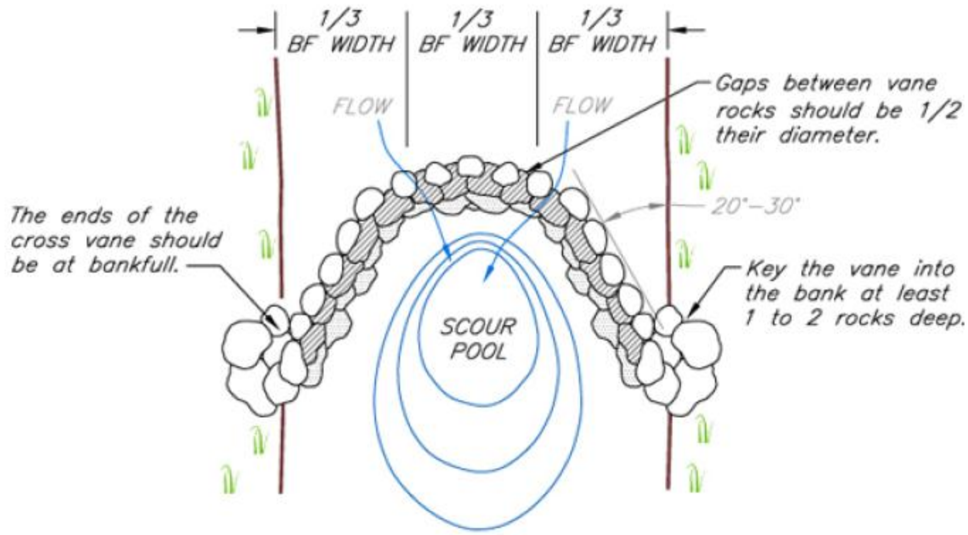


Figure 11HC-7
Typical Plan View of Rock Cross Vane
Reference: SSWMP, TDOT Environmental Division (2007)

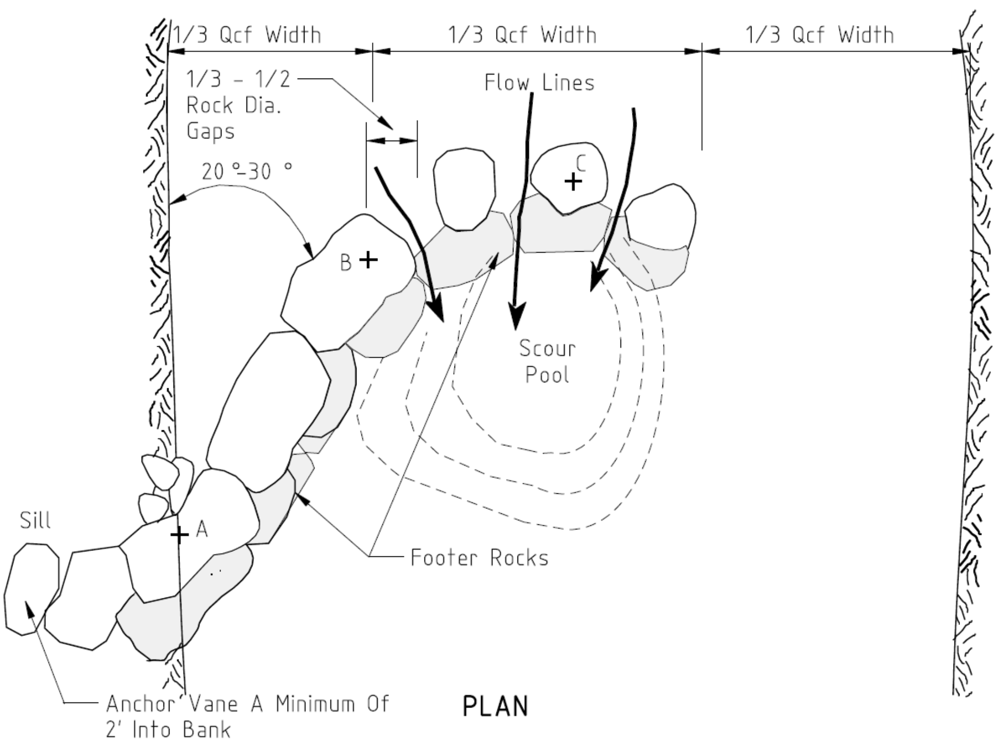


Figure 11HC-8
Typical Plan View of Rock "J" Hook Vane
Reference: Virginia DCR (2003)

The stones used to construct a rock vane should be heavy enough to remain immobile during the design peak flood discharge, usually for the 50-year event. In addition, the structure should be provided with a sufficiently deep foundation, and the gaps between the larger stones should be sealed to prevent the piping of fine materials. The criteria provided in the previous section on step pools should be applied in designing the foundation for a rock vane.

While a properly designed rock vane should provide adequate flow redirection for discharges up to the channel forming discharge, its performance during periods of higher discharges may be different. Thus, it is important to consider whether turbulence that may be created by the structure during large flow events could potentially cause erosion on the channel banks. This can be addressed by providing vegetative erosion prevention measures on the channel bank that have been designed to withstand the shear forces imposed by the design discharge. In addition, the arms should be keyed into the stream banks a minimum distance of 3 feet. This will help ensure that the ends of the structure will not be exposed in the event of unanticipated erosion on the bank.

Rock vanes should be applied with caution in channels composed of sand or other materials that could be pulled through the stones by the force of flowing water. This can result in undermining and the eventual failure of the structure. In order to prevent this, the base of the structure should be wrapped in Geotextile Fabric (Type III) (Erosion Control). This fabric should cover the entire trench for the rock vane and extend to the top of the upstream face of the structure. The fabric above the trench should be held in place by a layer of Machined Riprap placed on top of the fabric. The class of Machined Riprap should be selected based on the average flow velocity in the 50-year event.

The bottom of the footer stones for the structure should be embedded into the channel to a depth below the scour depth, which may be interpolated from Table 11HC-1. This table was derived by adapting Equation 11HC-3 to the specific situation presented by a rock cross vane or “W” weir.

Depth at Channel Forming Discharge (feet)	**Channel Forming Discharge / Channel Width (Q_{cf} / W) (cfs/ft)**								
	2	**4**	**7**	**10**	**15**	**20**	**30**	**40**	**50**
1	0.06	0.54	1.08	1.53					
2			0.44	0.95	1.68	2.29	3.34		
3				0.24	1.03	1.70	2.85	3.84	4.72
4					0.30	1.02	2.25	3.30	4.23
5						0.28	1.57	2.67	3.66

Table 11HC-1
Scour Depth in Feet for Cross Vanes or “W” Weirs

Proper construction is critical to the effectiveness and structural stability of a rock vane. Thus the Stream Relocation Plans should clearly communicate to the contractor the intended lines and grades for each vane structure by showing rock vane configurations on the Stream Relocation Plans. Stations for each control point used to define the location of each structure should be provided on the Stream Mitigation Data Table. In general, the control point will be located at the point where the proposed stream alignment crosses the rock vane structure. The table should also show the flow elevation at the channel forming discharge, the intended channel bottom elevation and anticipated scour depth so that the required depths of any required footer stones can be properly determined. Enter the minimum required boulder diameter into the Design Data column of the table. If Geotextile Fabric (Type III) (Erosion Control) is required, the required class of riprap is also entered into the Design Data column. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Rock vanes shall be paid for under the following item numbers:

- Item Number 209-03.37 Stream Mitigation-Cross Vane Structure, per Each
- Item Number 209-03.38 Stream Mitigation-J – Hook, per Each
- Item Number 209-03.39 Stream Mitigation-W – Weir, per Each
- Item Number 209-03.52 Stream Mitigation-J-Hook w/ Step, per Each
- Item Number 209-03.54 Stream Mitigation-Cross Vane Structure w/ Step, per Each
- Item Number 209-03.60 Stream Mitigation-Rock Vane, per Each

11.08.1.5.5 EXAMPLE APPLICATION

Given: A proposed bridge replacement project will include an intersection improvement just to the east of the existing bridge. Due to site constraints and the safety needs of the intersection improvement, it will be necessary for the proposed bridge to be located significantly further west from its present location. As a result, approximately 300 feet of the existing channel will have to be relocated within the existing floodplain.

Survey and field investigation indicate that the stream bed materials consist of a layer of sand and gravel 2 to 3 feet thick on top of bedrock. The existing stream exhibits a pattern of pools and riffles with an average spacing between riffles of about 150 feet. The width of the channel at the bankfull flow elevation is approximately 93 feet and the overall floodplain slope is equal to 0.6%. Analysis of the 50-year flood event yields a flow depth of 3.51 feet for a discharge of 2090 cfs.

It is proposed to utilize rock vanes to reestablish the existing pool and riffle structure in the relocated stream.

Find: Determine the appropriate type of rock vane for this project, as well as the required height, spacing and quantities.

Solution: Due to the width of the flow at the channel forming discharge, it is decided to utilize a “W” weir for this project. In addition, to help ensure the stability of the proposed rock vanes, it is decided that the structures should be constructed on top of footer boulders which are placed on the underlying bedrock.

In coordination with the Environmental Division, it is determined that the maximum drop height that will allow the passage of aquatic organisms is 1 foot. Assuming that the average depth of the sand and gravel is 2.5 feet, the height of the weir through the apex sections is proposed to be 3.5 feet. For a "W" weir, each of the legs of the vanes should occupy $1/6^{th}$ of the bankfull flow width. Since the channel width is 93 feet, each leg would occupy about 15.5 feet of the width, and, given an angle of 30° from the channel bank, the length of each leg would be 31 feet. A slope of 5% is assumed between the apex and the point at which the legs tie into the channel banks. Thus, the height of the structure will be about 1.5 feet greater, or 5 feet at the channel banks.

Equation 11HC-6 can be used to check the proposed spacing of the structures:

$$P_s = 8.25 W_{CF} \left(S_0^{\;-0.98} \right) = 8.25 (93) \left(0.6^{-0.98} \right) = 1266 \text{ feet}$$

It is judged that this result is unreasonable, particularly since the observed natural spacing is approximately 150 feet. Thus, this result is disregarded.

The pay item for this measure is:

<u>Item Number 209-03.39, Stream Mitigation - W-Weir, per Each</u>

Given a spacing of 150 feet over a reach length of 300 feet, the final quantity for W-weirs will be 2.

11.08.1.6 SPUR DIKES

Spur Dike Installation
Reference: USDOT, FHWA

11.08.1.6.1 DEFINITION AND PURPOSE

Spur dikes, also referred to as groins, are structures that extend outward from the bank of a stream to deflect high velocity flows from along the stream bank towards the middle of the channel. This reduces flow velocities adjacent to the stream bank in order to protect it from erosion. In some cases, spur dikes can help rebuild an eroded channel bank by encouraging sediment deposition between the structures. Spur dikes may also be utilized to realign the banks of a meandering channel to prevent a streamside structure or bridge abutment from being damaged by erosion. Although they are typically installed in a series along one bank of a stream, spur dikes can also be installed on alternate stream banks to produce a meandering thalweg and thus provide additional habitat benefits.

Because spur dikes work to focus the flow velocity towards the center of the channel, spur dikes can improve the sediment transport capacity and aquatic habitat of a stream. They can add complexity to the flows in the channel by creating regions of swift and slow flow adjacent to one another. The slack water between the structures can provide cover and resting areas, especially where spur dikes are combined with measures such as root wads. Spur dikes can also reduce sediment loads by helping to prevent the erosion on the channel banks.

Spur dikes should not be confused with bendway weirs which are typically applied on significantly large or navigable rivers. Because it not practical to relocate large waterways for a TDOT roadway project, bendway weirs are beyond the scope of this Manual.

11.08.1.6.2 APPROPRIATE APPLICATIONS

Spur dikes are one of the most commonly applied measures for countering lateral erosion on an outer stream bank. Because they are applied over specific small areas, they can be cost effective as compared to other bank protection measures, especially where the length of bank to be protected is long.

Spur dikes are best applied on wide shallow streams where the obstruction they would create in the channel will have a minimal effect on flood stages. They also function well in streams with moderate to heavy sediment loads, especially where their purpose is to help rebuild an eroded slope. They are also suitable for moderate to steep slopes where the flow is characterized by higher velocities but lower depths. Finally, they are most easily applied on streams with beds composed of bedrock or gravel but may also be applied in channels composed of finer materials provided that measures can be taken to provide an adequate foundation and prevent the piping of fine materials from beneath the structure.

Spur dikes may be applied to deflect current away from a stream bank which requires protection from erosion. A typical spur dike installation will consist of a series of dikes placed along the outside of a bend, or in an area where the outside stream bank has been subject to erosion. Because the radius of curvature affects the spacing of the dikes, this measure may be applied only on moderate bends. For bends with a long radius, the required spacing is so wide that the measure becomes ineffective. Conversely, on very tight bends, the spacing becomes so close that the measure is no longer cost effective.

11.08.1.6.3 LIMITATIONS

Spur dikes are not well suited for comparatively deep or confined channels, and are not effective where an eroded bank is subject to mass stability problems. They may also result in the “scalloping” of the bank until the system stabilizes, and thus may require erosion protection on the toe of the slope between dikes.

The placement of spur dikes on a stream will likely result in short-term instability as the channel adjusts to the redirection of the flow. Initially, the hydraulic capacity of the channel may be reduced due to the obstruction imposed by the dikes. However, the channel will typically regain all of the needed flow area either by becoming deeper or by becoming wider due to erosion that may occur on the opposite stream bank. The designer should carefully consider the potential effects of these adjustments.

Spur dikes are usually composed of machined riprap, and in some settings may require very large stone sizes. They should not be applied in locations which do not provide adequate access for heavy equipment or sufficient room to stockpile materials. Further, it may be difficult to use this measure in small streams if large rock sizes are required.

Although spur dikes can be effective at dealing with lateral instability issues, they should not be applied on streams that are subject to degradation or aggradation.

11.08.1.6.4 PLANNING AND DESIGN CRITERIA

Spur dikes require detailed design as well as a clear understanding of the flow patterns within the stream reach. Each stream presents unique circumstances, and careful consideration should be given to flow depths for the channel forming and design discharges, the alignment of the stream both upstream and downstream of the project reach, potential lateral migration of the channel, and the materials in the channel bed.

Figure 11HC-9 provides approximate criteria for determining the minimum longitudinal extent of an installation of spur dikes. The longitudinal extent indicated by this figure should be adjusted to ensure that the proposed installation will cover the entire area of active scour. This can be determined based on a field check and inspection of aerial photography. Past experience with spur dikes has indicated that many installations have not extended far enough downstream. Thus, the downstream length indicated by Figure 11HC-9 should be assumed to be a minimum. In particular, the downstream movement of meander bends should be considered in establishing the downstream extent of protection.

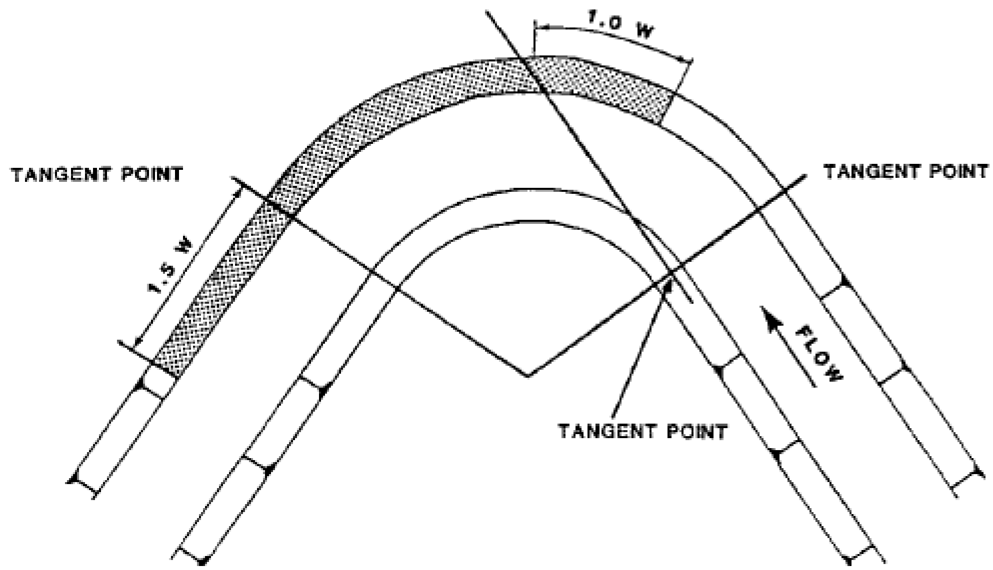


Figure 11HC-9
Longitudinal Extent of a Spur Dike Installation
(Note: W equals the bottom width of the channel)
Reference: USDOT, FHWA, HEC-23, Volume 2 (2009)

A proposed spur dike installation is usually laid out by creating a sketch similar to Figure 11HC-10. The first step in the process is to determine a desired alignment for the top of bank through the reach where the dikes are to be installed. This alignment should be based on maintaining a consistent channel width between the project site and the upstream and downstream channel reaches. In reaches where the channel has not eroded, the desired bank alignment may coincide with the existing top of bank.

The next step is to sketch a line along the stream to represent the proposed tips of the spur dikes. For the proposed spur dikes to effectively deflect flows in the channel, this line should be located such that the spur dikes will encroach about 20 percent of the channel width.

Once the desired bank alignment and the line delineating the ends of the spur dikes have been established, it is possible to begin determining for locations each dike. The first dike is normally placed at the downstream end of the proposed installation. The distance to the next upstream dike is a function of spur length, the degree of curvature of the bend and the expansion angle of the flow from the tip of the spur. As shown in Figure 11HC-10, each spur dike should be located such that the flow expansion from the spur would just touch the desired bank line at the next downstream spur.

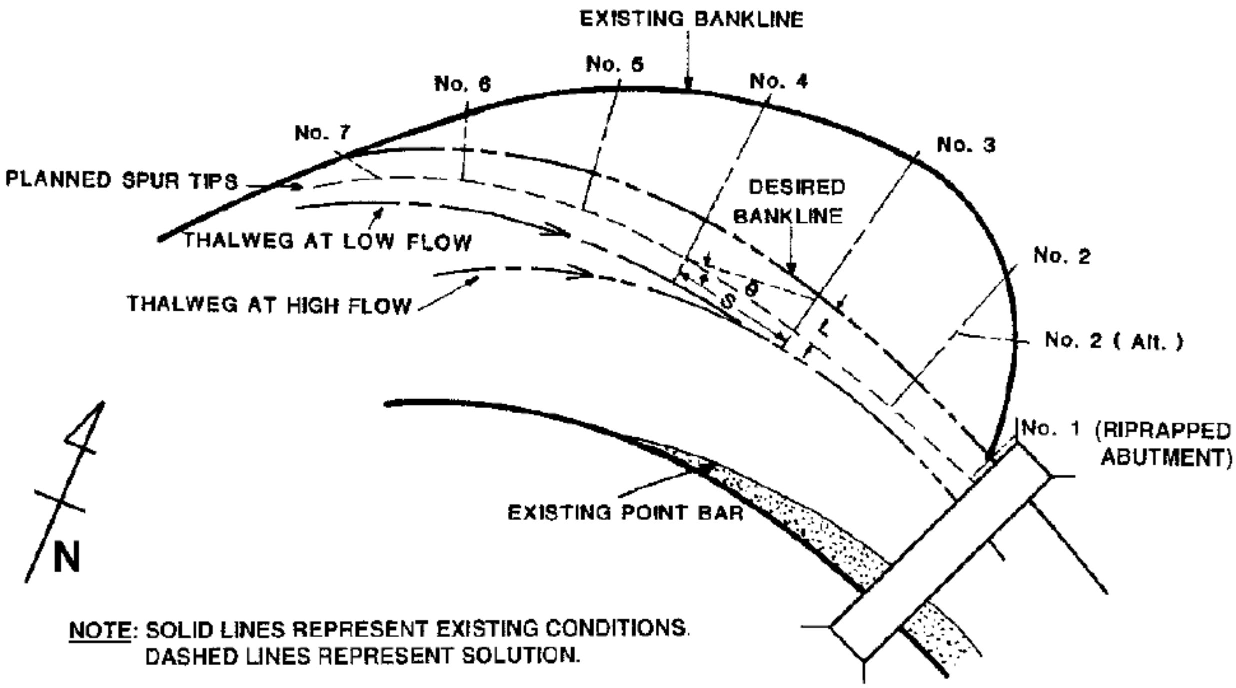


Figure 11HC-10
Typical Spur Dike Layout Sketch
Reference: USDOT, FHWA, HEC-23, Volume 2 (2009)

Mathematically, this relationship can be expressed by Equation 11HC-7 as:

$$S_s = \frac{L}{\tan\theta} \qquad \text{(11HC-7)}$$

Where: S_S = spacing between successive dikes, (ft)
L = length from the bank line to the tip of the dike, (ft)
θ= flow expansion angle, (degrees or radians)

For spurs composed of machined riprap, the expansion angle, θ, may be assumed to be 17 degrees.

With the exception of the most upstream structure, each spur dike should be oriented at an angle perpendicular to the direction of the flow. It is recommended that the most upstream dike be placed at an angle of approximately 150 degrees from the upstream bank in order to provide a smooth transition for the flow approaching the spur installation. This will help to prevent excessive local scour at the nose of the spur.

Where spur dikes are to be placed in a stream characterized by a pool and riffle structure, the designer should consider whether backwater effects from the installation would affect any existing riffle areas. This would be of particular concern if flow velocities upstream of the installation would be sufficiently reduced to cause deposition of finer sediments on a riffle.

Spur dikes should be designed to be above the water surface during normal flow levels. Typically, a spur would intersect the bank at a level equal to the flow depth at the channel forming discharge. However, the height of the spur should not exceed the channel bank height because erosion on the overbank at the end of the spur could increase the probability of failure due to erosion during periods of high stream stages. The crest of the spur should slope downward away from the bank line. Due to settlement or other forces on the structure, a level spur would likely develop a low point in its crest profile where overtopping could cause damage due to the movement of particles in the spur, or erosion damage to the stream bank. The spur would typically have a trapezoidal cross section with a minimum top width of approximately 3 feet. The side slopes should be determined based on minimizing the width of the spur while providing a stable side slope.

A typical spur dike will be constructed from machined riprap. For flow velocities up to 12 ft/sec, the class of riprap used should be determined based on the criteria provided in Section 11.04.6.2. Where the flow velocity exceeds 12 ft/sec, Equation 11HC-8 may be used to determine the required d_{50} of the stone.

$$d_{50} = C\, y \left[\frac{V_{des}}{\sqrt{K_1 (SG-1) g\, y}} \right]^{2..5} \qquad \text{(11HC-8)}$$

Where: d_{50} = median stone diameter, (ft)
C = adjustment for angularity of the rock and safety factor, (dimensionless)
y = depth at the tip of the spur, (ft)
V_{des}= design velocity (see below), (ft/sec)
K_1 = side slope correction factor, (dimensionless)
SG = specific gravity of the stone, (usually 2.65)
g = acceleration due to gravity, (32.2 ft/sec^2)

The design velocity, V_{des}, is usually adjusted based on the ratio of the radius of curvature of the bend, R_c, to the width of the channel bottom, W. First, the average velocity in the natural cross section, V, is determined based on the Continuity Equation (see Section 5.03.2). Where the ratio R_c/W is greater than 26, V_{des} may be assumed to be equal to the average flow velocity. Otherwise, the design velocity may be computed using Equation 11HC-9:

$$V_{des} = V\left[1.74 - 0.52\log\left(\frac{R_c}{W}\right)\right] \qquad \text{(11HC-9)}$$

Where: V_{des} = design velocity, (ft/sec)
V = average velocity in the cross section, (ft/sec)
R_c = radius of curvature of the bend, (ft)
W = channel bottom width, (ft)

Values for side slope correction factor, K_1, may be determined from Table 11HC-2 based on the proposed side slope of the dike. Where the side slope of the spur is flatter than 4H:1V, the value of K_1 will be 1.0.

Side Slope (_H:1V)	**K_1**
1	0.21
2	0.87
3	0.98
4	1.00

Table 11HC-2
Side Slope Correction Factors for Spur Dike Riprap Sizing
Reference: FHWA, HEC-23, Volume 2 (2009)

A spur dike should be designed to resist at least three potential modes of failure: local scour, piping and flanking. Local scour generally occurs at the tip of the dike due to the local acceleration and turbulence which will occur in this area. Currently, little practical guidance exists for estimating the depth of scour hole which will occur. Until more detailed guidance becomes available, a conservative estimate of the scour hole depth may be obtained from Equation 11HC-10:

$$y_s = y_{avg}\left[1.8 - 0.051\left(\frac{R_c}{W}\right) + 0.0084\left(\frac{W}{y_{avg}}\right)\right] \qquad \text{(11HC-10)}$$

Where: y_s = maximum scour depth, (ft)
y_{avg} = average depth in the cross section before scour, (ft)
R_c = radius of curvature of the bend, (ft)
W = channel bottom width, (ft)

The above equation is intended to be used to estimate the depth of scour which would occur on the outside of a channel meander bend in the absence of spur dikes or any other erosion prevention measures. It was developed by examining natural streams where the ratio R_c/W ranged from 1.5 to 10 and where the ratio W/y_{avg} was at least 20. If this equation is applied to streams where these ratios are less than these minimum values, it is recommended that the minimum values be used in the equation. It is also recommended that this equation be applied for the flow conditions that would exist for the channel forming discharge. The average depth, y_{avg}, may be computed by determining the cross sectional flow area at a nearby straight reach and dividing that area by the top width of the flow.

The designer should bear in mind that Equation 11HC-10 will likely yield conservative results. If possible, the results should be checked against the depth of any existing scour pools which may have developed for similar structures in the stream. This equation should also only be applied to natural streams. It is not valid for streams that have been altered by channelization or the placement of hardened channel lining materials.

Two possible approaches are available for designing a spur dike to resist local scour. One approach is to extend the length and width of the dike at the tip in order to provide material that can be “launched” into the scour hole as it develops. The second is to place the foundation of the dike at a level below the anticipated depth of scour. The choice of method should be based on a consideration of the channel substrate materials, anticipated depth of scour and constructability issues.

Piping may be an issue where the materials in the stream bed include significant portions of sand, silt, or clay. This occurs where the flow of water though the voids in the riprap used to construct the dike is sufficient to draw soil particles from beneath the structure. The resulting voids can cause settlement or subsidence of the structure, which can reduce its effectiveness or even cause structural failure. Where this is a concern, a trench should be excavated in the stream bed so that the foundation of the dike can be placed on competent materials. In addition, the foundation should be wrapped in Geotextile Fabric (Type III) (Erosion Control) or be provided with a suitable granular filter.

The third mode of failure is referred to as flanking and can occur when high flows erode the stream bank, thus exposing the outer end of the dike. Even if the materials of the dike are sufficient to remain stable, this condition can result in severe damage to the channel bank. To prevent this from occurring, the spur dike should be keyed into the existing stream bank by a distance of at least 5 feet. However, where the ratio R_c/W is less than 5, the length of the key should be computed using Equation 11HC-11:

$$L_{key} = \left(\frac{L}{2}\right)\left(\frac{W}{L}\right)^{0.3}\left(\frac{S_s}{R_c}\right)^{0.5} \qquad \text{(11HC-11)}$$

Where: L_{key} = key length measured from the existing bank line to the end of the dike, (ft)
S_S = spacing between successive dikes, (ft)
L = length from the desired bank line to the tip of the dike, (ft)
R_C = radius of curvature of the bend, (ft)
W = channel bottom width, (ft)

The designer should also carefully consider the potential effects of a spur dike installation on the opposite stream bank. Since spur dikes are designed to deflect the high velocity flows towards the center of the channel, it is probable that flow velocities on the opposite stream bank will also be increased. Where the encroachment of the dikes is limited to 20% of the flow width at the channel forming discharge, any erosion on the opposite bank will probably not be excessive. However, this possibility should be investigated. In some cases, an installation of spur dikes may result in the removal of an existing point bar. While this is generally not considered to be an adverse effect, the designer should take into account any possible downstream impacts of the increased sediment load.

Due to the relative complexity of spur dike structures, drawings and design information for these structures should be provided in the Stream Relocation Detail Sheets. For each spur dike, the Stream Mitigation Data Table should show the following information:

- station and offset of the control point used to define the location of the dike
- channel forming flow elevation, channel bottom elevation, and anticipated scour depth
- reference to the appropriate Stream Relocation Detail Sheet number(s)

In general, the control point for locating each dike will be located at the point where the structure intersects the channel bank. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Spur dikes shall be paid for under the following item numbers:

- Item Number 209-03.61, Stream Mitigation – Spur Dike (Description), per Each

11.08.1.6.5 EXAMPLE APPLICATION

Given: A significant bank erosion problem has occurred along the outside of a meander bend of an existing stream adjacent to a TDOT roadway. To prevent damage to the roadway, it is proposed to use spur dikes in the eroded area in order to reestablish the original line of the top of bank. The meander bend has a radius of curvature, R_c, of approximately 250 feet and the internal angle of the bend is 85°. In its original configuration, the channel has the following characteristics:

- Channel bottom width, W = 8 feet
- Channel side slopes = 2.5H:1V
- Channel bank height = 6.0 feet
- Longitudinal slope of the stream = 1.35%

Based on the channel characteristics listed above, it has been found that the depth and flow velocity for the 50-year flood event are 6.11 feet and 8.81 ft/sec, respectively. In addition, the depth of flow at the channel forming discharge has been found to be 3.23 feet.

Find: Determine the design and required quantities for the proposed spur dikes.

Solution: The design of the proposed spur dikes will involve the following factors:

Spacing: Based on Equation 11HC-7, the required spacing of the dikes is a function of the dike length from the desired top of bank line to the tip of the dikes. Since the channel banks are at a slope of 2.5H:1V up to a height of 6.0 feet, the horizontal distance from the top of the bank to its toe would be 15.0 feet. Since the tip of the dike should encroach approximately 20% of the channel bottom width, the length of the spur dikes should include an additional 1.5 feet for a total length of 16.5 feet. Thus, the spacing may be computed as:

$$S_s = \frac{L}{\tan\theta} = \frac{16.5}{\tan(17°)} = 54 \text{ feet}$$

Length of Key: For this site, the ratio R_c/W is approximately 32, which is much greater than 5. Thus, the length of the key should be 5 feet.

Material: The material used to construct the proposed spur dikes should be determined based on the flow velocity for the 50-year flood event. Since the 50-year flow velocity is between 5 and 10 ft/sec, the dikes should be constructed from Class B Machined Riprap.

Height: The total height of the spur dikes should include both the height of dike above the channel bottom and the depth below the channel bottom required to accommodate the anticipated scour depth. Thus, Equation 11HC-10 may be used first to compute the anticipated scour depth for the 50-year storm event. However, to apply this equation it is necessary to evaluate the ratios R_c/W and W/y_{avg}. Based on the information given above, the ratio R_c/W is approximately equal to 31. Because this value is greater than the minimum recommended value, it will be used for the computation. On the other hand, because the depth for the 50-year event is equal to 6.11 feet, the ratio W/y_{avg} is equal to 1.3, which is less than the minimum recommended value of 20. Thus the minimum value will be used, and the scour depth may be computed as:

$$y_s = y_{avg}\left[1.8 - 0.051\left(\frac{R_c}{W}\right) + 0.0084\left(\frac{W}{y_{avg}}\right)\right] = 6.11\left[1.8 - 0.051(31) + 0.084(20)\right]$$
$$y_s = 2.4 \text{ feet}$$

Based on this result, the total height of the dike at the desired bank line will be equal to the scour depth plus the flow depth at the channel forming discharge, or 5.6 feet. Because the dike will be sloped at 2% from this point to its tip, the height at the tip will be reduced by 0.3 feet so that the total height at the tip will be 5.3 feet.

The pay item for spur dikes is:

<u>Item Number 209-03.61, Stream Mitigation-Spur Dike (Description), per Each</u>

To determine the number of spur dikes required, it will be necessary to compute the total length of reach over which they will be required. Based on the information given above, the total stream length through the bend, L_b, may be computed as:

$$L_b = \pi D\left(\frac{\Theta}{360}\right) = \pi\left(2 \times 250\right)\left(\frac{85}{360}\right) = 371 \text{ feet}$$

It is also necessary to extend the total length of the protected area by a distance equal to 1.5 times the channel bottom width, W, or 12 feet. Thus, the total length over which dikes will be required is 383 feet. Based on a spacing of 54 feet, 7 dikes would be required. However, since there will be dikes at both the start and at the end of the reach, the final quantity would be 8 dikes.

11.08.1.7 CONSTRUCTED RIFFLES

Constructed Rock Riffle
Reference: Iowa Dept. of Natural Resources (2006)

11.08.1.7.1 DEFINITION AND PURPOSE

In natural streams, riffles are areas in the stream bed that are characterized by shallow flow over coarse materials such as gravel or cobbles. They are an important component of the vertical profile in streams which are characterized by a pool and riffle structure. During periods of normal flow, riffles provide a number of benefits to the habitat for fish and other aquatic organisms. They create turbulence in the flow of the water thereby increasing the amount of dissolved oxygen, and also serve to maintain pools and the associated pool habitat. In addition, the gravel substrate in a typical rock riffle provides productive habitat for aquatic organisms and areas for fish to spawn.

Three types of constructed riffle are available for TDOT stream relocation projects: rock riffles, log riffles and boulder riffles.

A rock riffle is constructed by placing gravel or larger coarse particles in the channel bed, while a log riffle is constructed by placing two or three logs across the channel and filling the spaces between the logs with gravel. While both of these measures are intended to mimic the existing structure of a natural stream to be relocated, neither of them should be considered to be permanent. The gravels used to construct a rock riffle will likely be mobilized during periods of high flow and will tend to be sorted by the natural fluvial processes in the stream to form another riffle at a new location. Although logs placed in the stream bed will tend to hold the coarse materials in place, they are subject to decay and will eventually release the gravel.

Boulder riffles consist of small boulder spurs that extend into the channel from the bank. In contrast to rock and log riffles, these structures are intended to be permanent.

Log riffles provide some of the same habitat values as rock riffles, especially the addition of oxygen. The woody material also helps to provide substrate for aquatic organisms. Boulder riffles create a series of low-velocity flow areas as well as small scour pools.

11.08.1.7.2 APPROPRIATE APPLICATIONS

Constructed riffles are utilized to recreate a pool and riffle structure that may exist in a stream to be relocated. They should be utilized on a TDOT stream relocation project when the existing channel is a stable alluvial channel characterized by a pool and riffle structure, or where large trees have fallen across the existing channel. In some cases, it may be apparent that riffle formation will occur in a channel simply due to the presence of coarse sediments such as gravel and boulders in the larger stream system. Where this is the case, a constructed rock riffle may be applied to augment the natural riffle-building process.

Log riffles are subject to decay over a period of 5 to 15 years and thus are most appropriately applied where a temporary structure is needed. It may also be appropriate to apply log riffles where the riparian vegetation along the relocated stream will include a significant number of trees. In this situation, falling trees or other inputs of woody debris may be sufficient to replace the habitat value of the riffles after they have decayed.

Although boulder riffles are most beneficially applied in a stable alluvial stream, they may also be used to add complexity to the flow pattern and increase dissolved oxygen levels in a threshold stream. In either case, boulder riffles should be applied in straight reaches.

11.08.1.7.3 LIMITATIONS

Constructed riffles should not be applied in streams that are vertically unstable. In a degrading stream, the measure is likely to be subject to structural failure, while in an aggrading stream, it is likely to be buried. Further, rock riffles should be applied with caution in streams which carry a high sediment load. The deposition of fine sediments in the gravel can greatly diminish the habitat value of the measure.

Although constructed riffles generally impose a minimal restriction on the hydraulic conveyance of the channel, the designer should consider whether a proposed riffle design will create increased backwater during periods of high flow.

Where rock riffles are applied on low gradient streams with channels composed of fine sediments, undermining of the rock structure could be a problem. It may be necessary to provide additional measures, such as filter fabric or a foundation of larger rock to minimize the potential from this from occurring.

Rock riffles and log riffles should not be applied in threshold channels.

11.08.1.7.4 PLANNING AND DESIGN CRITERIA

Because the purpose of a constructed riffle is to duplicate the existing characteristics of a relocated stream channel, detailed design is generally not required. As described in Section 11.04.2, the design of a constructed riffle should be based on information determined from the survey of the existing channel.

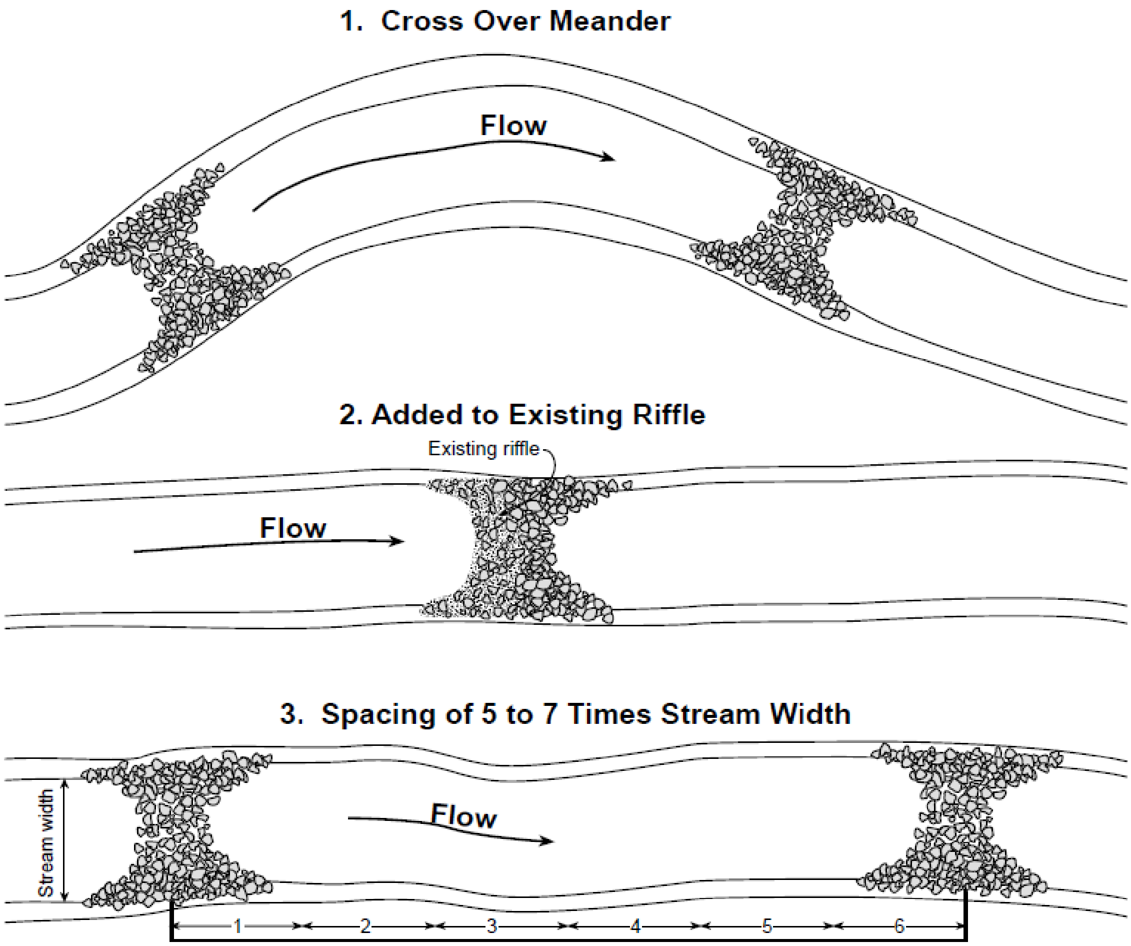


Figure 11HC-11
Suggested Placement of Rock Riffles in a Meandering Channel
Reference: Ohio Department of Natural Resources, (2003)

Where a channel follows a meandering planform, the riffles should be placed in the straight reaches between bends, as shown in Figure 11HC-11. However, where a meandering planform is not apparent, the design of rock riffles should include a determination of the locations for the riffles based on the following variables:

- riffle spacing, Xr
- riffle length, Lr
- pool length, Lp
- pool to riffle ratio, Rpr
- riffle height, hr

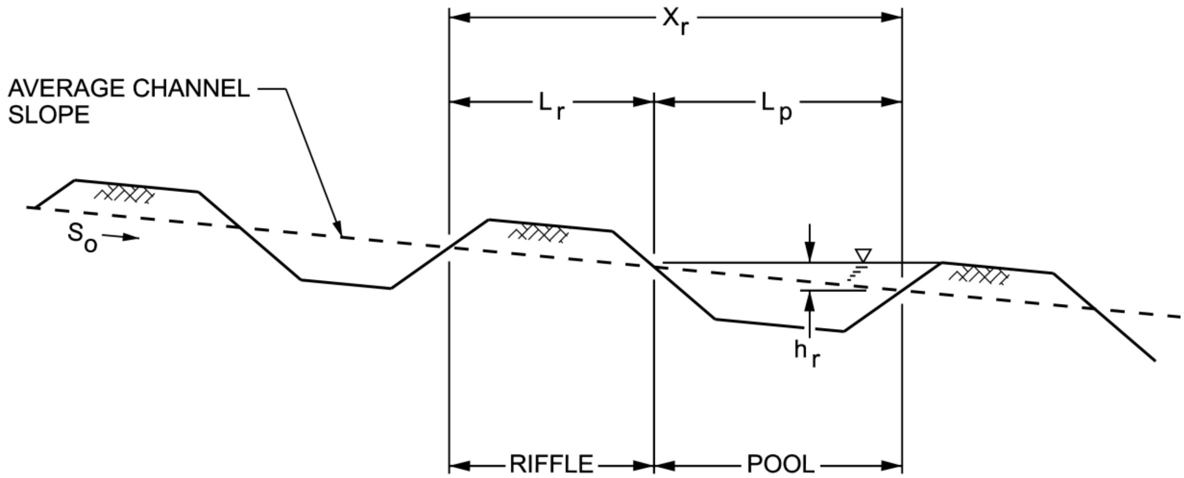


Figure 11HC-12
Definitions for Rock Riffle Design Variables

To simplify the placement of a system of rock weirs, the lengths of the pool and riffle will be defined as illustrated in Figure 11HC-12. The riffle length extends from the upstream end of the first riffle to the point at which the channel profile intersects the average channel slope. The pool length is measured from that point to the beginning of the next downstream riffle. Although these definitions ignore the concepts of the “run” and the “glide” commonly found in the literature on stream ecology, they allow for a practical means of arranging the constructed riffles through a relocated stream reach. These definitions should be used only for the computations described in this section. Another important definition is that of the pool to riffle ratio, R_{pr}. Based on Figure 11HC-12, this may be defined using Equation 11HC-12 as:

$$R_{pr} = \frac{L_p}{L_r} \qquad (11HC\text{-}12)$$

In nature, riffle spacing is a function of a variety of factors, including the slope of the stream. Although research into these factors is ongoing, the riffle spacing for a stream of moderate slope should be approximately 5 to 7 times the width of the channel. This allows sufficient room for the development of pools so that the structural integrity of the adjacent constructed riffles will not be undermined. In addition, the lengths of the constructed rock riffles should generally range from 2 to 4 times the channel width. Both of these criteria should be considered rules of thumb, and the riffle spacing and lengths may be adjusted as needed to achieve the desired pool to riffle ratio.

Usually, the starting point for laying out a series of rock riffles is to determine a value for this ratio. It may be possible to determine the pool to riffle ratio by examination of pools and riffles that may exist at other locations along the stream, or by coordination with the Environmental Division.

The next step is to estimate a value for riffle spacing, based on either conditions in the existing stream or on the alignment of the relocated channel as illustrated in Figure 11HC-11. The riffle length may then be computed as:

$$L_r = \frac{X_r}{1 + R_{pr}} \tag{11HC-13}$$

The pool length should then be computed as:

$$L_p = X_r - L_r \tag{11HC-14}$$

As shown in Figure 11HC-12, the riffle height, h_r, is generally measured from a line representing the average channel slope. In general, the height of the riffle should be determined such that the pool formed upstream will intersect the average channel slope at the point where it crosses the proposed channel invert profile. Thus, the riffle height may be computed as:

$$h_r = L_p S_o \tag{11HC-15}$$

Where: S_o = average channel slope, (ft/ft)

Once values for riffle height and length have been determined as described above, they should be evaluated to ensure that the resulting design will be appropriate. If the riffle length is less than 2 times the channel width, it may not be sufficiently long to provide the needed stream habitat functions. The riffle height should not be greater than the depth of water at normal flow, so that it will not unduly restrict the hydraulic efficiency of the channel. In small or moderately sized streams, the height should generally be less than one foot. Where either of these criteria is not met, the riffle spacing should be adjusted and the process described above should be repeated. In some cases, it may also be necessary to adjust the desired pool to riffle ratio.

The materials used to construct a rock riffle should have a particle size distribution identical to the size distribution determined for riffles in the existing channel. Where possible, riffle materials from the existing channel should be utilized to construct the riffles in the relocated channel. In general, it is important that the materials in the riffle be sized such that they would be stable at low and medium flows, but could be mobilized at bankfull or higher flows.

Rock riffles should be carefully constructed to minimize the potential for erosion of the channel banks. In order to concentrate lower stream flows, a riffle should be slightly lower at the center than at the sides. In addition a rock riffle should be constructed from both banks so that the stone in the middle of the stream can be placed last. Because flow follows the path of least resistance, placing rocks in the middle of the stream first could cause scour on the channel banks. Thus, the designer should ensure that access to the site can be provided from both sides of the stream, and evaluate the potential need for additional erosion protection measures.

Log riffles typically consist of two logs placed across the channel perpendicular to the flow, with a third log placed at an angle between them to form a “Z” on the channel bottom. The spaces between the logs are then filled with gravel or other coarse materials as described above for rock riffles. The logs provide a temporary means of retaining the rock within the riffle and add a variety of ecological benefits for aquatic organisms. The primary design considerations for log riffle structures are the stability of the logs, the rate at which the logs will decay and ensuring that the logs will not be undermined by erosion.

The forces that could act to displace the logs in a constructed log riffle include shear (drag) forces imposed by flow over the structure and the buoyancy of the logs. These forces must be counteracted by the weight of the logs combined with ballast or other means of anchoring the logs. The logs may be anchored by keying the ends into the channel banks and by placing riprap on the banks above the logs. The riprap also will assist in preventing erosion on the banks, and should be sized based on the flow velocity at the channel forming discharge using the criteria provided in Section 11.04.6. In addition, it is recommended that log riffles be used primarily at sites with perennial flows sufficient to ensure that the logs will remain submerged at all times. Because waterlogged wood is significantly heavier than dry wood, keeping the logs submerged will increase their weight and help contribute to the overall stability of the structure. Logs anchored in this manner should be stable for stream flow velocities as high as 10 ft/sec.

Because log riffles are temporary structures, the designer should make an attempt to provide a design that will maximize the life of the structure and should also consider what may occur at a riffle site once the logs have decayed. The life of the logs can be maximized by selecting wood species that decay relatively slowly, such as cedar, white oak, etc., assuming that trees of these species are readily available near the site. Selecting a site with a sufficient perennial flow as described above will also help to maximize the structure life as a permanent waterlogged installation will decay more slowly than an installation which is subject to an alternating cycle of wet and dry periods. Where logs have been keyed into the channel banks, they may leave voids as they decay, which could result in subsidence on the bank. Where riprap is used to help anchor the logs, a small quantity may be added to fill into these voids as they form.

Another factor to consider in the design of log riffles is whether there is a potential for the structure to be undermined, especially where the measure is applied in sand bed streams. Typically, undermining can be adequately addressed by spacing riffle structures as described above for rock riffles. However, where a channel is characterized by non-cohesive materials, it may be prudent to place additional logs beneath the riffle logs to act as a key.

Boulder riffles should be constructed below the channel forming discharge flow elevation and be keyed into the bank a minimum of 3 feet. Each spur of the riffle should extend from the bank to the center of the channel or slightly beyond, at a slope between 5% and 10%. The spurs should extend from each bank in an alternating pattern in order to create a meandering alignment for low flows. Refer to Section 11.08.1.5 for criteria on selecting rock size, design of footer rocks, estimation of the scour depth, etc.

Constructed riffles should be indicated in the Stream Relocation Plan sheets by using the appropriate symbol for the type of riffle being specified. In general, two control points will be used to define the location of the riffle, one at the upstream end of the riffle and the other at the downstream end. These control points should be located at the points where the proposed stream alignment crosses the ends of the riffles. The Stream Mitigation Data Table should provide stations for these control points as well as the intended channel bottom elevation. The information entered into the Design Data column of the Stream Mitigation Data Table will vary according to the type of riffle:

- for rock riffles, enter the required D50 of the gravel used to form the riffle
- for log riffles, enter the minimum required log diameter and the required D50 of the gravel
- for boulder riffles, enter the minimum required stone diameter

An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Constructed riffles shall be paid for under the following item numbers:

- Item Number 209-03.40, Stream Mitigation - Log Riffle, per LF
- Item Number 209-03.41, Stream Mitigation - Boulder Riffle, per LF
- Item Number 709-05.80, Log Riffles, per Each
- Item Number 709-05.81, Rock Riffles, Lump Sum

11.08.1.7.5 EXAMPLE APPLICATION

Given: A 250-foot reach of a degraded urban stream is to be relocated as a part of a roadway widening project. As a part of the Natural Stream Design for the project, it is determined that constructed boulder riffles should be employed to restore a more natural pool and riffle structure to the stream profile. However, because the stream is degraded, the original stream profile is not known and it is necessary to base the design on examination of a nearby reference reach. Because the reference reach has a similar slope and is has channel substrate materials similar to those in the project reach, it is assumed that the pool to riffle ratio, R_{pr} of the two streams will be similar so that the lengths of the riffles and pools of the two streams will be proportional to the channel widths.

Based on survey data and field inspection, the following information has been determined for the reference reach:

- Average channel bottom width, w* = 16 feet
- Average riffle length, Lr* = 44 feet
- Average riffle spacing, Xr* = 100 feet
- Slope for both channels = 0.65%

It has also been determined that the average channel width for the project reach, w, is 11 feet.

Find: Determine the average spacing and length for the proposed boulder riffles and determine the required quantity.

Solution: Since the riffle spacing and length is roughly proportional to the channel width, the proposed stream will have the following characteristics:

$$X_r = X_r*\left(\frac{w*}{w}\right) = 100\left(\frac{11}{16}\right) = 69 \text{ feet}$$

$$L_r = L_r*\left(\frac{w*}{w}\right) = 44\left(\frac{11}{16}\right) = 30 \text{ feet}$$

The pool length, L_p, may then be computed as:

$$L_p = X_r - L_r = 69 - 30 = 39 \text{ feet}$$

Next, the riffle height, hr, is computed as:

$$h_r = L_p S_o = 39 \times 0.0065 = 0.25 \text{ feet}$$

Based on this result, it determined that the gravel material used to construct the boulder riffles should have a d_{50} of 3 inches.

The pay item for boulder riffles is:

Item Number 209-03.41, Stream Mitigation-Boulder Riffle, per LF

Based on a spacing of 69 feet, 3 riffles would be required in the project reach. Since the proposed riffle length has been determined to be 30 feet, the final quantity for this item would be 90 LF.

11.08.1.8 LARGE WOODY DEBRIS

Root Wad Revetment
Location: Clear Creek, Redding, CA

11.08.1.8.1 DEFINITION AND PURPOSE

Large woody debris is a general term referring to trees, branches, stumps or logs that occur naturally or have been artificially placed in a stream channel. It is generally defined as any portion of a tree that has a diameter of at least 4 inches or a length of at least 6 feet. A number of different types of best management practice can be constructed using large woody debris, including:

- root wads which consist of the lower portion of a tree trunk along with the root fan
- rack structures which consist of layers of logs (usually with root fans) that are placed in stacks, with each layer at right angles to form an interlocking structure
- felled trees which consist of entire trees placed into the channel
- log structures which are placed in the channel along the bank for various purposes

Large woody debris may also be used to construct artificial log jams; however, this practice should not be employed for a TDOT stream relocation project.

Structures created using large woody debris may be utilized to as temporary revetments to protect channel banks from erosion and to add complexity to the horizontal profile of the stream. Properly designed large woody debris structures can be used to form scour pools, encourage the formation of a pool and riffle structure or cause the deposition of sediments. This increased complexity provides important resting and refuge areas for fish and other aquatic organisms in the stream. In addition, it has been demonstrated that the presence of wood in the channel can enhance the available habitat for aquatic organisms by encouraging a number of mechanisms which can increase the food supply.

11.08.1.8.2 APPROPRIATE APPLICATIONS

Large woody debris may be applied to TDOT stream relocation projects at locations where a significant quantity of large woody debris is present in the existing channel. In situations where large woody debris is absent from the existing channel, its addition into the relocated channel would be inconsistent with TDOT's policy on stream enhancement projects. Further, the ecological benefits of large woody debris are limited where they are not supported by the characteristics of the larger stream system. Structures created from large woody debris may be applied in a number of different ways to duplicate the habitat values provided by natural woody debris in the existing stream. Typically, this will involve applying large woody debris to prevent erosion and create habitat diversity.

Root wads may be embedded into the outside bank of a stream meander bend to protect the bank from erosion. The structures are placed at an angle so that the root wads project into the flow area and face upstream. Rootwads placed in series will act to deflect high velocity flows away from the bank towards the center of the channel, thus reducing erosive forces against the bank and creating scour pools downstream of each root fan.

Rack structures may be placed in eroded areas on the outside of a bend where there is a sufficient shelf of soil to act as a foundation to support the structure and provide a base for installing anchors. These structures act to reduce flow velocities against the banks, resulting in the reduced potential for erosion. In addition, where the structures are properly designed and constructed, they can reduce flow velocities sufficiently to cause sediment deposition in the voids between the members of the structure, thus helping to rebuild an eroded bank.

Felled trees are a relatively simple form of large woody debris structure. Trees can be placed on the side slope of a channel with the root wad anchored at the top of bank and with the trunk aligned downstream at an angle of 10° to 15° from the channel bank so that the branches are placed into the active flow area. This helps to prevent erosion on the bank by directing flows towards the middle of the channel while also creating scour holes and cover which benefit the habitat for fish and other aquatic organisms.

Finally, logs may be placed along the banks of a channel to provide an erosion resistant temporary lining. In this manner, they may be used as an erosion prevention measure while more permanent vegetative measures such as willow posts grow to maturity.

Large woody debris may also be combined with more traditional revetments such as machined riprap to increase the effectiveness of erosion prevention and to create complexity in the stream profile.

The economic viability of large woody debris structures depends on the availability of locally available trees of the appropriate species. Where these are not available, it may be necessary to consider other mitigation practices.

11.08.1.8.3 LIMITATIONS

Because woody materials in the stream environment are subject to decay, structures created using large woody debris should be considered as temporary. Even where a structure is securely anchored, within 3 years decay can weaken the structural integrity of the wood to the point that breakage will begin to occur, and this can result in the failure of the structure. This is particularly true for rack structures because the interlocking of the logs is an important component of the overall integrity of the structure. Structural failure can result in the release of the woody debris into high flows as they occur. The designer should consider the potential effects of this material on downstream structures such as bridges or culverts as well as the potential for this material to form logjams.

Large woody debris should be applied only on streams where the existing channel has a significant riparian tree cover and woody debris is present in the channel and floodplain. As wood in an artificially constructed debris measure decays, the values it provides to the stream will be lost unless they can be replaced by naturally occurring inputs of branches and trees. Because of this, large woody debris may be of limited value in urban areas where the channel and overbanks have been cleared of vegetation. Further, the successful implementation of an appropriate re-vegetation plan is a key factor in the success of this measure. Further, this measure may not be economically viable where the trees necessary to construct the woody structures are not readily available.

Research has shown that inputs of woody debris have a significant effect on the horizontal planform and vertical profile of a stream channel. Although large woody debris may be used intentionally to manage the form of a channel, a poorly designed installation can have unintended effects such as increased bank erosion or the creation of new meanders in the stream.

As a general rule, large woody debris structures that depend on anchors for stability should not be applied in stream beds that consist primarily of sand or other non-cohesive materials. Scour underneath these structures can cause them to shift with the result that the anchors would no longer function as intended, leading ultimately to the failure of the structure.

Large woody debris structures should also not be applied in streams subject to aggradation or degradation.

The presence of large amounts of woody debris in a channel is generally considered to be an obstruction to the hydraulic efficiency of the stream. When specifying measures composed of large woody debris, the designer should evaluate the effect of the measures on the hydraulic roughness of the channel, and whether an increased roughness would significantly increase flood elevations. Because of this consideration, engineered logjams should not be applied to TDOT stream relocation projects.

11.08.1.8.4 PLANNING AND DESIGN CRITERIA

Ideally, the design of a large woody debris structure should include an analysis of the forces acting on the debris. The forces tending to destabilize a structure include the buoyancy of the wood and the drag imposed by flows through and over the structure. These forces are resisted by the weight of the wood in the structure, the weight of ballast such as boulders, and the strength offered by various anchoring systems which may be used. Typically, the information needed to calculate these forces will be unavailable and a detailed design would be impractical. However, as a general rule, a structure composed of large woody debris will typically remain stable where the flow velocity in the design flood event is 10 ft/sec or less.

A variety of systems are available for anchoring a large woody debris structure. Typically, the type of system and the materials used (steel cable, rope, etc.) will be selected by the contractor based on the specifications provided by the designer for tensile strength and design life. The primary means of stabilizing debris structures is by embedding the trunks into the stream bank. However, during periods of high flow, debris structures are subjected to alternating forces which tend to cause the members to oscillate. Mechanical anchors are needed to resist this movement to help ensure the integrity of the structure.

The tensile strength and design life of an anchor should be selected based on the temporary nature of a large woody debris structure. In general, an anchor system should maintain its full strength for a minimum of 5 years. Where the individual members of a structure are keyed into the stream bank, the required tensile strength of an anchor may be determined by computing the drag forces on the structure and applying an appropriate factor of safety. The drag force, F_d, may be estimated using Equation 11HC-16:

$$F_d = \frac{\gamma_w V^2 A C_d}{2g} \tag{11HC-16}$$

Where:
F_d = drag force on the debris structure, (lbs)
γ_w = specific weight of water, (62.4 lbs/ft^3)
V = flow velocity at the debris structure, (ft/sec)
A = cross sectional area of debris structure, perpendicular to flow, (ft^2)
C_d = drag coefficient, (dimensionless)
g = acceleration due to gravity, (32.2 ft/sec^2)

The value of the drag coefficient, C_d, generally varies with depth, but for design may be assumed to be 0.9. Because large woody debris structures are typically placed on the outside of a bend, the flow velocity at the structure may be greater than the average flow velocity in the channel. It is recommended that the average flow velocity be multiplied by 1.5 to estimate the flow velocity at the structure. Due to the temporary nature of a large woody debris structure, the drag force may be computed for the 10-year event, rather than for the 50-year design event.

It is recommended that a factor of safety of 4 be applied to the result obtained when using Equation 11HC-16. This will account for buoyant forces which may not be completely addressed by embedding the woody materials into the bank. The strength of any given anchor will be affected by the strength of the soils into which it is embedded, and this can vary widely in the stream environment. Where possible, anchors should be secured into the floodplain soils, or attached to immobile objects on the floodplain such as living trees.

The principal design factors for a system of root wads are the placement and sizing of the structures as well as the means to secure the structures in place. These factors are important to ensure that the measure will function as intended to direct high-velocity stream flows from and eroding bank and provide aquatic habitat.

Root wads are typically placed in a series on the outer side of a stream bend where bank erosion is a problem. To effectively deflect flows, the trunks of the root wads should be placed at an angle to the bank so that the bottom of the root fan will face into the oncoming stream flow. The spacing between root wads is typically 3 to 4 times the length that they project from the bank so that the stream flow is deflected from one root wad directly into the next downstream root wad. In this way, the stream flows are directed towards the middle channel, away from the stream bank.

The length of a root wad is typically determined based on maximizing the potential habitat benefits. Placing the root fan within 3 feet of the bank allows for consistent water circulation on both sides of the fan, which creates habitat niches throughout the root structure as well as small scour pools.

Root wads are typically sized based on the minimum diameter of root fan required for a given location. In general, the root fan should be of a size sufficient to extend from the maximum anticipated scour depth to a level equal to the flow level at the channel forming discharge. Where materials of a sufficient diameter are not locally available, multiple smaller root wads may be stacked to achieve the needed height.

One of the primary means of securing a root wad installation is to key the structure into the bank of the stream. The trunk of the root wad should be placed in an excavated trench which is then backfilled to grade. On streams with channel widths up to 15 feet, the length of the key should be approximately 10 feet, while for larger streams the key length should be approximately 20 feet. Where they are locally available, large boulders may be placed around and on top of the trunk to help hold the root wad in place. Finally, mechanical anchors may be required to completely secure the structure.

Root wad installations should include a footer log to help prevent the subsidence of the structure. The root wad should be placed directly on the footer log at a 90° angle. The footer log should be at least 3/4 the diameter of the root wad trunk and should be placed in an excavated trench to minimize the potential for this log to affect the hydraulic capacity of the channel.

Since a root wad is a temporary measure, its long-term success will depend on proper re-vegetation of the stream bank. At a minimum, this should consist of installing willow poles or posts on the bank area in the areas immediately upstream from the root wad and downstream in the area between the root wad trunk and the footer log.

As shown in Figure 11-13, rack structures consist of layers of logs with root fans, placed at right angles on the stream bank. The key members are embedded into the stream bank and interlock with the rack members to form a rigid structure. The design factors for a rack structure include the length and alignment of the key members, the height of the structure, the spacing of structures placed in series and the means of anchoring the structures in place.

The length of the key members should be determined by judgment based on consideration of one or more of the following factors: the size of any “snags” that may be present in the existing channel, the proposed channel width and minimizing the impact of the structures on the hydraulic efficiency of the channel. The key members in the structure should be aligned at an angle of approximately 15 degrees upstream with respect to the direction of the flow passing through the structure. This will tend to redirect the direction of flow away from the bank and assist in reducing flow velocities along the bank.

Rack structures may also be placed in series in order to direct the highest flow velocities toward the center of the channel through the length of a meander bend. When used for this purpose, they should be spaced at a distance equal to 1.5 to 2 times the length of the key members. The lowest members of the structure should extend to the anticipated scour depth while the uppermost members should match the flow level at the channel forming discharge.

Figure 11HC-13
Engineered Rack Structure Installation
Location: Topashaw Creek, Mississippi (2001)

Because of the interlocking nature of the structure, rack structures are particularly vulnerable to failure due to the displacement of members within the structure. Thus, it is important to ensure that the structure will be securely anchored. To achieve this, approximately 3/4 of the total length of the key members should be keyed into the channel bank and the members of the structure should be secured with mechanical anchors at the points where the key members overlap the rack members.

Although felled trees are a relatively simple form of large woody debris, they can present a unique challenge to the contractor since it will be necessary to maneuver an entire tree as a single piece. For the tree to lie properly on the bank, it will typically be necessary to remove a few branches from the side of the tree which will face down. The contractor should be directed to minimize branch removal and to remove branches from one side of the tree only.

The Stream Relocation Plans should clearly communicate to the contractor the intended location and type of large woody debris structure. Woody debris configurations should be shown on the Stream Relocation Plans by using the appropriate symbol for the type of measure being specified. Stations the control points used to define the locations of each measure should be provided on the Stream Mitigation Data Table. The locations for root wads and felled trees should be defined by single control points located where the tree trunk intersects the channel bank. Rack structure locations can be defined by a single control point located at the center of the structure. Two control points will be required for log revetments, one at the beginning of the measure and the other at the end. The Stream Mitigation Data Table should provide stations and offsets for these control points as well as the channel forming discharge flow elevation and intended channel bottom elevation. For all large woody debris measures, the information entered into the Design Data column of the table should includes the minimum log diameter. For rack structures, felled trees, and log revetments, the table should also provide the minimum tensile strength for the required anchors. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Large woody debris structures shall be paid for under the following item numbers:

- Item Number 209-03.62, Stream Mitigation – Root Wad (Size), per Each
- Item Number 209-03.63, Stream Mitigation – Rack Structure (Size), per Each
- Item Number 209-03.64, Stream Mitigation – Felled Tree (Size), per Each
- Item Number 209-03.65, Stream Mitigation – Log Revetments (Description), per LF

11.08.1.8.5 EXAMPLE APPLICATION

Given: It has been determined that temporary erosion protection will be required for a distance of 150 feet along the outside of a bend in a proposed relocated stream channel. Because clearing operations for the associated roadway widening project will require the removal of a number of trees, it is decided to utilize the root fans of these trees to provide the required protection to allow the permanent woody vegetation to have an opportunity to establish.

Find: Determine the average spacing and required quantity of root wads used for this project.

Solution: Because the proposed stream channel is of a moderate size, it decided to minimize the length of the root wads to avoid unduly affecting the hydraulic efficiency of the stream. Thus, the length of the root wads will be limited to 3 feet. Based on this, it is determined that the root wads should be placed at a spacing of 9 feet. Based on coordination with the Environmental Division, live woody vegetation will also be planted along the outside of the bend. In this way, future tree falls will replace the ecological benefits provided by the root wads after they have decayed.

The pay item for root wads is:

<u>Item Number 209-03.62, Stream Mitigation-Root Wad (Size), per Each</u>

Based on a spacing of 9 feet, the final quantity for this item would be 17 root wads.

11.08.2 STABILIZATION MITIGATION PRACTICES

This section describes best management practices for bank stabilization and protection that may be used on TDOT stream relocation projects where natural stream design and construction methods are used. The measures presented in this section have been classed as stabilization practices, since they are typically deployed above, along, on, or at the toe of a stream bank where mitigation practices are needed. Stabilization measures are generally not considered suitable for use within the stream channel where flowing waters will compromise their installation and effectiveness.

11.08.2.1 COCONUT FIBER (COIR) ROLLS

Coconut Fiber (Coir) Rolls
Reference: Montgomery Co., MD DEP (2005)

11.08.2.1.1 DEFINITION AND PURPOSE

Coconut fiber rolls (also referred to as coir rolls) are a longitudinal mitigation practice consisting of natural interwoven coconut husk fibers that are bound together in a cylindrical manner with twine or netting typically woven from coconut or other biodegradable material.

Fiber rolls are primarily used to provide temporary bank stabilization for small stream relocation projects where low shear stresses are expected by acting as a medium for vegetation propagation. Staked coconut rolls are used at locations where rapid stabilization at the toe of a stream bank is required. The rolls provide temporary physical protection to a site while vegetation becomes established and natural biological protection takes over. The coconut rolls can also provide a substrate for plant growth once the materials in the roll begin to decay. Rooted coconut rolls (those with vegetative plantings) lock into the natural stream bank providing adequate stabilization and habitat along the stream bank as a complete unit. The staked rolls can also be used as a transition from one re-vegetation technique to another.

11.08.2.1.2 APPROPRIATE APPLICATIONS

Coconut fiber rolls (coir rolls) should be used as a temporary bank stabilization practice for streams with gravel or sand beds, stable bends, and base flow for a significant portion of a normal growing season. They are generally installed at the toe of a stream bank and should be considered for use with other natural mitigation practices such as coir matting or vegetative plantings that can be used to stabilize upper bank areas. Coconut fiber rolls will typically biodegrade within 2 to 3 years; therefore, their removal is not required. This makes them a good, low-maintenance choice for use on stream relocation projects where post-construction disturbance is not desired.

11.08.2.1.3 LIMITATIONS

The designer should avoid using coconut fiber rolls in areas where channel shear stresses are moderate to high. This measure is not appropriate for use along the banks of channels or streams with high flow velocities, bedrock channels, or in streams where there is potential for, or that are actively experiencing scour. Coconut fiber rolls should also not be used in streams with unstable beds that are actively incising (down-cutting) or in stream reaches where large debris loads are expected. Finally, their use in locations where full shade is expected is not recommended since sufficient sunlight is needed for colonizing plant growth.

11.08.2.1.4 PLANNING AND DESIGN CRITERIA

Formal design is not required; however, the following guidelines should be considered when specifying coconut fiber rolls for use on a natural stream design project.

The use of coconut fiber rolls for temporary stream bank stabilization will depend on the stream size, slope of the subject bank, and the computed stream velocity. The rolls should be installed from the toe of the bank to a height equal to the depth at the channel forming discharge. Coconut fiber rolls also should not be installed where flow velocities at the channel forming discharge will exceed 10 feet per second.

For most coconut fiber roll applications, the stream bank slopes should be no steeper than 3H:1V. This measure may be installed on steeper slopes provided that adequate stabilization practices such as erosion control blankets or turf reinforcement mats are employed on the slopes above the rolls.

Coconut rolls are typically manufactured commercially in 8, 12, 16, 18, and 20-inch diameters rolls (logs), and are normally shipped in 20 foot lengths. Thus, they are easily installed by hand when the rolls are dry at the time of installation.

The following additional criteria should be considered by the designer when using this measure:

- The rolls should normally be installed on the surface or within a shallow excavated trench at the toe of the bank slightly below channel grade
- The maximum depth of the excavated trench should be 25 percent of the roll diameter
- Fiber rolls are flexible and should be molded to the curvature of the stream bank
- The lowest roll in an installation should be placed so that between 30 and 50 percent its height is below the normal base flow level of the stream
- The upstream and downstream ends of the roll should be keyed into a stable bank to reduce the potential for failure of the measure due to wash out behind the ends of the roll
- Because coconut fiber rolls are buoyant, they should be securely anchored at the time of installation. This can be accomplished by means of hardwood stakes placed on 3 to 4 foot centers along both sides of the roll, along with heavy biodegradable twine which should be used to lash down each roll
- The tops of the stakes should generally not extend above the top of the roll

Since fiber rolls will begin to biodegrade after a few years, the best results will be achieved when native plant species are seeded in the roll. Coconut fiber rolls tend to trap sediments that encourage plant growth within the roll and once the vegetation is fully mature, it should provide a root system that will offer protection against erosion once the rolls have degraded. The species of appropriate plants to be used should be specified on the Plant List provided by the Environmental Division.

Coconut Fiber (Coir) roll locations should be indicated in the Stream Relocation Plan sheets by using the appropriate symbol. In general, two control points will be used to define the location of the roll, one at the upstream end and the other at the downstream end (excluding the portion of roll that may be set into the bank to prevent undermining). The Stream Mitigation Data Table should provide stations and offsets for these control points, and the Design Data column should indicate the minimum required roll diameter. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

The following pay item should be used when specifying coconut fiber rolls:

- Item Number 209-03.31, Stream Mitigation - Coconut Fiber Roll, per LF

11.08.2.1.5 EXAMPLE APPLICATION

Given: A stream relocation project will involve 200 feet of a small stream that currently has no riparian vegetative cover. Because the stream reaches upstream and downstream of the project have well-vegetated banks, it is decided that the banks of the relocated channel should be provided with woody vegetation in order to provide a continuous riparian corridor.

The existing stream channel is fairly small, with a bottom width of 5 feet and 1.5H:1V side slopes. Hydraulic analysis of the stream for the channel forming discharge yields a flow depth of 2.5 feet and a velocity of 3.7 ft/sec. Based on these factors and a consideration of the channel substrate materials, it determined that coconut fiber rolls will provide an effective cover for the new vegetation as it establishes.

Find: Estimate the quantity of coconut fiber roll required for this project.

Solution: The pay item for coconut fiber rolls is:

<u>Item Number 209-03.31, Stream Mitigation-Coconut Fiber Rolls, per LF</u>

The length along the slope required to install the coconut fiber rolls from the toe of the slope to the height of the flow at the channel forming discharge will be equal to 1.5 times 2.5 feet, which is 3.75 feet or 45 inches. This length can be covered by providing three runs of 16-inch diameter rolls stacked along the slope. To provide an adequate key at the ends of the rolls, the required length will be extended by 5 feet at each end which makes the total length of each run of fiber rolls 210 feet. Since there will be three runs of roll on each side of the channel, the final quantity will be 1260 LF.

11.08.2.2 VEGETATED RIPRAP

Vegetated Riprap along Stream Bank
Reference: NRCS, Engineering Field Handbook 6

11.08.2.2.1 DEFINITION AND PURPOSE

Vegetated riprap, also referred to a live rock revetment or joint planting, consists of machined riprap combined with dormant live woody vegetation cuttings that are placed into the openings between the rocks. The live plantings can be placed either in conjunction with the installation of a new riprap lining or into an existing riprap lining.

Vegetated Riprap can be a cost effective means of preventing erosion in locations subjected to high flow velocities or wave action. It can also be effective on steep banks that cannot be graded, or which experience high volumes of seepage. The use of rock riprap as a means of stabilizing stream banks is often undesirable due to its potential negative impacts on the ecology of the stream. However, these impacts can be mitigated by the addition of live cuttings to diversify the riparian habitat. The vegetation can reduce local flow velocities and trap sediment, thus encouraging the growth of other types of vegetation. In addition, the plantings act to shade the stream, which provides temperature control, wildlife habitat, and increased contribution of organic matter to the stream ecosystem.

11.08.2.2.2 APPROPRIATE APPLICATIONS

Vegetated riprap may be placed on stream banks at any location where erosion prevention is required or where lateral migration of the stream would cause damage to the roadway or other facility. If the riprap is to be placed on a side slope steeper than 3H:1V, the designer should consult Chapter 4 of the FHWA publication *HEC-15* to insure that the riprap will be stable. Although the addition of vegetation may contribute to the overall slope stability of the riprap slope, this should not be considered in determining the maximum acceptable slope for a given site.

Vegetation can also be added to an existing riprap slope to improve the habitat of the stream at a minimum of cost.

11.08.2.2.3 LIMITATIONS

The use of any riprap, including vegetated riprap, should be minimized for stream relocation projects. Thus, its use should be limited to only those locations where hard armor is required, typically along the outside of a stream meander bend. The following additional factors should be considered prior to specifying vegetated riprap for a stream relocation project:

- Planting must be implemented during the dormancy period of the chosen plant species which is typically late fall to early spring.
- It is sometimes difficult to place the live stakes between the individual stones of the riprap lining and through the underlying filter fabric.
- For best results, the stakes must be in contact with the soil below the riprap and should preferably extend below the ground water level.
- Supplemental irrigation may needed during the first few years to ensure survival if the plantings cannot be placed deeply enough to extend below the ground water level.
- Special tools may be required for planting in riprap that is greater than 3 feet in depth.

11.08.2.2.4 PLANNING AND DESIGN CRITERIA

Riprap is warranted for locations where the shear stresses imposed by the flow at the design discharge exceed the permissible shear stress for a vegetated lining. This will usually occur at the outside of bends in the channel alignment, and the designer should determine the hydraulic conditions (velocity, shear, and height of the flow) at the site based on the criteria provided in Section 11.04.5. The class of machined riprap to be utilized on the site should be selected based on the criteria provided in Section 11.04.6.2. At sites where the average flow velocity exceeds 12 ft/sec, additional measures may be needed to provide sufficient erosion protection. However, it may be preferable to adjust the realignment of the stream to reduce the high flow velocities.

Undermining of the riprap toe protection has been identified as one of the primary mechanisms of riprap revetment failure. Thus, the riprap should be keyed into the streambed as described in Section 11.04.6.2.

Riprap thickness for most stream bank protection projects should be based on the TDOT Standard Specifications. Riprap selection and design should be in accordance with this Drainage Manual and FHWA's HEC-15.

The specific plant species to be used for the live stakes should be coordinated with the Environmental Division.

It is important that any site where vegetated riprap is to be placed be provided with adequate access for large construction equipment. Because the site disturbance caused by this equipment can be extensive, the designer should carefully consider possible routes that would be available for construction access.

Locations for the placement of vegetated riprap should be indicated as a hatched area on the Stream Relocation Plan sheets using the appropriate plan symbol. In general, two control points will be used to define the extent of a vegetated riprap installation, one at the upstream end and the other at the downstream end. The Stream Mitigation Data Table should provide stations and offsets for these control points, and the Design Data column should indicate the required class of riprap. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Vegetated riprap shall be paid for under the following pay item number:

- Item Number 209-03.43, Stream Mitigation – Vegetated Rip-Rap (Description), per CY

11.08.2.2.5 EXAMPLE APPLICATION

Given: Vegetated riprap is being proposed as an alternate to the coconut fiber rolls specified in the Example Application in the previous section. As noted in that example, the existing stream channel is fairly small, with a bottom width of 5 feet and 1.5H:1V side slopes. Hydraulic analysis of the stream for the channel forming discharge yields a flow depth of 2.5 feet and a velocity of 3.7 ft/sec. The hydraulic analysis for the 50-year event yields a flow velocity of 5.66 ft/sec.

Find: Estimate the quantity of vegetated riprap required for this project.

Solution: The pay item for vegetated riprap is:

Item Number 209-03.43, Stream Mitigation-Vegetated Riprap (Description), per CY

Based on the hydraulic analysis for the 50-year event, it determined that Machined Riprap Class B would be required for this project. Based on the TDOT Standard Specifications, the minimum depth of the riprap layer should be 2.5 feet.

The length along the slope over which riprap is to be installed will be equal to 1.5 times 2.5 feet, which is 3.75 feet. The quantity of vegetated riprap for each side of the channel can be determined by computing the required volume of riprap as follows:

$$V = (3.75)(2.5)(200) = 1875 \ \text{ft}^3$$

Thus, the total volume for both sides of the channel will be 3750 ft^3 which can be divided by 27 to determine the final quantity of 138.9 CY.

11.08.2.3 WILLOW CUTTINGS (POSTS AND POLES)

Live Willow Cuttings
Reference: Iowa Dept. of Natural Resources 2006

11.08.2.3.1 DEFINITION AND PURPOSE

Willow cuttings, which can be either willow posts or willow poles, consist of live dormant woody vegetation driven into the stream bank for stabilization and improvement to the riparian habitat. As the name implies, the woody vegetation is usually taken from willow trees, but the use of other species may be coordinated with the Environmental Division. The only distinction between poles and posts is the size of the material placed. Willow poles can range in size from 3 to 10 feet long and ¾ to 3 inches in diameter, while willow posts can range in size from 5 to 20 feet long and 3 to 8 inches in diameter. This measure can also be referred to as live posts. It is distinctive from brush layering or vegetated MSE wall in that the willow cuttings are driven into the stream bank, while the other two measures are placed as a part of a backfill operation.

Dormant willow posts were first utilized by the Civilian Conservation Corps in the 1930's to stabilize stream banks by reducing the stream velocity and creating a living root mat that stabilizes the soil. Willow cuttings store root hormones and food reserves that promote sprouting of stems and roots during the growing season. This sprouting of roots helps to stabilize the bank and quickly re-establishes riparian vegetation, thereby enhancing conditions for colonization of native species.

11.08.2.3.2 APPROPRIATE APPLICATIONS

Willow cuttings may be applied in heavily eroded areas on a stream bank to provide erosion protection and to reinforce the soils in the slope. Willow cuttings provide roughness which acts to slow the flow of water against the bank, and this either reduces the rate of erosion or helps to rebuild the bank by encouraging the deposition of sediment.

Willow cuttings require little maintenance and establish themselves easily over time to stabilize a site; however, they are not an ideal measure in all circumstances. They are best suited for smaller streams which provide a minimum of 4 feet of soil to accommodate the planting of the cuttings, and on slopes no steeper than 1H:1V. Although it may be possible to utilize willow cuttings in a variety of settings, they are best applied in settings where erosion has widened the channel as compared to the upstream and downstream reaches. This will help to minimize the potential impact that the mature vegetation could have on the conveyance capacity of the channel.

11.08.2.3.3 LIMITATIONS

Willow cuttings require an abundant source of moisture and at least partial sunlight to establish and grow. The use of this measure should be avoided where bedrock or rocky soil is present or on high banks where the moisture may be limited. In general, this measure should be specified only where there is sufficient soil for the cuttings to be planted to a depth of at least 4 feet, which is the minimum necessary for the willow cuttings to establish. Willow cuttings should also penetrate at least 2 feet below the water level in the stream to ensure that the cuttings will not be undercut below the root zone.

Due to the roughness introduced by the mature vegetation, willow cuttings may affect the hydraulic efficiency of the channel. Thus, this measure should not be applied at sites where the vegetation could potentially choke the channel or cause additional erosion problems. Typically, this would include sites where the channel reaches upstream and downstream of the project location are stable and offer sufficient hydraulic capacity but the channel through the project reach has been widened due to some form of bank erosion. In addition, this measure should not be applied on both banks of a small stream.

Willow cuttings should not be used where cattle or other livestock graze or where beavers are active. The first growing season after installation of the cuttings is critical to the success of the measure, since the willows produce food for future re-growth from leaf photosynthesis. If the sprouting leaves are grazed by cattle or if the tops of the plants are cut off by beaver during this time, the plants are likely to die. Therefore, it is important to keep cattle off the area during the first year of growth, and to avoid areas where it is apparent that there has been recent beaver activity. After the first growing season, the plants should be sufficiently established to be self-repairing if they are damaged.

Willow cuttings require good soil contact with soil to permanently establish. Thus, they should not be utilized on gravel bed streams where there could be insufficient contact due to voids within the gravel.

Additional limitations that the designer should consider include:

- Willow cuttings should be cut and installed during the dormant season which generally runs from October to March.
- Cuttings will not establish well in shaded areas or on north facing slopes.
- To minimize the need for supplemental watering, the cuttings be planted to a depth below the ground water level. Thus, this measure may not be suitable for intermittent streams where it may be difficult to determine the depth of the water table during the dry season. Willow cuttings should not be utilized on ephemeral streams.

- Willows are fast growing plant material that can become unruly. In urban areas, it may be necessary to provide regular cutting back to maintain aesthetic preferences.
- Willow installations adjacent to a roadway may collect litter, resulting in a maintenance issue.

11.08.2.3.4 PLANNING AND DESIGN CRITERIA

The choice between using either poles or posts at a site should be made based on the depth to the dry season water table into which the plant materials need to extend. Since posts are longer than poles, they may be utilized higher on the side slope of the channel, while the use of the smaller poles on the lower portions of the slope may help minimize the effect of the measure on the hydraulic efficiency of the channel. For a perennial stream, the level of the dry season water table may be assumed to be nearly equal to the bottom of the channel.

Willow poles and posts are best used in locations where the channel banks upstream and downstream of the project site are stable and free of erosion. Channel stability is important because an eroding channel could cut behind the upstream end of the reach where willow cuttings have been installed causing the entire bank to erode. Thus, this measure should be applied with caution on actively meandering alluvial streams. Where willow cuttings are to be utilized on the outside of a bend, they should be placed over the longitudinal extent described in Section 11.04.6.2.

Figure 11SB-1
Live Stakes Placed at Outside of Channel Bend
Location: SR-15, Furnace Branch, Wayne Co., TN (2011)

Since most species of willow will not thrive the below normal base flow elevation, this portion of the bank may be subject to undercutting. Thus, it is important that the toe of the bank be reinforced to ensure that it will not scour and fail before the willow cuttings have had an opportunity to become established. Typically this can be accomplished by the use of longitudinal stone toe protection to prevent the slippage of the bank.

Since willow cuttings do not provide immediate stabilization, they should be used in combination with additional mitigation measures to prevent erosion on sites where erosion must be immediately addressed. For example, live fascines or brush mattresses could be used on an eroding slope for temporary erosion prevention while the willow cuttings take root and grow.

A number of willow species are available for use. The choice of species should be coordinated with the Environmental Division.

Willow cuttings are typically installed in square or triangular patterns beginning just above the normal waterline and continuing up the stream bank to at least the depth of the channel forming discharge. The quantity should be estimated based on assuming a spacing of 3 to 5 feet between poles.

Locations for the installation of willow cuttings should be indicated as a hatched area on the Stream Relocation Plan sheets. In general, two control points will be used to define the extents of a willow cutting installation, one at the upstream end and the other at the downstream end. The Stream Mitigation Data Table should provide stations and offsets for these control points, and the Design Data column should indicate the species of plant to be utilized. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Willow poles and posts shall be paid for under the following pay item number:

- Item Number 209-03.44, Stream Mitigation – Willow Poles (Species), per Each

11.08.2.3.5 EXAMPLE APPLICATION

The quantity for Willow Poles or Posts will usually be determined in coordination with the Environmental Division. Typically, the Environmental Division will provide a Planting Table sheet (or the data needed to complete the sheet) for the plans which will specify the density of planting (in terms of stems per acre) for specific species of woody plant materials and the areas in acres over which they are to be planted.

11.08.2.4 LIVE FASCINES

Live Fascines Installation
Reference: NRCS, NEH654 Tech. Supplement 14-I

11.08.2.4.1 DEFINITION AND PURPOSE

Live fascines, also referred to as willow wattles or brush bundles, are long bundles of live dormant branch cuttings bound together into a cylindrical structure and then staked into a shallow trench along a stream bank. Typically, the depth of the trench will be approximately half of the diameter of the bundle so that the top of the fascine will protrude above the ground surface. When securely anchored with stakes, live fascines offer immediate protection from surface erosion in much the same manner as a filter sock or sediment tube installed on a slope (see Chapter 10). The difference between these two types of measures is that live fascines will establish roots and grow. Thus, even though both types of measures can break a slope into a series of discrete smaller steps, live fascines go a step further by providing an effective soil stabilization technique once the roots are established.

Live fascines are inexpensive to construct and install, and can be used in a number of ways to prevent stream bank erosion. The most common use of live fascines is as an erosion prevention measure placed longitudinally along a slope or stream to intercept runoff that comes over the banks and could potentially cause gullies. They can be placed at an angle to the slope in order to divert upslope runoff away from sensitive areas. With some limitations, they may be used to secure the toe of the stream bank side slope. They are also useful manage groundwater seepage from wet slopes and to help prevent trampling caused by wildlife or livestock. Because live fascines are installed at a shallow depth, they create very little site disturbance compared to other types of measures. Thus, they are well suited for use on slopes or stream banks with limited access. Live fascines are frequently installed in conjunction with other erosion prevention measures, such as erosion control blanket.

11.08.2.4.2 APPROPRIATE APPLICATIONS

Successful use of live fascines requires careful assessment of site conditions, knowledge of installation procedures, and proper maintenance. Streams best suited for live fascines will have a hydrologic regime that allows the roots to reach the water table during most of the growing season and where enough soil is available to allow for root penetration. It is essential that the banks be composed of a material that can be easily trenched and that can hold moisture to support growing vegetation. The presence and predominance of fine soil particles and organic matter will meet this requirement, while banks composed of sand and gravel will not. The site also needs to receive full sunlight since fascines are typically composed of tree/shrub species that are intolerant of shade.

Live fascines may be used for slope stabilization at any location along the banks of small headwater streams, or can be placed above the height of bankfull flow in larger streams. They are intended for use with shallow sheet flows and moderate amounts of erosion and should not be placed where they would be exposed to concentrated or open channel flow.

In some situations, live fascines can also provide immediate erosion protection at the toe of the channel side slope. Installed in this location, they are not intended to grow as they would if they were installed higher on the bank, but act principally to protect the toe of the stream bank until other vegetation becomes established. In this context, they are called Insert Fascines. Streams best suited for insert fascines are low gradient perennial streams which are small to moderate in size, and have a relatively consistent normal water surface elevation associated with a well-sustained base flow.

In addition to providing stabilization of the bank and toe, fascines also provide excellent habitat for fish and wildlife as well as shading for the water. This shading helps to stabilize the water temperature and increase the aquatic life in the stream. On slopes, live fascines can provide small shelves that collect native seeds and hold water, so that native vegetation can become established and assist in the stabilization of the stream bank.

11.08.2.4.3 LIMITATIONS

Live fascines are not appropriate in locations where site conditions would discourage the growth of the cuttings. Because the cuttings require sufficient moisture and full sunlight to thrive, placement of live fascines should be avoided in areas characterized by rocky soils, dry or well drained slopes or heavy shade.

To function properly as erosion control devices, live fascines should be securely staked into the slope. Thus, they may not be suitable for sites which would present difficulties in staking. In rocky areas, special equipment or staking materials may be required to achieve anchor penetration. In areas characterized by non-cohesive materials, such as sand or silt, anchoring may be problematic due to a lack of friction. To counteract this, it may be necessary to use longer stakes and to install them at closer intervals.

The use of live fascines is not appropriate in areas subject to erosion by flowing water unless they are integrated with other measures to prevent erosion at the site. Where it is necessary to use fascines in bank areas below the bankfull elevation, erosion control blankets or turf reinforcement mats should be used to protect the soil around the fascine from erosion. It may also be necessary to include measures to protect the geotechnical stability of the stream banks. For example, it may be necessary to utilize riprap to protect the toe of the bank to prevent undercutting that would cause the failure of the bank behind the live fascines. Riprap or other materials may also be used to protect the upstream and downstream edges of the bank area where live fascines are to be placed. This will prevent flanking or an undercutting by erosion along the sides of the installation. Live fascines are not appropriate on bank slopes undergoing mass movement. This is a more complicated situation which usually can be addressed only by structural methods.

Additional limitations that the designer should consider include:

- Due to the use of dormant cuttings, it is essential that live fascines be installed only during the dormant season, after leaf drop in the fall and before bud break in the spring.
- Willow is the primary cutting material that is used for live fascines; and a large quantity of cuttings is typically required for the measure to be effective. Therefore, use of this measure should be limited to locations where willow is readily available in abundance.
- The use of live fascines should be limited in areas where human traffic is concentrated or where grazing of cattle is not restricted.
- Due to their shallow installation, if live fascines are not installed correctly may dry out over time and become damaged. Thus, watering may be required to ensure that the cuttings establish properly. However, even if the measures do dry out during a drought period and do not grow, they can still act mechanically to prevent erosion provided that they have been well installed.

11.08.2.4.4 PLANNING AND DESIGN CRITERIA

The arrangement of live fascines on a slope should be determined based on whether ground water seepage will occur. On a dry slope, fascines should be arranged parallel to the contour to prevent rills and gullies caused by overland runoff coming into the channel. Where the slope is excessively wet, the fascines should be installed at an angle ranging from 45 to 60 degrees to capture and direct the flow. These fascines can also be arranged in a “vee” pattern so that the low points will converge at a trench with live cuttings placed vertically along the slope. This vertical structure is known as a pole drain and can be used to direct ground water seepage to the toe of the slope The designer should ensure that a row of fascines are also placed at any ground water seepage line or spring to intercept and control ground water seepage.

As illustrated in Figure 11SB-2, live fascines should be installed on the slope in shallow trenches so that the roots of the vegetation will penetrate the ground above the water table, but still receive sufficient moisture. The fascines are then staked firmly in place with both dead and live stout stakes at not more than 3 feet on center. The dead stakes should be placed vertically through the middle of the fascine, while the live stake should be installed on the down-slope side of the fascine. This allows the stakes to work in tandem to firmly compress the bundle. Finally, the rows of fascine bundles should be partially covered with soil to improve contact with the ground and retard the loss of moisture. The soil should be worked down into the fascine bundle and compacted, normally by walking on the fascine. The top 10 to 25 percent of the fascine should be left exposed to view after backfilling with soil.

Although detailed design is not required for live fascines, flow velocity and shear should be checked for the design discharge to ensure that the fascines will not fail due to erosion. Generally, the primary modes of failure for live fascines are undercutting, flanking, and anchor failure. Undercutting can occur when the toe of the slope or the soil between the rows of fascines is eroded. The toe of the slope may be protected by riprap or by means of a vegetated mitigation measure. The slope between the rows of fascines should be protected by means of a vegetated lining material as described in Chapter 5. Where the vegetated lining employs an erosion control blanket or turf reinforcement mat, the installation of the erosion control blanket should be continued through the trench for each row of fascines to prevent the pull-out of the fabric.

Flanking occurs when the upstream ends of the live fascines are exposed by erosion on the bank upstream of the installation. In order to protect against this, a minimum of 3 linear feet of the fascines should be keyed into the bank at both ends. Where a stream bank is potentially susceptible to significant erosion, the upstream ends of the fascines should be protected a layer of machined riprap which is also keyed into the bank.

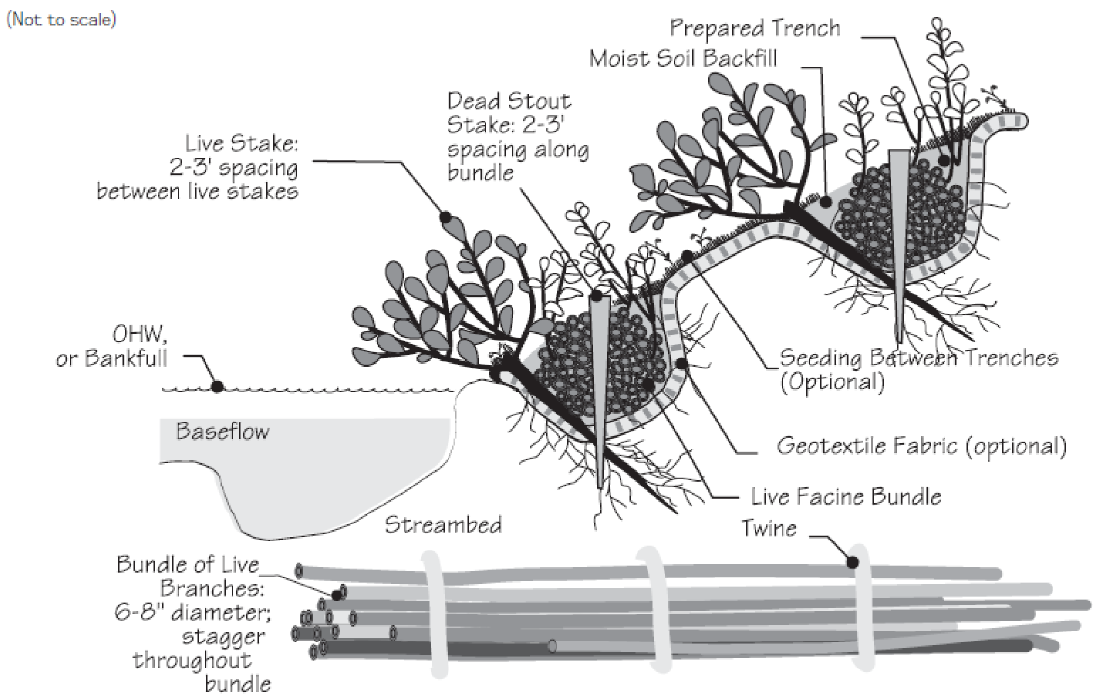


Figure 11SB-2
Typical Live Fascine Installation
Reference: USDA, Soil Bioengineering Guide (2002)

Anchor failure occurs when the flow velocity or shear stress exceed the capacity of the stakes to hold the cuttings in place. As shown in Table 11SB-1 installed live fascines can resist the forces imposed by flow velocities ranging up to 12 feet per second, depending on whether the upstream ends of the fascines have been protected by machined riprap and whether the fascines have been installed on the contour or at an angle to the bank. Table 11SB-1 should be used to evaluate proposed live fascines based on the hydraulic conditions imposed by the design discharge. However, appropriate caution should be used in the application of this table.

Fascine Configuration	Velocity	Shear
At an angle without machined riprap protection	< 8 ft/sec	1.2 to 2.1 lb/ft^2
At an angle with machined riprap protection	< 12 ft/sec	>3.1 lb/ft^2
On the contour without machined riprap protection	< 6 ft/sec	0.1 to 0.6 lb/ft^2
On the contour with machined riprap protection	< 8 ft/sec	>2.0 lb/ft^2

Table 11SB-1
Allowable Shear Stress and Velocity for Various Live Fascine Installations

The vertical spacing of the fascine bundles on the bank face should be determined based on the composition of the soils in the bank as well as the slope. Table 11SB-2 provides the recommended vertical spacing between rows of live fascines for various slopes and soil types.

In cohesive soils, a stake length of 30 to 36 inches should be adequate to anchor the live fascine bundles. However, in non-cohesive soils, longer stakes may be required to anchor the fascines to the stream bank. In either case, the length of the dead stakes is the same as the length of the live stakes. Further, in non-cohesive soils it may be necessary to use a spacing of less than 3 feet between the stakes due to the erosive nature of the soil.

Slope	Soil Type	
	Cohesive	Non-cohesive
1H:1V	3 *	NA
1H:1V – 2H:1V	3–4 *	NA
2H:1V – 3H:1V	4-5 *	3-4 *
3H:1V – 4H:1V	5-6	4-5 *
4:1 or flatter	6-8	5-7

* Use of an erosion control fabric between the live fascine and the bank is recommended.

Table 11SB-2
Live Fascine Spacing Requirements (Feet)
Reference: Sotir, R.B., and Fischenich, J.C. (2001), “EMRRP Technical Notes Collection (ERDC TN-EMRRP-SR-31) U.S. Army Engineer Research and Development Center, Vicksburg, MS.

The stems and roots put out by the cuttings combine with the stakes and binding materials used to create the fascines to provide an integrated system that holds the soil in place. When properly designed and installed, live fascines should require a minimal amount of maintenance. However, as willows grow and mature, they lose their vigor and become subject to insect and disease problems. As they become brittle with age, branches will tend to break off and fall into the stream potentially causing maintenance problems downstream. These problems can be avoided by periodic pruning of the willows to a convenient height or down to a stump. The willows will re-sprout and the function of the stabilization practice will remain intact.

The following additional design criteria should be considered before specifying live fascines for a project:

- Each fascine bundle should range in length from 6 to 20 feet and can be custom built to fit almost any situation.
- When compressed firmly and tied, each bundle should be between 6 and 8 inches in diameter at the center.
- Where bundles overlap an additional pair of stakes through the ends of both bundles should be used at the midpoint of the overlap. The overlap should be staked with one pair of stakes through the end of both bundles while on the inside of the end tie of each bundle. The length of the overlap should be approximately 1 to 2 feet.

Locations for the placement of live fascines should be indicated in the Stream Relocation Plan sheets by using the appropriate symbol. Two control points will be used to define the location of each fascine installation, one at the upstream end and the other at the downstream end. The Stream Mitigation Data Table should provide stations and offsets for these control points, and the Design Data column should indicate the required bundle diameter and the species of plant to be utilized. If additional rows of fascines are used up the bank, the designer should provide this information using footnotes to the mitigation item. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Live fascines shall be paid for under the following pay item number:

- Item Number 209-03.45, Stream Mitigation – Live Fascines (Species), per LF

11.08.2.4.5 EXAMPLE APPLICATION

Given: The south bank of a small relocated channel will have a height of 10 feet and a slope of 2H:1V. Although Longitudinal Stone Toe Protection will be utilized to protect the channel up to the height of the flow at the channel forming discharge, there will be a need to protect the slope from erosion above the top of the stone. Based on the soil types in the proposed channel bank, it has been determined that live fascines can be used to help provide erosion protection. The area over which this additional protection will be required is approximately 78 feet long.

Find: Determine the quantity of live fascines required for this project.

Solution: Based on hydrologic and hydraulic analysis of the proposed channel, the following information can be determined:

- Flow depth at the channel forming discharge: 1.35 feet
- Flow velocity at Q50: 5.78 ft/sec

- Maximum shear at Q50: 2.6 lb/ft^2

Since the depth at the channel forming discharge is 1.35 feet, the vertical height of the longitudinal stone toe is determined to be 1.4 feet. The remaining 8.6 feet of the bank height will be divided into three sections by placing live fascines at a vertical spacing of 2.8 feet (i.e. – 5.6 feet along the slope). This spacing should provide more protection than actually required by Table 11SB-2. The fascines will be installed on the contour, but the ends will be keyed into the bank and protected by Machined Riprap Class B.

The pay item for live fascines is:

Item Number 209-03.45, Stream Mitigation-Live Fascines (Species), per LF

An extra 3 feet of length will be required at each end of the fascines in order to key the ends into the slope. Thus, the total length of each run of fascine will be 84 feet. Since there will be two runs of fascine, the final quantity will be 168 LF.

11.08.2.5 LIVE SILTATION

Live Siltation Construction
Location: Pembina River, Alberta, Canada

11.08.2.5.1 DEFINITION AND PURPOSE

Live siltation, also referred to as live brush sills, consists of rows of live cuttings inserted into an excavated trench. This measure is similar to brush layering except that the orientation of the branches is more vertical. This measure has a number of purposes including:

- providing roughness
- slowing flow velocities
- encouraging the deposition of sediment
- securing the toe of the bank
- creating fish rearing habitat
- providing surface stability for the planting and establishment of vegetation
- trapping debris, seed, and vegetation at the shoreline
- promoting seed germination for natural colonization

Although this measure is called live siltation, it can also be used as a non-living system at the water's edge. This is a temporary but very effective and simple method using local plant material to provide immediate cover and fish habitat while other vegetation plantings become established.

11.08.2.5.2 APPROPRIATE APPLICATIONS

A live siltation system is typically placed along the toe of a stream bank at the ordinary high water level. It serves to prevent scour along the toe by slowing flow velocities, deflecting the current away from the bank, and providing an environment where sedimentation can occur. Live siltation is recommended for sites with velocities ranging from 0.8 ft/sec to 6.6 ft/sec such as the inside of meander bends, side channels, and in areas of bank scour behind obstructions. This measure is also well suited for locations where formation of a new bank is desired; however this requires a moderate to high sediment load in the stream to be successful. It is essential that live siltation be used in locations where the stream bank is not subject to erosion, or else be used in conjunction with other measures which can protect the toe of slope.

In addition of the typical use described above, live siltation can also function in other areas of the stream bank. Live siltation can be placed on a stream bank at a slope oriented as much as 15 degrees downstream from perpendicular to the bank in order to improve bank stability. This type of layout is recommended for banks with flat slopes to reduce erosion and provide for additional sedimentation where it is desired. Once established, live siltation systems provide deep, strong roots which can add resistance against slope failure due to sliding or shear displacement. This also helps to create a stable environment for riparian and fish habitat.

When used in conjunction with hard armor measures such as large natural stone, coir logs, root wads, etc., live siltation can be an excellent measure in areas subject to high flow velocities. Hard armor can work with a live siltation system to prevent toe erosion (and potentially failure of the upper bank), scour of the middle and upper banks, erosion by wave action or other forms of local scour. When used with appropriately sized riprap, live siltation should be able to resist shear stresses of more than 6 lb/ft^2 or velocities of more than 12 ft/sec. However, these permissible values are based on full establishment of the roots and branches, which could require 2 to 3 years.

Finally, live siltation systems can serve to prevent erosion in dry channel beds to resist the formation of rills and gullies or in bends to resist meander cutoffs.

In any of these applications, more than one row may also be placed along the stream bank to increase the effectiveness of the measure.

11.08.2.5.3 LIMITATIONS

The following factors should be considered prior to specifying live siltation systems for a project:

- Cutting for branches to be installed should be done during the dormant season if using a living system. This will have an impact on the time of year that the construction may take place.
- During the dry season, mechanical irrigation may be needed to ensure that establishment of the plant materials will occur.
- The system requires relatively low flow velocities.

11.08.2.5.4 PLANNING AND DESIGN CRITERIA

It is important that a live siltation system be placed no lower than the ordinary high water mark (OHWM) elevation. The OWHM elevation is not based on a hydraulic analysis of the stream. Rather, it is the level at which the vegetation on the stream bank changes in nature from aquatic to terrestrial, and is usually part of the data collected in the project survey. If a live siltation system is placed below the OHWM, the space between the base of the vegetation and the water table will be inadequate and the cuttings will drown. Thus, a live siltation system installed below the OHW elevation should be considered a temporary measure to provide cover during the establishment of other vegetation. For projects where the OHWM elevation is unknown, it may be necessary to utilize other measures in lieu of live siltation.

The flow velocity at the design discharge is an important factor to consider when specifying live siltation systems. For the system to effectively capture sediments, the flow velocity (not considering the roughness provided by the cuttings) should be at least 0.8 ft/sec. However, the velocity should not be more than approximately 6 ft/sec where live siltation has been installed without other measures to prevent erosion. These other measures could include riprap, boulders, coir logs, root wads, and other measures that would protect the toe of slope along the bank.

In some situations, it may be desirable to place multiple live siltation rows parallel to the stream. The spacing between the rows should be between 5 to 15 feet depending on the slope and soil types and overall stability of the stream bank. Actively eroding sites, sites with steep slopes and sites subject to high velocity flows would require a closer spacing.

Willows are an excellent species for use in live siltation systems. The selection of a native species appropriate for the project location should be coordinated with the Environmental Division.

The following additional design criteria should be considered when specifying live siltation for a project:

- Installation should begin at the toe of the bank to be treated.
- The live cuttings should be installed into a trench 2 to 3 feet deep and 1 to 2 feet wide, with one vertical side and the other side angled towards the shoreline in a v-shape.
- The cuttings should be placed into the trench at a spacing of approximately 12 branches per lineal foot.
- The live cuttings should be collected locally, if possible. If they cannot be installed the day that they are harvested, they should be soaked for 14 days prior to installation.
- Large rock, coconut logs or other measures can be placed on the upstream side of the installation to safeguard against washout along the top of the backfilled trench.
- Where multiple live siltation rows are utilized, the areas between the rows should be seeded with species that do not compete with the woody vegetation.
- Supplemental watering may be required to ensure establishment.

Locations for the installation of live siltation should be indicated in the Stream Relocation Plan sheets by using the appropriate symbol. In general, two control points will be used to define the location of each installation, one at the upstream end and the other at the downstream end. The Stream Mitigation Data Table should provide stations and offsets for these control points, and the Design Data column should indicate the species of plant to be utilized. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Live siltation shall be paid for under the following pay item number:

- Item Number 209-03.46, Stream Mitigation – Live Siltation (Species), per CY

11.08.2.5.5 EXAMPLE APPLICATION

Given: The bank along the inside of a curve on an existing alluvial stable stream is fairly wide and flat. Because this bank is somewhat low, it is below the flow level at the channel forming discharge. At the same time, it is also above the ordinary high water mark, and is thus a good location for the installation of live siltation. Although the longitudinal slope of the stream is fairly low, it carries a high sediment load and it is determined that live siltation should be used to encourage the deposition of sediments on this bank. The length of the curve over which the measure is to be applied is approximately 175 feet.

Find: Determine the quantity of live siltation required for this project.

Solution: The pay item for live siltation is:

Item Number 209-03.46, Stream Mitigation-Live Siltation (Species), per CY

The quantity for live siltation is typically determined based on the volume of the trench needed to install the measure. Based on the criteria in this section, the trench should be triangular, 2 feet wide and 3 feet deep. However, because of typical excavation practices, the volume of excavation will be based on assuming that the trench will be rectangular. Thus, the cross sectional area of the trench will be assumed to be 6 ft^2. Over a distance of 175 feet, the total volume of excavation would be 1050 ft^3. Dividing by 27 ft^3 / CY yields the final quantity of 38.9 CY.

11.08.2.6 LONGITUDINAL STONE TOE

Longitudinal Stone Toe
Location: Little Walnut Creek, Austin, TX

11.08.2.6.1 DEFINITION AND PURPOSE

A longitudinal stone toe consists of a machined riprap dike placed at the toe of a steep, caving stream bank. This measure serves to protect against scour at the toe of the bank and provides hard armoring that serves to hold an immovable location for the toe. It is important to note that this measure is not intended to stabilize the entire stream bank. Rather, it is assumed that the upper portions of the bank will continue to fail until a stable slope is reached. However, stability can be assisted by the establishment of vegetation along the slope.

11.08.2.6.2 APPROPRIATE APPLICATIONS

Longitudinal stone toes may be used along an alluvial channel in areas where the lower bank is subject to erosion and requires permanent rigid toe protection. Stone toes are especially well suited for areas where the upper bank slopes is fairly stable, but the toe is in need of extra protection from scour or erosion. This measure is typically applied on narrow, small to medium-sized streams and is not suited to locations where the channel bed is composed of exposed bedrock. The success of longitudinal stone toe protection is based on the premise that as the toe of the bank is stabilized, upper bank failure will continue until a stable slope is attained and the bank is stabilized. Stability of the toe of bank is assisted by the establishment of vegetation along the bank above the stone.

In some situations, a longitudinal stone toe can be used to provide a smooth alignment where the outside of a channel bend is characterized by abrupt changes (scallops, coves, or elbows). This method is also applicable where a roadway or other facility requires protection against future meandering of the stream. Where there is sufficient room to allow for the establishment of a stable slope above the riprap, a longitudinal stone toe can be an alternative to providing hard armor on the entire bank.

11.08.2.6.3 LIMITATIONS

Longitudinal stone toes provide protection only to the toe itself and thus do not directly protect middle and upper bank areas. Additional measures such as vegetation, erosion matting, and brush mattresses should be put into place to protect these areas since establishment of vegetation above the stone toe is essential for long-term success. The designer should be aware that some failure of the bank above a longitudinal stone toe may occur during high flows and the possible effects of this failure should be considered in the overall project design.

Where a longitudinal stone toe is applied in an alluvial stream, the channel should be stable as defined in Section11.03.2; otherwise, channel degradation could cause the overall failure of the measure.

The use of riprap in channels is typically considered an unnatural method by a number of agencies with environmental permitting authority. Thus, specifying a longitudinal stone toe for a project should be coordinated with the Environmental Division.

Because the placement of a longitudinal stone toe requires the use of heavy equipment for excavating the trench and placing the rock, this measure should be utilized only where there is adequate access to the project area.

11.08.2.6.4 PLANNING AND DESIGN CRITERIA

The basic design parameters for a longitudinal stone toe are its cross section and alignment. These parameters will typically be determined based on site specific conditions and the purposes to be served, including protecting a bank from erosion, establishing an immovable channel boundary and preventing the failure of the channel bank by mass wasting.

As shown in Figure 11SB-3, the cross section of a longitudinal stone toe will usually be wedge-shaped. Depending on the purposes to be served, the measure may either be placed in front of an eroding bank, or be built into a reconstructed channel bank. The cross section should also include a means of ensuring that the structure will not be undermined by scour. This can be accomplished by providing extra riprap at the base of the structure so that, as scour occurs, this material would be launched into the hole to provide armoring. At some sites, the needed protection may be accomplished by providing a key trench that extends from the base of the stone toe to a depth either below the anticipated maximum scour depth or 1.5 times maximum stone diameter of the machined riprap, whichever is greater. The crest of the longitudinal stone toe should be no lower than the flow depth at the channel forming discharge. In addition, where a longitudinal stone toe is to be used to protect against mass wasting, the design of the proposed cross section should be coordinated with the Geotechnical Engineering Section.

Where a longitudinal stone toe is built into a reconstructed channel bank, Geotextile (Type III) (Erosion Control) should be installed behind the rock to prevent the piping of embankment materials into the machined riprap.

The proposed alignment of a longitudinal stone toe should be carefully evaluated with regards to its effect on the overall stream system. In particular, the measure should be designed to minimize its impact on the hydraulic capacity of the channel. Further, introducing an immovable boundary into an alluvial stream may have impacts on the alignment of the channel in other areas. The designer should make an effort to anticipate these potential impacts and adjust the proposed project design accordingly.

Where a longitudinal stone toe is to be placed in front of an eroding slope, it should be provided with perpendicular stone dikes, or tie-backs, as illustrated in Figure 11-X. These tie-backs should be keyed into the bank and are important to ensure that the longitudinal stone toe will function as intended. Typically, tie-backs should be placed on a spacing of about 75 to 100 feet.

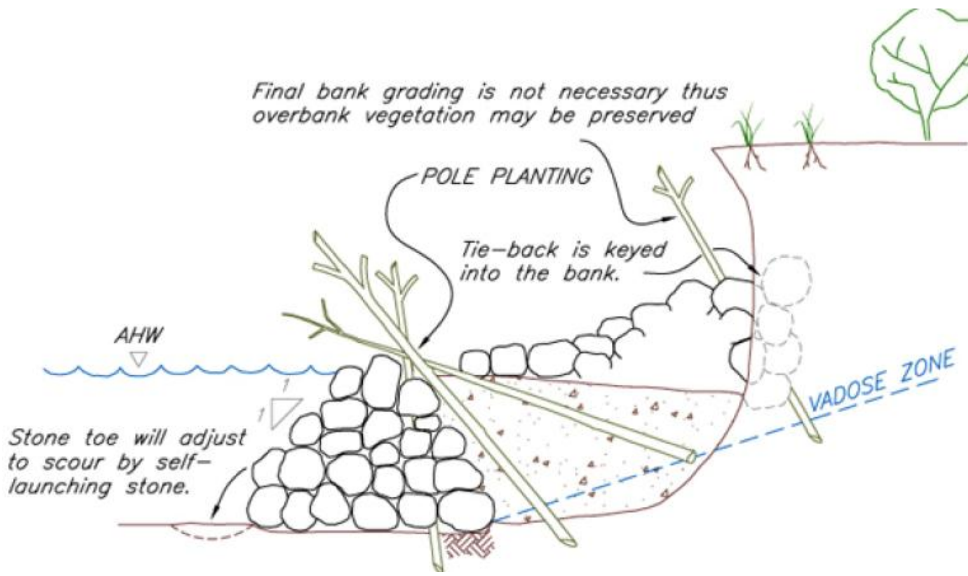


Figure 11SB-3
Possible Cross Section Configuration for a Longitudinal Stone Toe
Reference: TDOT SSWMP (2007)

The upstream and downstream ends of a longitudinal stone toe should also be keyed into the channel bank to prevent erosion from occurring behind the structure. It is important that these keys be trenched into the bank at an angle of approximately 30° to the flow direction in order to provide for more gradual flow transitions at the upstream and downstream ends of the structure. In the past, placing these keys at an angle perpendicular to flow has resulted in the failure of the longitudinal stone toe.

The placement of riprap in a stream channel is often viewed by environmental permitting agencies as less than ideal. Where feasible, the impact of a longitudinal stone toe can be minimized by constructing it with vegetated riprap, which is described earlier in this section. In addition, the establishment of vegetation on the areas of the stream bank above the stone toe is also critical to the success of this measure.

A failed riprap structure can cause considerable environmental damage; thus, it is important that the riprap in the structure be properly sized. In general, the class of machined riprap used to construct a longitudinal stone toe may be selected based on the criteria presented in Section 11.04.6.2.

Due to the different purposes a longitudinal stone toe may serve, there is no standard cross section that may be applied in all settings. A detail of the proposed cross section of the riprap should be provided in the Natural Stream Design plan set. In addition, the proposed alignment (typical alignment shown in Figure 11SB-4) of the structure should be indicated in the plan view and in the cross sections. The cross sections should be labeled with the proposed elevation of the crest of the structure.

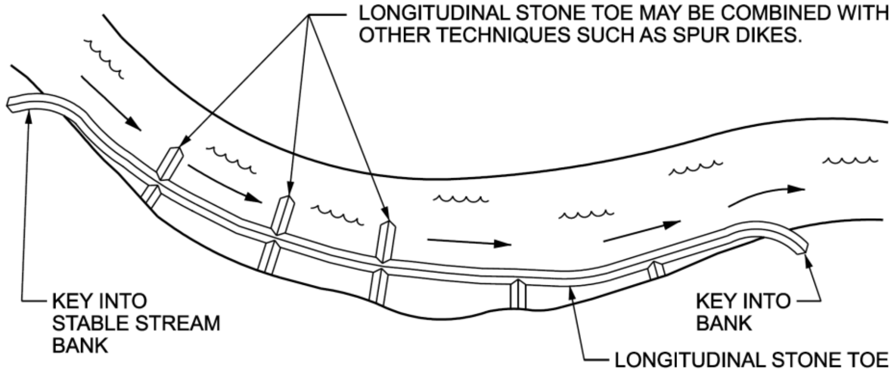


Figure 11SB-4
Typical Longitudinal Stone Toe Alignment
Reference: Adapted from TDOT SSWMP (2007)

Because a detailed design is necessary to ensure that a longitudinal stone toe will perform as intended, drawings and design information for these structures should be provided in the Stream Relocation Detail Sheets. The Stream Mitigation Data Table should show the following information:

- station and offset of the control points used to define the upstream and downstream ends of stone toe
- channel forming flow elevation, channel bottom elevation, and anticipated scour depth
- reference to the appropriate Stream Relocation Detail Sheet number(s)

In general, the control point for locating each dike will be located at the point where the crest of the structure intersects the channel bank. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Longitudinal stone toe shall be paid for under the following pay item numbers:

- Item Number 209-03.47, Stream Mitigation – Longitudinal Stone Toe (Description), per CY
- Item Number 740-10.03, Geotextile (Type III) (Erosion Control), per SY

11.08.2.6.5 EXAMPLE APPLICATION

Given: A proposed roadway widening project will result in two new lanes being built in close proximity to the outside of a meander bend in a stable alluvial stream. Although stream relocation will not be required for the project, there will be a need to ensure that future progress of the meander bend will not threaten the foundation of the new travel lanes. Based on a review of the materials in the channel banks, it is determined that longitudinal stone toe protection will be a suitable means of securing the toe of the existing channel bank.

The existing channel has a bottom width of 12 feet and 2H:1V side slopes. Hydrologic and hydraulic analysis of the stream indicated that the depth at the channel forming discharge is 3.60 feet, while the flow velocity for the peak 50-year discharge is 7.14 ft/sec at a depth of 6.90 feet. In addition, the length of the curve adjacent to the roadway is 150 feet, and the radius of curvature is 375 feet.

Find: Determine the required cross section and quantity for longitudinal stone toe protection required for this project.

Solution: Based on the flow velocity in the 50-year event, the longitudinal stone toe protection will be constructed from Machined Riprap Class B. The cross section of the stone will consist of a trapezoidal shape with a top width of 2.5 feet which is the minimum thickness of the stone layer for this class of machined riprap. Based the depth of flow at the channel forming discharge, the height of the trapezoid will be 3.6 feet. Based on 2H:1V side slopes, the bottom of the trapezoid will be 16.9 feet wide.

It will also be necessary to ensure that the proposed riprap will not become undermined. Because the proposed longitudinal stone toe protection is to be built into the existing slope, it may not be practical add material to the toe that could be launched into a potential scour hole. Thus, the depth of the stone will be increased by an amount equal to the anticipated scour depth. This scour depth can be estimated using Equation 11HC-10 provided in Section 11.08.1.6. As described in that section, it is necessary for the designer to check the values of the ratios R_c/W and W/y_{avg} before applying this equation. For this project,

$$\frac{R_c}{W} = \frac{375}{12} = 31$$

Since this value is greater than the minimum, it will be used in computing the scour depth. Since the depth in the 50-year event is 6.90 feet, the other ration may be computed as:

$$\frac{W}{y_{avg}} = \frac{12}{6.90} = 1.74$$

Because this ratio is much less than the minimum value of 20, a value of 20 will be used to compute the anticipated scour depth.

$$y_s = y_{avg}\left[1.8 - 0.051\left(\frac{R_c}{W}\right) + 0.0084\left(\frac{W}{y_{avg}}\right)\right] = 6.90\left[1.8 - 0.051(31) + 0.0084(20)\right]$$

$$y_s = 2.67 \text{ feet}$$

Based on this result, the longitudinal stone toe will be provided with a riprap key that is 2.7 feet deep by 2.7 feet wide.

Although the curve length to be protected is 150 feet, it will be necessary to extend the length of the protection upstream of the curve by a distance equal to the channel bottom width and downstream of the curve by a distance equal to 1.5 times the channel bottom width. Thus, the total length of the longitudinal stone toe will be 180 feet.

The pay item for longitudinal stone toe protection is:

<u>Item Number 209-03.47, Stream Mitigation-Longitudinal Stone Toe (Description), per CY</u>

Based on the computations above, the cross sectional area of the trapezoidal cross section combined with the riprap key will be 42.21 ft^2. Thus, the final quantity for this measure may be computed as:

$$Volume = 42.21 \times 180 = 7597.8 \text{ ft}^3 = 281.4 \text{ CY}$$

11.08.2.7 VEGETATED GABIONS

Gabion with Willow Tree
Reference: GA DNR-CRD, (2006)

11.08.2.7.1 DEFINITION AND PURPOSE

Gabions are rectangular baskets or mattresses made of heavily galvanized wire mesh that is filled with small to medium size rocks. The individual units are tied together and installed at the base of a bank to form a structural toe or sidewall. Vegetation in the form of willow poles or other types of live cuttings can either be inserted into the baskets as they are filled or installed between the gabion baskets. It is also possible to install container plants within the stone fill. The addition of vegetation can enhance the stability of the gabion structure as the roots develop and bind into the bank soils. Because they are relatively flexible, vegetated gabions can be an effective means of securing an eroding slope. They may also improve the drainage characteristics of the bank soils through plant transpiration.

11.08.2.7.2 APPROPRIATE APPLICATIONS

Vegetated gabions are effective where the bank is too steep for riprap or other erosion protection measures and needs moderate structural support. With appropriate caution, they may be used to prevent erosion where high flow velocities result in shear stresses that exceed the permissible shear stress levels for vegetative stream bank protection measures. They may also be utilized at locations where machined riprap is not readily available.

As a general rule, the use of gabions should be avoided for a stream relocation project. However, as described in Section 5.04.7.1.5, there may be situations in which gabions would be the best means of providing erosion protection or bank slope stability. The addition of vegetation is essentially a means of mitigating the impact of having to construct a gabion structure in the first place. Thus, vegetated gabions should not be utilized in situations where un-vegetated gabions would not be required.

11.08.2.7.3 LIMITATIONS

Vegetated gabions are not appropriate in streams where conditions would tend to abrade the coatings which protect the wire from corrosion. If the protective coating is damaged, the wires will corrode to the point that they break and the integrity of the structure is lost. Thus, use of gabions should be avoided where the flows will transport significant amounts of coarse sand, rock or gravel at relatively high velocities. One study has found that the average life expectancy of a gabion in these conditions is approximately 9 to 15 years. Gabions are also not suitable where ice action is a possibility or in streams where the pH of the water is low.

Construction of gabions can be labor-intensive, particularly where vegetation is being added. Further, once a gabion has been assembled, it can only be moved by large equipment due to its weight and flexibility. Since adjustments in the field are a frequent occurrence, appropriate access to the project location is a necessity.

11.08.2.7.4 PLANNING AND DESIGN CRITERIA

Vegetated gabions can be used to prevent the erosion of a stream bank or to stabilize slopes that are steep, where there are present seepage problems, or are characterized by non-cohesive soils. Section 5.04.7.1.5 provides a discussion of situations where the use of gabions would be appropriate. Once the vegetation in an installation of vegetated gabions matures, it will help to provide shade for the stream.

Vegetated gabions are typically specified by volume in the same way that un-vegetated gabions are specified. Gabions are typically 3 feet wide, although widths of 4.5 or 6 feet may also be available. Gabions are available in heights of 1, 1.5 and 3 feet, and in lengths of 6, 9 and 12 feet. In general, gabions are available in any combination of these standard widths, heights and lengths. However, the designer should contact a vendor to ensure that a given combination will be available.

Gabion walls that are to be over three baskets tall in height shall be designed by the Structures Division. Vegetative plantings and limits of wall will be determined by the designer and modified during installation as needed or directed by the Construction Engineer.

The stability of the foundation is important to the integrity of an installation of gabions. Thus, an effort also should be made to estimate scour depths along the toe of the gabion installation, and to place the first row of gabions below that depth. In this way, the foundation of the structure would be below any loose alluvial soils associated with the fluvial activity of the stream. Although this should generally be adequate to ensure that the bottom of the gabion structure would rest on well-compacted natural soils, the allowable bearing pressure of these soils should be coordinated with the Geotechnical Engineering Section.

Vegetated gabions are typically placed end to end in single or multiple rows. The installation should lean towards the bank to be protected, either by means of battering the installation or by providing a stepped-back configuration. This configuration is typically easier to build when the wall is greater than 10 feet in height. The proposed configuration of the baskets should be shown on the Stream Relocation Cross Section sheets.

Geotextile Fabric (Type III) (Erosion Control) should be placed between the vegetated gabions the surface of the soils behind the structure. This fabric should meet the requirements of the standard specification for geotextiles, AASHTO designation M-288, Erosion Control.

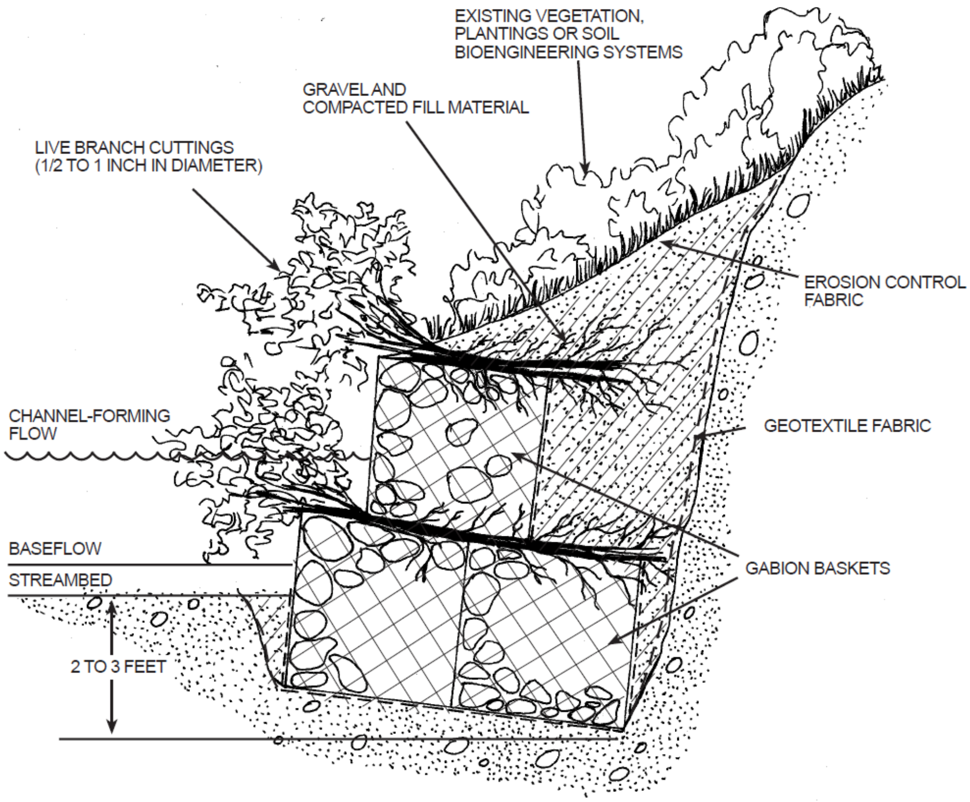


Figure 11SB-5
Typical Installation Detail of Vegetated Gabions
Reference: Ohio DNR (2003)

As the gabions are being filled, poles or other live cuttings are inserted through the baskets into the bank. Soil should be added and compacted over the cuttings to remove excess air pockets and secure them into place. If container plants are to be utilized, they can be added to the gabions in the same manner. The live cuttings should be long enough to reach beyond the gabion baskets and penetrate into the bank soils, preferably far enough to extend into the normal water table. The species of vegetation to be used should be coordinated with the Environmental Division.

Any type of gabion installation will require a detailed design to ensure that the gabion structure is built to the lines and grades necessary to fulfill the purpose of the structure. Thus, design information for these structures should be provided in the Stream Relocation Detail Sheets. The Stream Mitigation Data Table should show the following information:

- station and offset of the control points used to define the upstream and downstream ends of gabion installation
- channel forming flow elevation, channel bottom elevation, and anticipated scour depth
- reference to the appropriate Stream Relocation Detail Sheet number(s)

An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Vegetated gabions shall be paid for under the following item numbers:

- Item Number 209-03.48, Stream Mitigation – Vegetated Gabions (Description), per CY
- Item Number 740-10.03, Geotextile (Type III) (Erosion Control), per SY

11.08.2.7.5 EXAMPLE APPLICATION

Given: An existing stream is experiencing bank slope stability problems adjacent to a TDOT roadway which could affect the integrity of the roadway subgrade. The affected channel bank is approximately 6 feet high and extends a distance of 50 feet along the road. The stream has a bedrock channel bed and hydraulic analysis indicates that the channel velocity in the 50-year flood event will be 7.23 ft/sec.

Find: Determine the required quantities for vegetated gabions for this project.

Solution: Based on coordination with the Geotechnical Engineering Section, it has been determined that sufficient structural integrity can be achieved by stacking two rows of gabions to form a nearly vertical wall. To meet the 6-foot height of the channel bank, it is determined that the wall should be constructed to 3 x 3 x 6 foot gabion baskets. Further, lateral stability will be ensured by cutting a shallow groove into the exposed bedrock to serve as a foundation for the gabion wall.

Because the flow velocity in the 50-year event is 7.23 ft/sec, the gabions will be constructed using Machined Riprap Class B. Although the flow velocity appears to be somewhat high for the use of gabions, it is anticipated that the presence of vegetation along the face of the structure will reduce flow velocities and thus help to prevent abrasion of the wire coatings.

The pay items for this installation are:

Item Number 209-03.48, Stream Mitigation - Vegetated Gabions (Description), per CY
Item Number 740-10.03, Geotextile (Type III) (Erosion Control), per SY

Each layer of the wall will be constructed by placing 3 x 3 x 6-foot gabions end to end. Thus, 9 gabions will provide a length of 54 feet, and an additional gabion will be placed to provide a sufficient length of erosion protection past the end of the curved section of the channel alignment. Thus the wall will contain 20 gabions, each with a volume of 54 ft^3 for a total volume of 1080 ft^3 or 40 CY.

The geotextile will be placed across the top and down the inside face of the wall. In order to provide additional protection against the piping of fill through the wall, an additional length of 3 feet will be placed on the bedrock at the toe of the wall to form an apron. Thus the total surface area of the geotextile may be computed as:

$$Area = (3+6+3)\times 60 = 720.0 \text{ ft}^2 = 80.0 \text{ SY}$$

11.08.2.8 VEGETATED MECHANICALLY STABILIZED EARTH (MSE) WALLS

Vegetated MSE Wall
Location: West Bouldin Creek, Austin, TX

11.08.2.8.1 DEFINITION AND PURPOSE

Vegetated MSE Walls encompass a broad range of soil retaining structures which utilize a porous fascia connected to horizontal reinforcing structures (referred to as tensile inclusions) which are integrated into the soil behind the face of the wall to transfer and distribute soil loads. The fascia and tensile inclusions act together to create a reinforced soil block which acts as a solid unit to resist lateral soil loads through the dead weight of the reinforced mass. A variety of materials are available for both the porous fascia and the tensile inclusions. These materials can be combined to form two broad categories of structure: geocell structures and wrapped soil systems. Table 11SB-3 provides a general description of the general types of systems which may be utilized.

Vegetated MSE walls are typically not vertical. Depending on the materials used to build the structure, the slope of the wall could range from nearly vertical to 1H:1V. Structures at a flatter slope are sometimes termed reinforced soil slopes. However, since the distinction between these two types of structure is not clear, the discussion in this section is limited to walls.

The environmental benefits of a vegetated MSE wall vary depending on the type of vegetation utilized. Where seeded grasses are used, the primary benefit is that the wall provides a cooler environment along a stream than would occur for a non-vegetated MSE wall. The vegetation on the wall absorbs the heat of direct sunlight and minimizes the potential for heating of the air or any nearby water in the stream. Live cuttings will provide a larger number of benefits, including shading the stream and providing inputs of leaves or twigs that provide nutrients for aquatic organisms. In either case, vegetated MSE walls present a more natural aesthetic.

11.08.2.8.2 APPROPRIATE APPLICATIONS

Vegetated MSE walls have a number of possible applications beyond the stream environment. However, in the context of a stream relocation project, vegetated MSE walls are primarily used for slope stabilization where horizontal constraints such as the roadway itself or right-of-way limits leave little room for the construction of the channel bank slope. A vegetated MSE wall provides a means to stabilize a steep slope while still maintaining a relatively natural appearance.

11.08.2.8.3 LIMITATIONS

The strength of a vegetated MSE wall can be adversely affected if the embankment soils become saturated for extended periods of time. Thus, this measure should be applied only in the middle to upper portion of the channel bank, above the level of the channel forming discharge. In addition, the toe of the embankment beneath a vegetated MSE wall should utilize hard armoring such as a longitudinal stone toe to provide protection from scour.

Vegetated MSE walls should be applied with caution in areas where they would be exposed to rapidly flowing water. Permissible shear stresses for vegetated MSE walls are not currently well understood, and high velocity flows have the potential to erode sediments from the face of any type of wall, especially walls composed of geocells.

The application of vegetated MSE walls may be complicated by the presence of poor foundation soils. Although the reinforced soil mass is self-supporting and will tend to act as a single solid unit, it may be subject to an unacceptable amount of settlement where the underlying soils do not provide sufficient bearing capacity. It may be possible to provide geogrids to reinforce poor soils, or to excavate the foundation to a depth sufficient to provide a competent foundation. However, the excavation required for these options will cause an extensive disturbance adjacent to the stream.

In some applications, establishing vegetation on the face of the wall may be difficult. Where this is the case, the wall should be applied in areas where there will be sufficient access for watering equipment. In addition, once the overall project construction is complete, it may be necessary to arrange for continuing maintenance during the period of time required for establishment of the vegetation.

The construction of a vegetated MSE wall may require an extensive amount of excavation. The designer should ensure that the required construction equipment will have adequate access to the proposed wall site.

Vegetated MSE walls may not be as cost effective as other soil retention options which may require more space. Thus, the use of a vegetated MSE wall should be considered only in areas that are limited by horizontal constraints. As a rule of thumb, vegetated MSE walls are cost effective only to heights of 10 feet or less. However, the final selection of a measure to be used should be based on a comparative cost analysis.

11.08.2.8.4 PLANNING AND DESIGN CRITERIA

Like any other type of MSE wall, a vegetated MSE wall is a complex structure which will require specialized design. The designer should coordinate the design of these structures with the Geotechnical Engineering Section. The design should consider external forces acting on the soil mass, including overturning and sliding forces, as well as the bearing capacity of the underlying soils. Design considerations for internal forces include the tensile strength of the horizontal inclusion, the ability of the inclusions to resist pullout, internal sliding, connection strength between the fascia and the tensile inclusions and the potential for bulging of the facing. Vegetated MSE walls should be designed in accordance with TDOT Standard Specification for Road and Bridge Construction and the current AASHTO Standard Specifications for Highway Bridges with interims.

A wide variety of vegetated MSE wall configurations are possible, including a number of propitiatory wall systems. The two most common types of vegetated MSE wall systems utilize either geocells or lifts of soil that are wrapped in a geosynthetic fabric. Table 11SB-3 summarizes these two types of systems. This table should not be considered all-inclusive and other types of wall systems may be considered, provided that they are based on sound engineering principles.

Fascia Type	Tensile Inclusions	Type of Vegetation	Additional Materials
Geocell	Geotextile (Type IV)(Stabilization), Geogrid or Metal Strips	Seeding	None
Wrapped Soil – Geotextile	Continuous with fascia material	Live Cuttings (optional) and seeding	None
Wrapped Soil – Geogrid	Continuous with fascia material	Live Cuttings (optional) and seeding	TRM is used to wrap fascia
Wrapped Soil – Welded Wire	Continuous with fascia material	Live Cuttings (optional) and seeding	TRM is used to wrap fascia

Table 11SB-3
Possible Configurations of Vegetated MSE Wall
(Note: This table provides only a general summary. Other configurations may be possible.)

A typical configuration for a vegetated MSE wall utilizing geocells consists of a fascia four cells deep combined with tensile inclusions that penetrate into the embankment. Once filled with a suitable soil, each of the geocells in the system functions as an individual container for the soil and vegetation. Where the tensile inclusions consist of geotextile or geogrid, these would be placed between successive layers of geocell so that they can be anchored to the fascia by friction. Where metal strips or similar materials are used, they should be mechanically anchored to the geocell fascia. This type of wall should not be vertical, as each layer of geocell should be stepped back from the layer below. The steepest practical slope of a geocell vegetated MSE wall should be approximately 0.5H:1V.

Geocells are available in a variety of heights. The cell height is typically determined based on both the required depth of soil lift specified by the geotechnical analysis of the MSE wall and the type of vegetation to be utilized. For example, the geotechnical analysis may require that tensile inclusions be provided at a vertical spacing of 1 foot. In this case, two rows of 6-inch high geocells or three rows of 4-inch high geocells could be used. The choice between these two configurations should be based on root depth requirements of the proposed vegetation and thus should be coordinated with the Environmental Division.

Geocells may also be either solid or perforated, and in general, perforated cells should be utilized for a vegetated MSE wall. This will allow for adequate drainage of the water within the embankment soils and will allow the roots of the vegetation to intertwine through the holes in the cells. Where the tensile inclusions consist of geogrids, the roots will also intertwine with the tensile members of the grid. This intertwining of the roots with the geocells and geogrid provides an extra factor of safety for binding the fascia to the tensile inclusions. However, this strength should not be considered in the structural design of the wall system. The exterior surface of the wall should be provided with a solid facing to prevent the loss of soil through any exposed perforations.

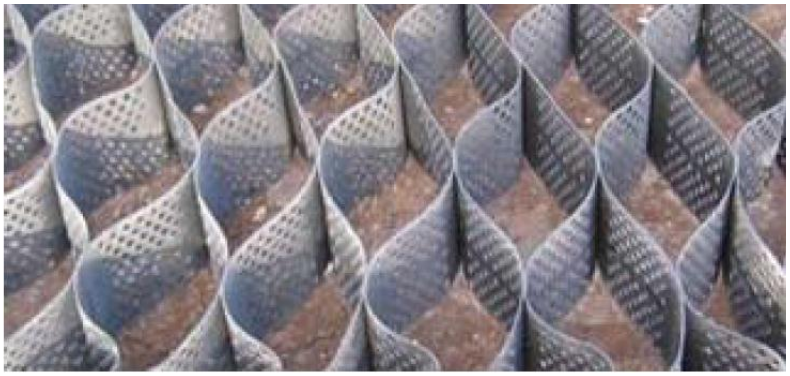


Figure 11SB-6
Typical Geocell System
Reference: NRCS NEH-654, Tech. Supp 14D (2007)

As shown in Figure 11SB-7, a typical wrapped geogrid vegetated MSE wall consists of four basic components: rock scour protection at the toe, lifts of compacted soil wrapped in some type of geosynthetic fabric, vegetation and a means of providing drainage, such as a chimney drain behind the structure. A wide variety of materials and configurations are available, depending on site-specific needs. Certain types of materials may be utilized to construct nearly vertical walls; however, wrapped soil MSE walls are more typically at slopes of 0.5H:1V or 1H:1V. The use of geosynthetic materials also allows vegetation to be added to the walls in a variety of ways.

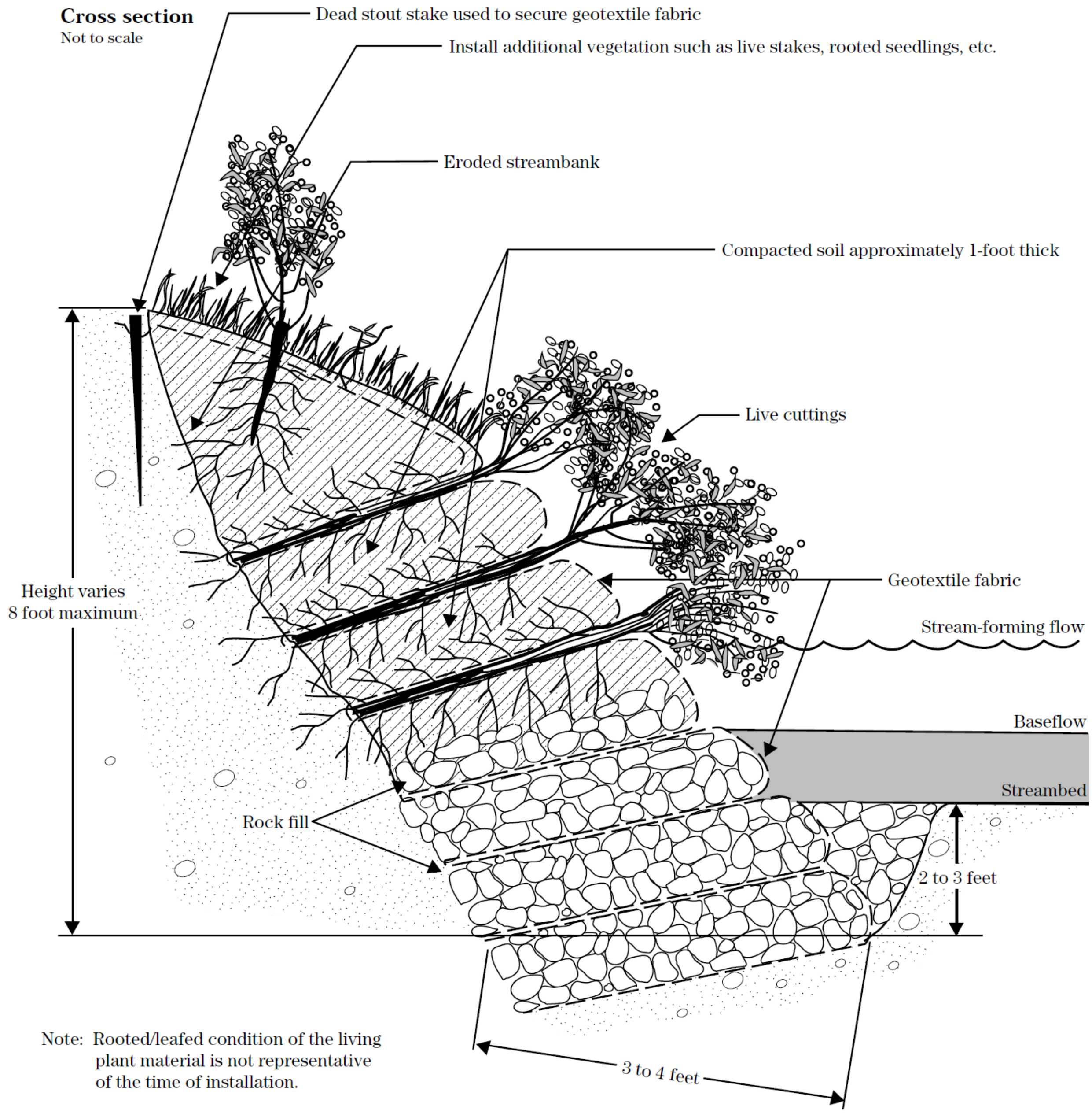


Figure 11SB-7
Sketch of a Typical Wrapped Soil Vegetated MSE Wall
Reference: USDA, NRCS, Engineering Field Handbook (1996)

Because each lift of compacted backfill in this type of MSE wall is wrapped in some type of geosynthetic fabric, the tensile inclusions are essentially integral with the fascia materials and should be sloped into the embankment at an angle of 10° to 15°. Although a number of different types of materials are available, the most commonly used materials are as follows:

- **Welded Wire:** This material is usually coated with vinyl to prevent corrosion. As long as the vinyl coating remains undamaged during construction, welded wire offers the longest design life of any of the materials available. Even with a vinyl coating, welded wire should be used with caution in soils which possess chemical properties that would tend to promote corrosion. To provide soil retention at the face of the wall, the wire fascia is wrapped with a layer of turf reinforcement mat (TRM).

- **Geogrid:** This material consists of man-made open plastic netting. As shown in Figure 11SB-8, this netting can have a primary axis in one direction (uniaxial) or utilize both lateral and transverse elements (biaxial). Geogrids provide a tensile strength similar to that of welded wire, but also offer superior resistance to pullout. It is important that geogrids be composed of materials that have been stabilized against the effects of ultraviolet light. However, exposure of the material to sunlight may affect the overall design life of the material. Like welded wire, this material should be wrapped with a TRM at the face to provide for retention of the soil.

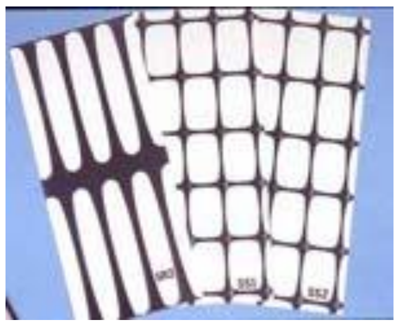


Figure 11SB-8
Examples of Uniaxial and Biaxial Geogrids

- **Geotextile:** The principal advantage of this material is that it does not require the addition of other materials at the face of the wall to retain the soil. They can consist of natural fibers, such as coconut fiber (coir) fabric, or of man-made polymeric materials. These materials tend to have shorter life spans than welded wire or geogrids, since natural fibers are often biodegradable and the man-made fabrics may be affected by ultraviolet light. An additional advantage of natural fiber geotextiles is that these materials tend to offer larger openings which are more effective in encouraging the germination of any seeds that have been placed into the soil.

Vegetation can be added to a wrapped soil MSE wall by two principal means. First, the soil directly behind the fascia can be seeded with small plants, vines, and grasses. Larger plants are not appropriate for this application due to the loads they can impose on the wall face. The selection of plant materials and the characteristics of the backfill soil should be coordinated with the Environmental Division. It may be difficult to provide a soil at the wall face that is both suitable for growing plant species and provides the required engineering properties in terms of soil compressibility, strength, and drainage.

The second means of providing vegetation is to place live cuttings (willow poles or posts) between successive lifts of soil. If this option is used, the species to be placed and the density of the plantings should be coordinated with the Environmental Division. A potential advantage of this option is that the roots from the live cuttings can extend into the undisturbed soil behind the structure and add a factor of safety to its overall stability. However, this should be treated as a bonus, and not be considered in analyzing the stability of the wall. The layers of vegetation can also provide a potential seepage path for water in the embankment, thus helping to relive pore pressure. In addition, shade provided by the vegetation once it matures may help to extend the life of the structure by reducing the penetration of ultraviolet light into the fascia materials. The main disadvantage of this option is that the live cuttings should be added to the embankment during the dormant season, and this may affect the construction schedule.

The two main factors that affect the cost of a vegetated MSE wall are its height and slope. Regardless of the type of wall proposed, it is generally possible to construct a wall up to a height of 20 feet. However, the economic feasibility of a proposed wall should be evaluated where the wall height would exceed 10 feet. In addition, the slope of a wall directly affects the loads to be carried by the MSE system. As the loads increase, the allowable lift height is reduced, the required lengths of the tensile inclusions will increase, along with the potential required quantity of excavation. Thus, the final configuration should be based on a consideration of the construction costs versus the costs of an increased right of way take.

Permissible shear stresses are generally not well understood for vegetated MSE walls. As a general rule, the permissible shear stress used to evaluate a proposed wall should be based on the permissible shear for the material lining the fascia. For example, permissible shear for a wrapped soil MSE wall utilizing welded wire or geogrid may be determined from the criteria provided for turf reinforcements mats provided in Section 5.04.7.1.1. Due to the presence of exposed soil at the tops of the geocells, a geocell vegetated MSE wall will be particularly susceptible to loss of soil due to the erosive forces of flowing water. The permissible shear a geocell MSE wall before the vegetation is established should be assumed to be equal to the permissible shear for bare soil. Where no other criteria are available, the following general criteria may be utilized:

- Prior to establishment of vegetation: Permissible shear ≈ 4 lb/ft^2, maximum velocity ≈ 5 ft/sec
- Fully vegetated: Permissible shear ≈ 8 lb/ft^2, maximum velocity ≈ 7 ft/sec

Shear on a MSE wall may be computed using Equation 5-10 for the 50-year design discharge. However, the depth of flow should be based on the depth at the toe of the wall, not the maximum depth in the channel cross section.

In most situations, a longitudinal stone toe will be needed to protect the vegetated MSE wall from undermining due to scour. This toe protection should be composed of natural boulders or riprap of sufficient size to resist the maximum anticipated flow velocity. The bottom of the stone should be at or below the anticipated scour depth and the top should be at least at the level of the flow at the channel forming discharge. An MSE wall installation can become unstable if the embankment materials are saturated for a long period of time. Placing a wall above the level of the channel forming discharge should ensure that it will not be inundated to a depth or for a period of time sufficient to compromise the strength of the system.

Due to the wide variety of possible configurations for a vegetated MSE wall, a typical cross section of the wall should be shown on the Stream Relocation Plan Details Sheet.

Vegetated MSE walls shall be paid for under the following item numbers:

An MSE wall is a complex structure that requires a detailed design to ensure it is built to the lines and grades necessary to fulfill the purpose of the structure. Thus, design information for these structures should be provided in the Stream Relocation Detail Sheets. The Stream Mitigation Data Table should show the following information:

- station and offset of the control points used to define the upstream and downstream ends of the MSE wall installation
- channel forming flow elevation, channel bottom elevation, and anticipated scour depth
- reference to the appropriate Stream Relocation Detail Sheet number(s

An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

- Item Number 209-03.49, Steam Mitigation – Vegetated MSE Walls (Description), per SF

11.08.2.8.5 EXAMPLE APPLICATION

Given: An existing stream bank slope stability problem needs to be corrected in conjunction with proposed improvements to a TDOT roadway facility. Due to aesthetic concerns within the community, it is determined that the slope should be repaired by means of longitudinal stone toe protection and a vegetated MSE wall.

The eroding bank is approximately 8 feet high and 150 feet long. Hydrologic and hydraulic analysis of the stream has yielded the following information:

- Stream slope = 1.05%
- Depth at the channel forming discharge = 3.20 feet
- Depth at the peak 50-year discharge = 7.52 feet
- Velocity at the peak 50-year discharge = 6.97 ft/sec

Find: Select an appropriate configuration for vegetated MSE wall and determine the required quantities.

Solution: The longitudinal stone toe protection will be constructed up to the height of the flow at the channel forming discharge, or 3.5 feet. Thus, the depth of flow on the wall during the 50-year flood event will be equal to 4.02 feet and the shear stress may be computed as:

$$\tau = \gamma\, dS = 62.4(4.02)(0.0105) = 2.63 \text{ lb/ft}^2$$

Although the average velocity in the channel is fairly high for the 50-year event, the actual velocity experienced at the vegetated MSE wall will be significantly less. Given the relatively small shear stress that has been computed for the wall, it is decided to use a geocell system to address aesthetic concerns.

The pay item for a vegetated MSE wall is:

<u>Item Number 209-03.48, Stream Mitigation- Vegetated MSE Walls (Description), per SF</u>

Based on coordination with the Geotechnical Engineering Section, it has been determined that the wall should be constructed at a slope of 0.5H: 1V. Since the vertical height of the wall will be 4.5 feet, the actual length of the wall along the slope may be computed as:

$$Height = \sqrt{4.5^2 + (4.5 \times 0.5)^2} = 5.0 \text{ feet}$$

Because the channel in the project area is relatively straight, it will not be necessary to provide an additional length of erosion protection past the end of the project. Thus, the final quantity for vegetated MSE wall may be computed as:

$$Area = 150 \times 5 = 750 \text{ ft}^2$$

11.08.2.9 ARTICULATED CONCRETE BLOCKS

Vegetated Articulated Block Protection
Location: Pennsylvania

11.08.2.9.1 DEFINITION AND PURPOSE

Articulated concrete blocks are flexible concrete revetments made of up multiple concrete blocks that are either interlocking or connected by steel cables to create a continuous mat. They are typically used on the shorelines of large bodies of water to protect against wave action or in steep channels, such as dam spillways, to resist the erosive forces exerted by large, high-energy flows. An advantage of this material is that the interlocking blocks form a flexible lining. Thus, this measure is able to conform to settlement or other limited changes in the underlying subgrade.

A number of types of articulated concrete block provide open spaces which may be vegetated. The presence of vegetation provides hydraulic roughness which can further assist in dissipating flow energy.

11.08.2.9.2 APPROPRIATE APPLICATIONS

Articulated concrete blocks may be applied as an alternative to concrete lining in areas where flow velocities exceed 12 ft/sec, which is the maximum allowable for Machined Riprap (Class C). This type of measure could be applied on the outside of bends on high gradient streams. Although articulated concrete block would be most appropriately applied on threshold streams, it may also be useful to maintain the alignment of an alluvial stream where the roadway or other stream side facility requires protection from erosion.

The block units used to form an articulated concrete block system may either be provided with an open space as shown in Figure 11SB-9, or be completely solid. Because the open block units are designed to allow the growth of vegetation, this type of block is preferred for application in stream relocation projects.

11.08.2.9.3 LIMITATIONS

There are generally two forms of articulated concrete mats and each type presents different limitations. One form utilizes steel cables to tie the blocks into a large flexible unit. These units are pre-assembled and delivered to the site as complete mats. Because placement of these mats requires large construction equipment, they should be utilized only at sites which offer sufficient access. The other form of articulated concrete mat is composed of individual interlocking blocks which are hand placed. While this measure may be utilized in areas with restricted access, they tend to be labor intensive. Interlocking block must also be carefully designed to ensure that the upstream and downstream ends of the lining will not be undermined by the erosion of the channel banks on either side of the lining. Significant erosion of the subgrade materials can result in the overall failure of the interlocking block system.

11.08.2.9.4 PLANNING AND DESIGN CRITERIA

An articulated concrete block system requires detailed design to select the most cost-effective style and size of block that will be adequate to resist the erosive forces imposed by the design discharge. Typically, vendors of specific block systems will offer software design tools or other design services to assist in selecting an appropriate system.

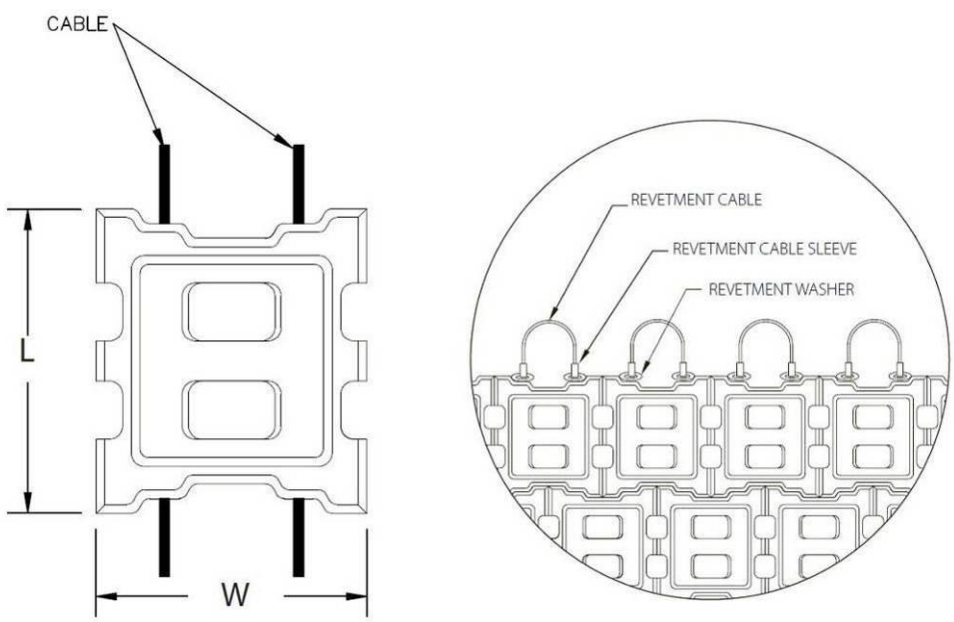


Figure 11SB-9
Typical Articulated Concrete Block System with Steel Cables
Reference: ConTech Construction Products, Inc.

Research into the performance of articulated concrete block systems under severe hydraulic loading conditions has been carried out by the manufactures of these systems, and the results of this research can often be found on the internet. In evaluating the results of this research the designer should bear in mind that the tests were conducted under “ideal” circumstances. It may be necessary to apply an extra factor of safety in the design to account for irregularities that may occur in the lining due to actual field conditions.

Where interlocking block systems are utilized, the upstream and downstream ends of the installation should be keyed into the bank a distance sufficient to prevent potential future erosion of the channel from undermining the block system.

The concrete used to cast the concrete blocks should have a compressive strength of at least 4000 lb/in^2. This will help ensure that the block will resist abrasion or damage by sediments or other materials carried in the flow.

Articulated concrete mats should be placed on properly prepared smooth surfaces, free from tree roots, projecting stones or any other foreign matter that would cause irregularities in the surface of the blocks. Geotextile Fabric (Type III) should be utilized under the blocks. This fabric should meet the requirements of the standard specification for geotextiles, AASHTO designation M-288, Erosion Control. Anchors may need to be placed depending on the type of mat being used. After the concrete mat is properly placed, the voids between blocks may be filled with topsoil and seed to encourage the growth of vegetation.

Locations for the placement of articulated concrete mats should be indicated as a hatched area on the Stream Relocation Plan sheets. In general, two control points will be used to define the extents of an installation, one at the upstream end and the other at the downstream end. The Stream Mitigation Data Table should provide stations and offsets for these control points, and details for the proposed block system should be provided in the Stream Relocation Detail Sheets. The Stream Mitigation Data Table should show the following information:

- station and offset of the control points used to define the upstream and downstream ends of the articulated concrete block installation
- channel forming flow elevation, channel bottom elevation, and anticipated scour depth
- reference to the appropriate Stream Relocation Detail Sheet number(s)

An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Articulated concrete mats shall be paid for under the following item numbers:

- Item Number 209-03.53, Stream Mitigation – Articulated Concrete Mat, per SY
- Item Number 740-10.03, Geotextile (Type III) (Erosion Control), per SY

11.08.2.9.5 EXAMPLE APPLICATION

Given: A potential erosion issue has been noted near the east abutment of the I-40 bridge over the Mississippi River in Memphis. Because the height of the erosion is somewhat limited, it appears that this issue is due to a combination of current and wave action at normal flow levels. The area for which extra protection is apparently needed is approximately 475 feet long and includes areas both above and below the normal water level.

It has been proposed to utilize articulated concrete block mats to address this issue.

Find: Evaluate the feasibility and determine the required quantities for articulated concrete mats for this project.

Solution: An evaluation of the project side indicates that there should be adequate access to the river bank, as well as sufficient clearance under the bridge to allow the operation of the equipment required for the project. Coordination with vendors of articulated concrete block systems indicates that a block system using steel cables will offer sufficient erosion protection and will be stable for the anticipated flow conditions.

Because of a requirement that the banks of the river also be vegetated, two different types of block will be used for this project. Directly beneath the bridge and under the normal water level, a solid type of block will be utilized. However, open cell blocks will be used on the river banks on either side of the bridge.

The pay items for this installation are:

Item Number 209-03.53, Stream Mitigation- Articulated Concrete Mat, per SY
Item Number 740-10.03, Geotextile (Type III) (Erosion Control), per SY

The quantities for both of these items will essentially be equal and may be calculated as follows:

$$Area = 475 \times (10 + 10) = 9500\ \text{ft}^2 = 1056\ \text{SY}$$

11.08.2.10 BRUSH MATTRESSES

Brush Mattress Installation
Reference: NEH654 Tech. Supplement 14-I

11.08.2.10.1 DEFINITION AND PURPOSE

Brush mattresses consist of a thick layer of live branches and cuttings that are uniformly installed along the bank of a stream and anchored by a system of stakes with biodegradable rope or wire. Brush mattresses are a live bank armoring practice that provides immediate erosion protection for the stream bank. As the live materials take root and grow, the level of erosion protection is increased as the roots assist in stabilizing the soils in the bank and the dense layer of new branches increases the roughness along the bank so that flow velocities are reduced.

Because a brush mattress is composed of a dense layer of branches and cuttings, it can provide immediate protection against erosion by reducing the velocity of the flows that may reach the underlying soil. As new branches grow and develop, flow velocities are reduced at the surface of the mattress, and this can act to capture sediment from the stream, which in turn helps to rebuild the bank and enhance its riparian habitat.

11.08.2.10.2 APPROPRIATE APPLICATIONS

Brush mattresses may be used on stream banks that are moderate in height and slope. Because the basal ends of the cuttings need to be installed below the normal water level, the height of the bank to be protected will be limited by the length of cutting that is available. Multiple layers can extend the protected height of the bank by only a small amount and the survival of the branches in the upper layer can be limited. This measure is best applied on banks with a slope of 2H:1V or flatter, but may be applied on steeper slopes with appropriate caution.

11.08.2.10.3 LIMITATIONS

The long-term success of a brush mattress installation depends on the ability of the cuttings to take root in the bank of the stream. Because this requires that the basal ends of the cuttings be kept moist, this measure may not succeed on streams which lack a perennial base flow.

The installation of a brush mattress should be done during the dormant season (October to March) and this may affect the construction schedule for the project. In addition, installing the mattress can be labor intensive. The designer should consider this cost in selecting the most cost effective measure for a given site.

The sediment load in the stream should be considered before brush mattresses are proposed. Deposition of sediments on a brush mattress due to a high sediment load can potentially cause the measure to be buried and make it ineffective.

11.08.2.10.4 PLANNING AND DESIGN CRITERIA

Detailed design is not required for this measure. The live cuttings should be placed on the slope perpendicular to the stream at the rate of approximately 20 to 50 every 3 lineal feet. The cuttings should packed together tightly to eliminate large air pockets and form a mattress between 2 and 12 inches thick.

The two factors that are most important to the success of this measure are a sufficient supply of water and close contact with the soil. Both of these factors need to be in place in order to encourage the branches to take root. To ensure an adequate supply of water, the lower portions of the live cuttings should remain submerged at all times. Thus, the basal ends of the cuttings should be placed into a trench below the normal water level parallel to the stream. This will ensure that the cuttings will remain submerged even in low flow conditions.

The slope of the bank will help to ensure adequate contact with the soil. Typically, it is difficult to establish good contact on slopes steeper than 2H:1V. In addition, the lower ends of the cuttings closest to the stream should be completely covered with soil, with the tops of the branches still exposed. If the stream bank consists of rocky material, soil should be placed over the rock prior to placing the mattress to ensure that the branches will have an adequate opportunity to take root.

In general, the slope length of the bank to be protected should not exceed the length of the cuttings that may be available. Rooting success for branches placed above the normal water level can be quite limited.

Once the trench has been backfilled, the toe of the slope should be provided with some type of erosion protection to prevent the mattress from being undercut by scour. This protection could be in the form of a longitudinal stone toe or another type of erosion prevention device such as a coconut fiber roll. The upstream and downstream ends of the mattress should be protected against flanking by means of a riprap key or other erosion prevention measure that has been keyed into the bank.

Once the brush has been placed on the bank, it is held in place by a system of notched wooden stakes to which wire or rope has been attached. In general, it is preferable to use a rope composed of natural fibers or other type of biodegradable material instead of wire. The stakes should be driven in a grid pattern (at 2 to 3 foot intervals) along the mattress. Initially, they are driven only partially into the bank so the wire or rope can be attached. Then they are driven completely into the ground so that the wire will provide tension on the brush and hold it firmly in place.

Typically, willow branches will be used to construct brush mattress since they have good rooting ability. The exact species to be used at a given site should be coordinated with the Environmental Division.

Permissible shear stresses for brush mattresses may be variable depending on the quality of the installation. Table 11SB-4 shows permissible velocity and shear levels for a brush mattress, based on research conducted by the U.S. Army Corps of Engineers. The values in this table may be taken as general guidance and should be evaluated based on sound engineering judgment.

Stone Toe Protection	Initial Construction		Established Vegetation	
	Velocity (ft/sec)	Shear (lb/ft^2)	Velocity (ft/sec)	Shear (lb/ft^2)
Without	< 4	0.4 – 3.0	< 5	4.0 – 7.0
With	< 5	0.8 – 4.1	< 12	4.0 – 8.0

Table 11SB-4
Permissible Velocity and Shear for Brush Mattress Staked to the Bank
Reference: U.S. Army Corps of Engineers, Research and Development Center (2000)

Locations for the installation of brush mattresses should be indicated as a hatched area on the Stream Relocation Plan sheets. In general, two control points will be used to define the extents of a brush mattress installation, one at the upstream end and the other at the downstream end. The Stream Mitigation Data Table should provide stations and offsets for these control points, and the Design Data column should indicate the species of plant to be utilized. An example of a completed Stream Mitigation Data Table is provided in Section 11.06.

Brush mattresses shall be paid for under the following item numbers:

- Item Number 209-03.59, Stream Mitigation – Brush Mattress, per SY

11.08.2.10.5 EXAMPLE APPLICATION

Given: A roadway widening project in west Tennessee will require the relocation of a portion of a small stream which has flat stream banks and a relatively low slope. It is determined that a form of natural erosion protection is needed along the curved sections of the channel where the relocated reach will be transitioned into the unaffected portions of the stream. Due to the configuration of the stream, the nature of the materials in the channel banks and the need to maintain a continuous riparian corridor, it is decided to utilize brush mattresses on both banks of the curved transition reaches.

Based on the project survey and hydraulic analysis of the stream, the following data are available to support the design:

- Stream slope = 0.35%
- Channel bottom width = 8 feet
- Channel bank slopes = 3H:1V
- Bank height = 4 feet
- Channel forming discharge = 250 cfs
- Velocity at the channel forming discharge = 3.15 ft/sec
- Shear at the channel forming discharge = 0.87 lb/ft^2
- Length of each transition curve = 105 feet

Find: Determine the required quantity for brush mattresses for this project.

Solution: Based on the velocity and shear values computed for the stream, it appears that stone toe protection will not be required for this project.

Although the curved transition reaches will be 105 feet, long, it will be necessary to ensure that erosion protection is provided for the channel banks upstream and downstream of the curves. As described in Section 11.04.6.2, the additional length of protection upstream of the curve will be equal to the channel bottom width, or 8 feet. Downstream of the curve, the protection length will be 1.5 times the channel bottom width or 12 feet. Thus, the total length of protection for both curves will be 125 feet.

The pay item for brush mattresses is:

<u>Item Number 209-03.59, Stream Mitigation - Brush Mattress, per SY</u>

To determine the final quantity, it is first necessary to compute the length along the slope of the channel bank. Since the banks are 4 feet at a 3H:1V slope, the slope length may be computed as:

$$Length = \sqrt{4^2 + (4 \times 3)^2} = 12.7 \text{ feet}$$

Because both sides of the channel are to be protected for both curves, the final quantity may be computed as:

$$Area = 125(2 \times 2)(12.7) = 6350 \text{ ft}^2 = 705.6 \text{ SY}$$

TDOT DESIGN DIVISION

DRAINAGE MANUAL

CHAPTER XI
APPENDIX 11A

SECTION 11.09 – APPENDIX

11.09 APPENDIX

11.09.1 FIGURES AND TABLES

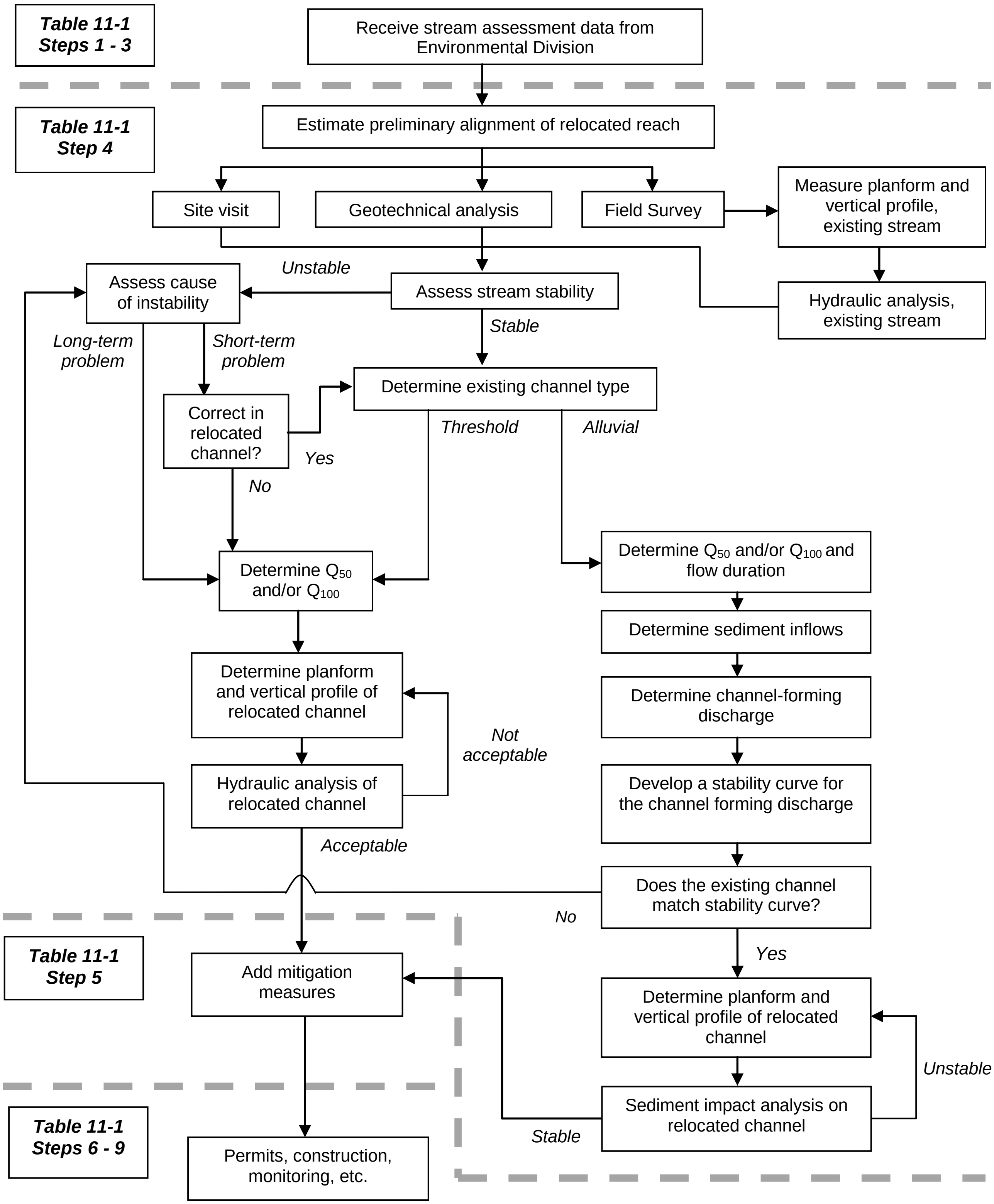


Figure 11A-1
Natural Stream Design Flow Chart

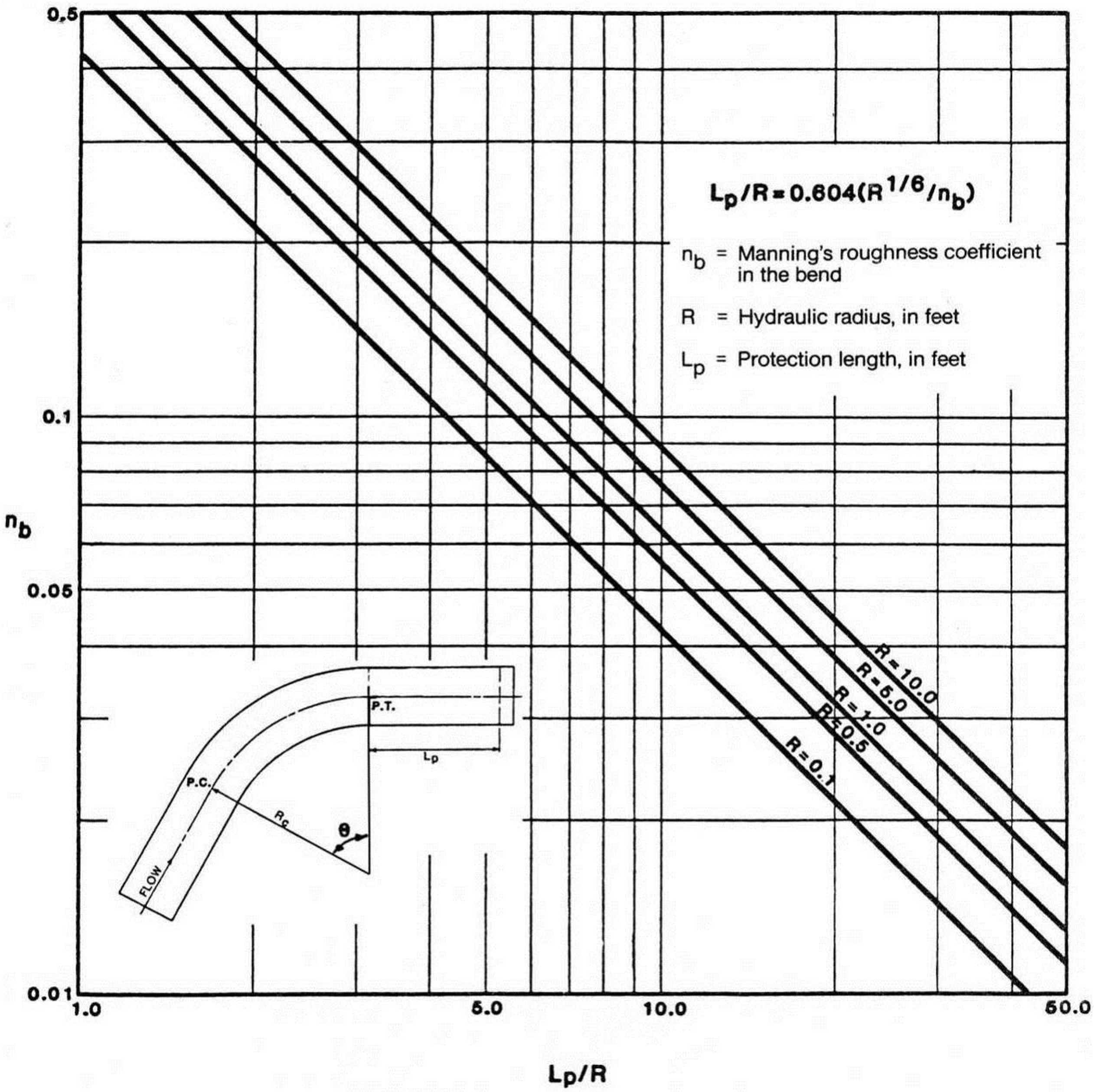


Figure 11A-2
Protection Length, L_p, Downstream of Channel Bend
Reference: USDOT, FHWA, HEC-15 (1988)

Description		Condition	Criteria	Value
n_0	Material Involved	Earth		0.020
		Rock Cut		0.025
		Fine Gravel		0.024
		Coarse Gravel		0.028
n_1	Degree of Irregularity	Smooth	Dredged, no erosion	0.000
		Minor	Dredge, slightly eroded	0.005
		Moderate	Moderately eroded and natural streams	0.010
		Severe	Badly eroded or sloughed sides	0.020
n_2	Variation in Channel Cross Section	Gradual	Gradual change, channel centered	0.000
		Occasional	Main flow occasionally changes from small to large sections	0.005
		Frequent	Main flow frequently changes in cross-sectional shape	0.010 – 0.015
n_3	Effect of Obstructions	Negligible	Few to no snags or debris	0.000
		Minor	Smooth obstructions, channel slightly encroached	0.010 – 0.015
		Appreciable	Woody debris, channel significantly encroached	0.020 – 0.030
		Severe	Channel entirely blocked with woody and other debris	0.040 – 0.060
n_4	Vegetation	Low	Long, flexible grasses, few small willows	0.005 – 0.010
		Medium	Stemmy or tall grasses, moderate brush	0.010 – 0.025
		High	Tall grasses equal to depth, mature willows with brush	0.025 – 0.050
		Very High	Tall grasses above depth, trees and brush, cattails	0.050 – 0.100
m_5	Degree of Sinuosity	Minor	Sinuosity < 1.2	1.000
		Appreciable	Sinuosity 1.2 to 1.5	1.150
		Severe	Sinuosity > 1.5	1.300

Table 11A-1
Coefficients for Computing Manning's n-Values
For Natural or Excavated Channels Using Cowan's Equation
Reference: Chow, Ven T., Open Channel Hydraulics (1959), Table 5-5, p. 109

Description of Stream:	Type	Gradient	Bed Material	Banks
	Alluvial	Low	Sand / Silt	Non-cohesive

Stream Mitigation Measure	APPLICATION									
	Temporary cover to establish permanent vegetation	Create / encourage pool and riffle structure	Introduce other flow complexity	Velocity Control	Prevent bank erosion	Restore eroded banks	Prevent mass wasting of banks	Capture sediment	Encourage aquatic habitat	Enhance riparian corridor
Boulder Clusters	0	1	3	0	0	0	0	0	3	0
Log Deflectors and Vanes	0	0	0	0	0	0	0	0	0	0
Log Drop	0	1	1	1	1	0	0	0	1	0
Step Pool	0	0	0	0	0	0	0	0	0	0
Rock Vanes	0	1	1	1	1	0	0	0	3	0
Spur Dikes	0	1	1	1	1	0	0	0	1	0
Constructed Riffles	0	3	3	1	0	0	0	0	3	0
Large Woody Debris	1	0	2	0	2	1	0	0	2	0
Coconut Fiber (Coir) Rolls	2	0	0	0	2	1	0	1	0	1
Vegetated Riprap	0	0	0	0	3	3	3	1	0	1
Willow Cuttings (Posts and Poles)	1	0	0	0	3	1	0	3	0	3
Live Fascines	1	0	0	0	1	1	0	3	0	3
Live Siltation	1	0	0	0	1	1	0	3	0	3
Longitudinal Stone Toe	0	0	0	0	3	3	3	0	0	1
Vegetated Gabions	0	0	0	0	3	3	3	1	0	1
Vegetated MSE Walls	0	0	0	0	3	3	3	1	0	1
Articulated Concrete Blocks	0	0	0	0	3	3	3	0	0	0
Brush Mattresses	3	0	0	0	3	1	0	3	0	3

Key:

- 0 = Measure is unsuitable or does not apply in this setting
- 1 = Measure must be applied with supporting measures to achieve the desired purpose
- 2 = Measure is effective on a temporary basis
- 3 = Measure is effective on a permanent basis

Table 11A-2a
Stream Mitigation Measure Selection Table for Low Gradient Alluvial Streams

Description of Stream:	**Type**	**Gradient**	**Bed Material**	**Banks**
	Alluvial	Medium	Gravel	Cohesive

Stream Mitigation Measure	**APPLICATION**									
	Temporary cover to establish permanent vegetation	Create / encourage pool and riffle structure	Introduce other flow complexity	Velocity Control	Prevent bank erosion	Restore eroded banks	Prevent mass wasting of banks	Capture sediment	Encourage aquatic habitat	Enhance riparian corridor
Boulder Clusters	0	1	3	0	0	0	0	0	3	0
Log Deflectors and Vanes	0	1	2	0	2	1	0	0	2	0
Log Drop	0	2	2	2	2	0	0	0	2	0
Step Pool	0	3	3	3	0	0	0	0	3	0
Rock Vanes	0	3	3	3	1	0	0	0	3	0
Spur Dikes	0	3	3	1	1	0	0	0	3	0
Constructed Riffles	0	3	3	1	0	0	0	0	3	0
Large Woody Debris	1	0	2	0	2	1	0	0	2	0
Coconut Fiber (Coir) Rolls	2	0	0	0	2	1	0	1	0	1
Vegetated Riprap	0	0	0	0	3	3	3	1	0	1
Willow Cuttings (Posts and Poles)	1	0	0	0	3	1	0	3	0	3
Live Fascines	1	0	0	0	1	1	0	3	0	3
Live Siltation	1	0	0	0	1	1	0	3	0	3
Longitudinal Stone Toe	0	0	0	0	3	3	3	0	0	1
Vegetated Gabions	0	0	0	0	3	3	3	1	0	1
Vegetated MSE Walls	0	0	0	0	3	3	3	1	0	1
Articulated Concrete Blocks	0	0	0	0	3	3	3	0	0	0
Brush Mattresses	3	0	0	0	3	1	0	3	0	3

Key:

- 0 = Measure is unsuitable or does not apply in this setting
- 1 = Measure must be applied with supporting measures to achieve the desired purpose
- 2 = Measure is effective on a temporary basis
- 3 = Measure is effective on a permanent basis

Table 11A-2b
Stream Mitigation Measure Selection Table for Medium Gradient Alluvial Streams

Description of Stream:	Type	Gradient	Bed Material	Banks
	Threshold	Medium	Rock	Cohesive

Stream Mitigation Measure	APPLICATION									
	Temporary cover to establish permanent vegetation	Create / encourage pool and riffle structure	Introduce other flow complexity	Velocity Control	Prevent bank erosion	Restore eroded banks	Prevent mass wasting of banks	Capture sediment	Encourage aquatic habitat	Enhance riparian corridor
Boulder Clusters	0	0	3	0	0	0	0	0	3	0
Log Deflectors and Vanes	0	0	0	0	0	0	0	0	0	0
Log Drop	0	0	0	0	0	0	0	0	0	0
Step Pool	0	0	3	3	0	0	0	0	3	0
Rock Vanes	0	0	3	3	1	0	0	0	3	0
Spur Dikes	0	0	0	0	0	0	0	0	0	0
Constructed Riffles	0	0	0	0	0	0	0	0	0	0
Large Woody Debris	1	0	2	0	2	1	0	0	2	0
Coconut Fiber (Coir) Rolls	2	0	0	0	2	1	0	0	0	1
Vegetated Riprap	0	0	0	0	3	3	3	1	0	1
Willow Cuttings (Posts and Poles)	1	0	0	0	3	1	0	0	0	3
Live Fascines	1	0	0	0	1	1	0	0	0	3
Live Siltation	1	0	0	0	1	1	0	0	0	3
Longitudinal Stone Toe	0	0	0	0	3	3	3	0	0	1
Vegetated Gabions	0	0	0	0	3	3	3	0	0	1
Vegetated MSE Walls	0	0	0	0	3	3	3	0	0	1
Articulated Concrete Blocks	0	0	0	0	3	3	3	0	0	0
Brush Mattresses	3	0	0	0	3	1	0	0	0	3

Key:

- 0 = Measure is unsuitable or does not apply in this setting
- 1 = Measure must be applied with supporting measures to achieve the desired purpose
- 2 = Measure is effective on a temporary basis
- 3 = Measure is effective on a permanent basis

Table 11A-2c
Stream Mitigation Measure Selection Table for Medium Gradient Threshold Streams

Description of Stream:	**Type**	**Gradient**	**Bed Material**	**Banks**
	Threshold	High	Rock	Rock

Stream Mitigation Measure	**APPLICATION**									
	Temporary cover to establish permanent vegetation	Create / encourage pool and riffle structure	Introduce other flow complexity	Velocity Control	Prevent bank erosion	Restore eroded banks	Prevent mass wasting of banks	Capture sediment	Encourage aquatic habitat	Enhance riparian corridor
Boulder Clusters	0	0	3	0	0	0	0	0	3	0
Log Deflectors and Vanes	0	0	0	0	0	0	0	0	0	0
Log Drop	0	0	0	0	0	0	0	0	0	0
Step Pool	0	0	3	3	0	0	0	0	3	0
Rock Vanes	0	0	3	3	0	0	0	0	3	0
Spur Dikes	0	0	0	0	0	0	0	0	0	0
Constructed Riffles	0	0	0	0	0	0	0	0	0	0
Large Woody Debris	0	0	0	0	0	0	0	0	0	0
Coconut Fiber (Coir) Rolls	1	0	0	0	0	0	0	0	0	1
Vegetated Riprap	0	0	0	0	0	0	0	0	0	1
Willow Cuttings (Posts and Poles)	0	0	0	0	0	0	0	0	0	0
Live Fascines	0	0	0	0	0	0	0	0	0	0
Live Siltation	0	0	0	0	0	0	0	0	0	0
Longitudinal Stone Toe	0	0	0	0	0	0	0	0	0	0
Vegetated Gabions	0	0	0	0	0	0	0	0	0	1
Vegetated MSE Walls	0	0	0	0	0	0	0	0	0	0
Articulated Concrete Blocks	0	0	0	0	0	0	0	0	0	0
Brush Mattresses	0	0	0	0	0	0	0	0	0	0

Key:

- 0 = Measure is unsuitable or does not apply in this setting
- 1 = Measure must be applied with supporting measures to achieve the desired purpose
- 2 = Measure is effective on a temporary basis
- 3 = Measure is effective on a permanent basis

Table 11A-2d
Stream Mitigation Measure Selection Table for High Gradient Threshold Streams

Particle Class Name	Size (mm)
Colloid	< 0.0024
Clay	0.0024 – 0.004
Silt	0.004 – 0.062
Sand, very fine	0.062 – 0.125
Sand, fine	0.125 – 0.25
Sand, medium	0.25 – 0.50
Sand, coarse	0.50 – 1.0
Sand, very coarse	1.0 – 2.0
Gravel, very fine	2.0 – 4.0
Gravel, fine	4 – 8
Gravel, medium	8 – 16
Gravel, coarse	16 – 32
Gravel, very coarse	32 – 64
Cobbles, small	64 – 128
Cobbles, large	128 – 256
Boulders, small	256 – 512
Boulders, medium	512 – 1024
Boulders, large	1024 – 2048
Boulders, very large	> 2048

Table 11A-3
Sediment Size Classes
Reference: ASCE, Sediment Engineering, 1977

Particle Size in mm		Size Class
from	to	
	< 0.002	Clay
0.002	0.004	Very Fine Silt
0.004	0.008	Fine Silt
0.008	0.016	Medium Silt
0.016	0.031	Coarse Silt
0.031	0.063	Very Coarse Silt
0.063	0.125	Very Fine Sand
0.125	0.25	Fine Sand
0.25	0.5	Medium Sand
0.5	1	Coarse Sand
1	2	Very Coarse Sand
2	4	Very Fine Gravel
4	8	Fine Gravel
8	16	Medium Gravel
16	32	Coarse Gravel
32	64	Very Coarse Gravel
64	128	Fine Cobble
128	256	Coarse Cobble
> 256		Boulder

Table 11A-4
Common Grain Size Classes

11.09.2 EXAMPLE PROBLEM

11.09.2.1 EXAMPLE PROBLEM #1: THRESHOLD STREAM DESIGN

INTRODUCTION:

The purpose of this sample problem is to illustrate the natural stream design process from start to finish for an actual stream in the State of Tennessee. The selected stream has a bedrock bottom and relatively stable banks and is thus a threshold stream. Since natural stream design for a threshold stream usually involves fewer steps, this choice of stream will allow the sample problem to adequately illustrate the design process without becoming excessively long. Following this sample problem are additional sample problems which illustrate the other procedures that would be required for natural stream design on an alluvial stream.

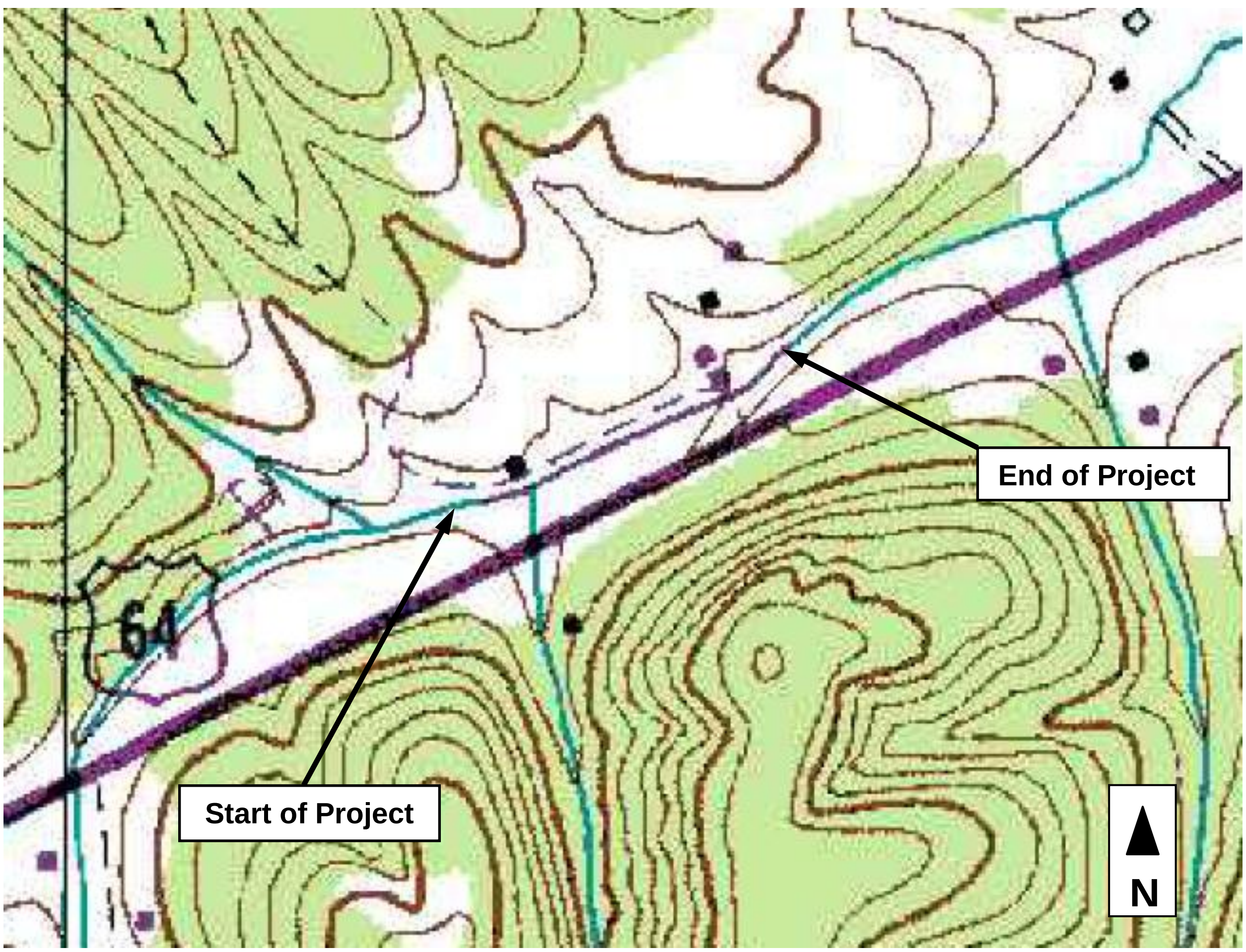


Figure 11A-3
Furnace Branch Natural Stream Design Project Reach
(Not to Scale)

GIVEN:

A proposed roadway widening project for SR-15 in Wayne County will involve widening the road from a two lanes to a four-lane cross section. It appears that this project will impact an approximately 1100-foot long reach of Furnace Branch located on the north side of the existing road. Natural stream design has been proposed for this reach of the stream to mitigate the impacts of the roadway project. While wholesale realignment of the stream will not be required, the proposed alignment of the channel may not be located any further south than the existing channel in order to avoid any potential interference with the new lanes of the widened roadway.

As indicated in Figure 11A-3, it appears that the stream may have been relocated at some time in the past to accommodate the construction of the current SR-15 alignment. This is further indicated by the fact that a portion of the channel is on a straight alignment that has been cut out of rock. Because of this, it is assumed that the project reach is not in a natural condition, and the natural stream design will be based on an evaluation of other adjacent reaches of the stream.

FIND:

Determine an appropriate natural stream design for Furnace Branch adjacent to the proposed SR-15 widening project.

Figure 11A-4
Example of Bedrock Shelf on the Stream Bed
Location: Furnace Branch, Wayne County, Tennessee (2010)

SOLUTION:

Step 1: Initial Planning

As described in Section 11.05, it is necessary to do some initial planning before attempting to conduct a natural stream design. The assessments conducted at this initial phase of the design process include determining the existing channel bed materials, channel type and establishing beginning and ending points for the proposed project.

Due to nature of the stream, it is possible to determine the existing channel type and channel bed materials based on a site visit. As shown in Figure 11A-4, the existing channel bed consists of nearly horizontal runs of bed rock followed by drops or steps in the profile. Because the banks of the stream also appear to be generally stable, it is possible to conclude that Furnace Branch is a threshold stream without any further analysis. Thus, by definition, the stream is not subject to aggradation or degradation. Due to its relatively steep slope, the stream is capable of transporting large sediments, and the wash load appears to consist of coarse gravel and pebbles which collect in the pools and other low points along the stream profile. Actual size of material in the wash load is shown in Figure 11A-5.

Figure 11A-5
Typical Sample of Wash Load
Location: Furnace Branch, Wayne County, Tennessee (2010)

Another important aspect of the initial planning is to determine the overall project length. As described in Section 11.04.6, it may be necessary to provide an extra length of erosion protection along the banks of a stream where the project reach begins or ends on a curved alignment. Details of the tie-in points provided to the designer are illustrated in Figures 11A-6 and 11A-7. As can be seen, the upstream tie-in point is on a tangent alignment and no extra length of protection will be required. Thus, the upstream tie-in point will be the beginning point for the natural stream design project. On the other hand, the downstream tie-in point is located on a horizontal curve with a radius of approximately 100 feet. The extra length of erosion protection downstream of the curved alignment should be determined based on the ratio of the radius of curvature, R_c, to the bottom width of the channel, B. The topographic data at the downstream end of the project indicates that the channel bottom width is approximately 30 feet, thus the ratio is computed as:

$$\frac{R_c}{B} = \frac{100}{30} = 3.33$$

Since the value of this ratio is greater than 3, the extra protection length is 1.5 times the bottom width of the channel, or 45 feet. Because the point of tangency for the horizontal curve is located at about station 15+60, the final end point for the project will be at station 16+05.

With these initial assessments complete, it is possible to continue with the natural stream design process.

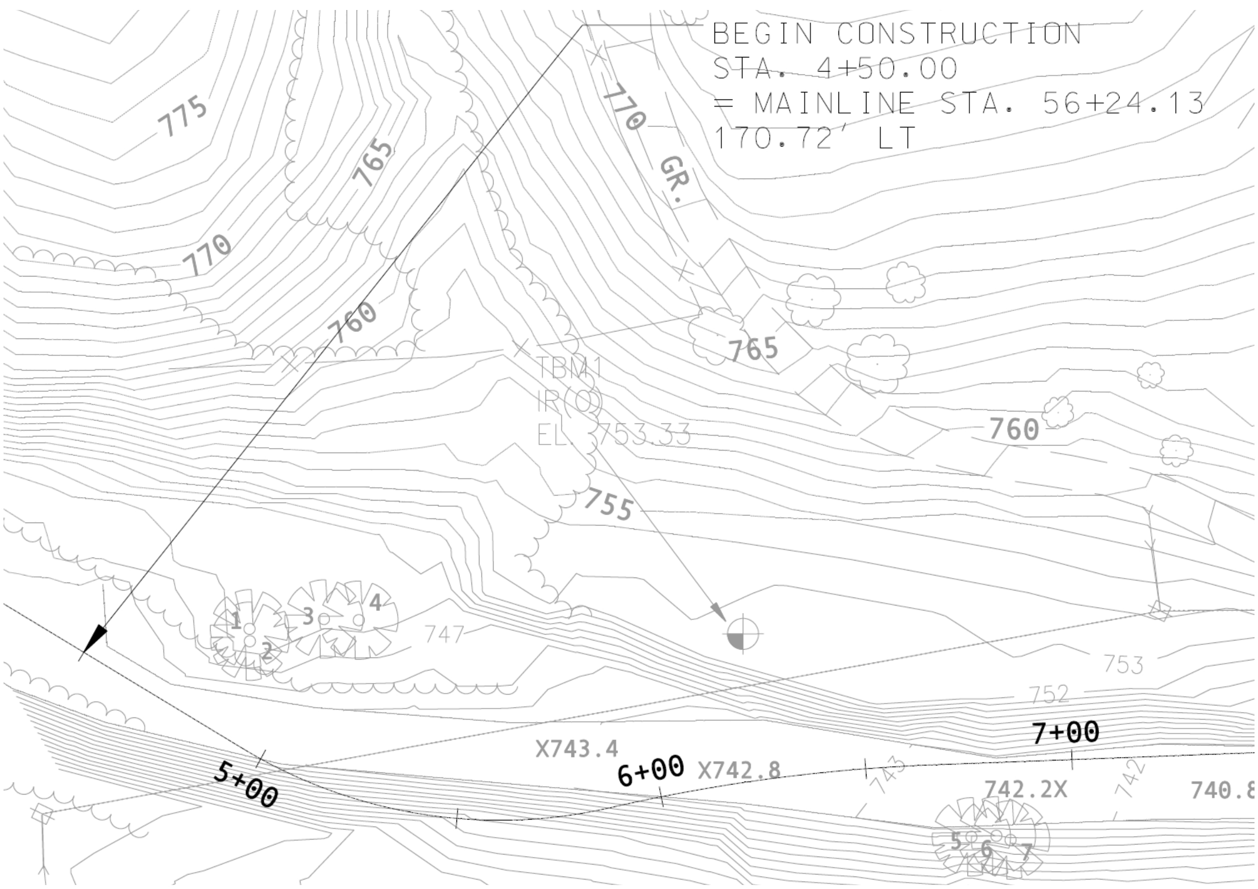


Figure 11A-6
Upstream Tie-In Point for the Natural Stream Design
(Not to Scale)

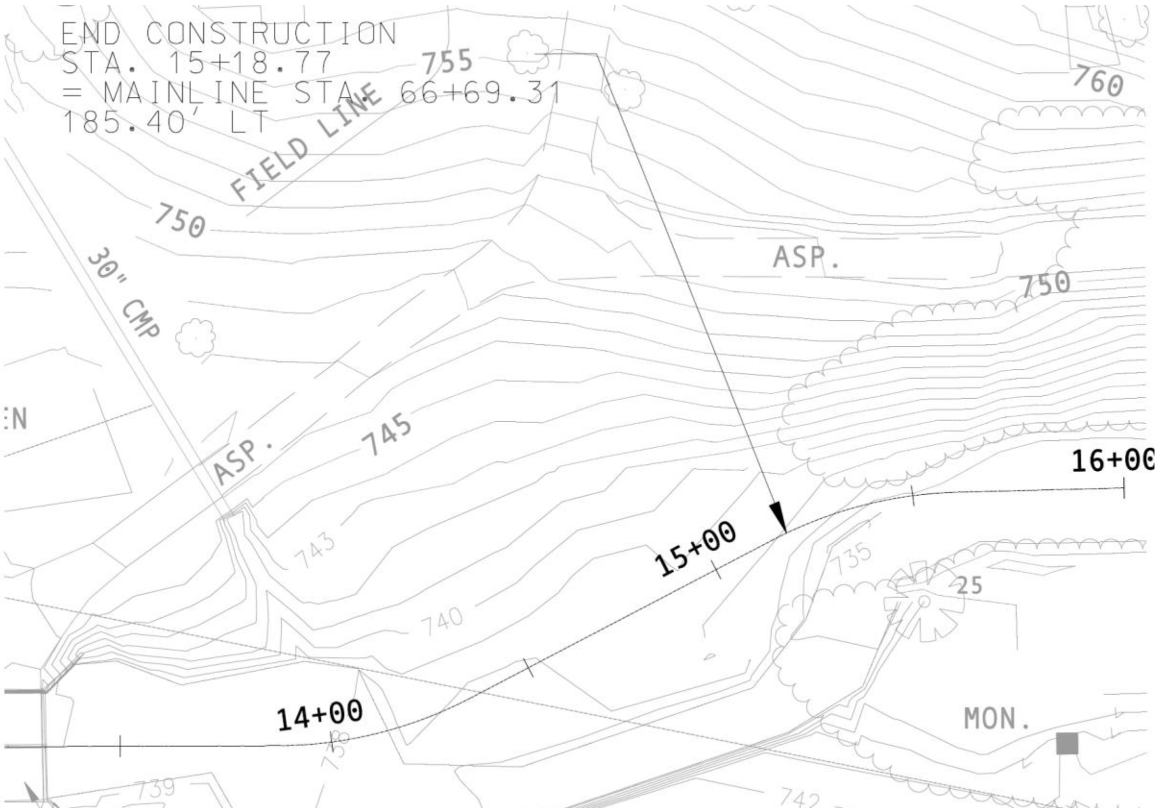


Figure 11A-7
Downstream Tie-In Point for the Natural Stream Design
(Not to Scale)

Step 2: Existing Stream Characteristics

Section 11.05 describes a number of factors which should be considered when determining the existing stream characteristics that should be recreated in the design of the proposed new channel. For a threshold stream, these factors include:

- length of the reach
- plan form, including the sinuosity ratio and the other meander characteristics
- vertical profile
- channel cross sections
- Manning's n-values for hydraulic analysis

As described above, the situation for this project is somewhat unique since the project reach appears to have been previously modified for an earlier roadway construction project. Thus, the stream characteristics to be created in the project reach will based on the assessment of nearby reaches of the stream which are assumed to still be in a natural state.

Reach Length and Sinuosity: Based on the conditions and alignment of the existing project stream reach, it appears that the length and sinuosity of the stream may have modified when it was previously relocated. Thus, the approach for this design problem will be to determine the sinuosity of a nearby representative reach and then apply this sinuosity value to calculate a length for the proposed conditions project reach length. Figure 11A-8 shows the downstream representative reach which was selected for determining the meander characteristics of the stream, along with the measured values for the valley length, L_v, and the channel length, L_{chan}. Based on the lengths measured from the map, the sinuosity of the representative reach is calculated as:

$$Sin = \frac{L_{chan}}{L_v} = \frac{3094\ ft}{2967\ ft} = 1.043$$

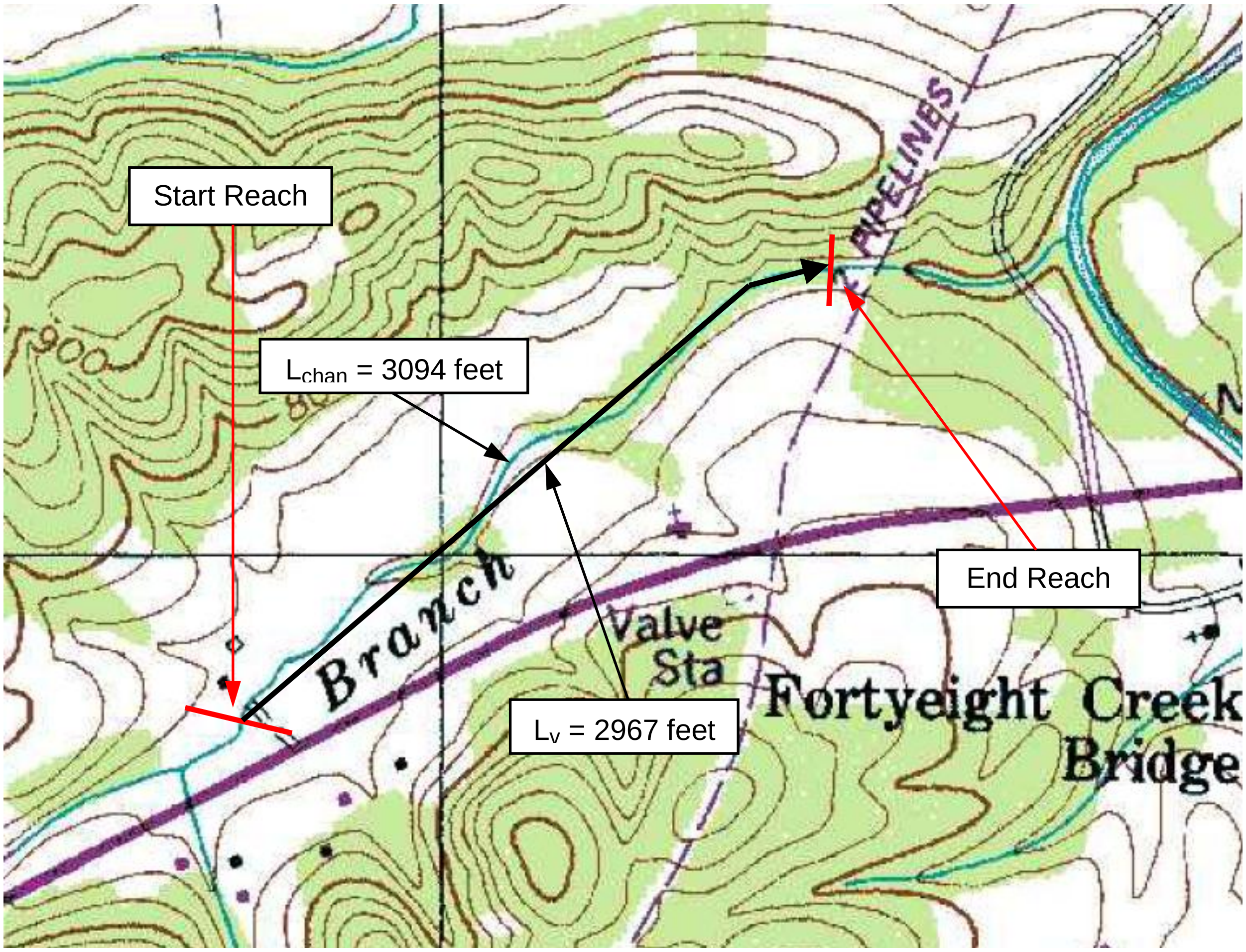


Figure 11A-8
Sinuosity Calculation on a Representative Reach
(Not to Scale)

To determine the other meander characteristics of the stream, the reach downstream of the project site was divided into nine separate curves as shown in Figure 11A-9. The arc angles, θ, for each of these curves were measured by drawing lines on the map perpendicular to the stream at the inflection points between each curve as illustrated for curves 7 and 8. In addition, the amplitude between each successive pair of curves is measured by drawing lines on the map as illustrated for curves 4 and 5. Although these measurements are based on the judgment of the designer, they should offer sufficient accuracy for the purpose of developing the proposed planform of the relocated stream. Table 11A-5 provides a summary of the results of these measurements for each of the curves on the representative reach.

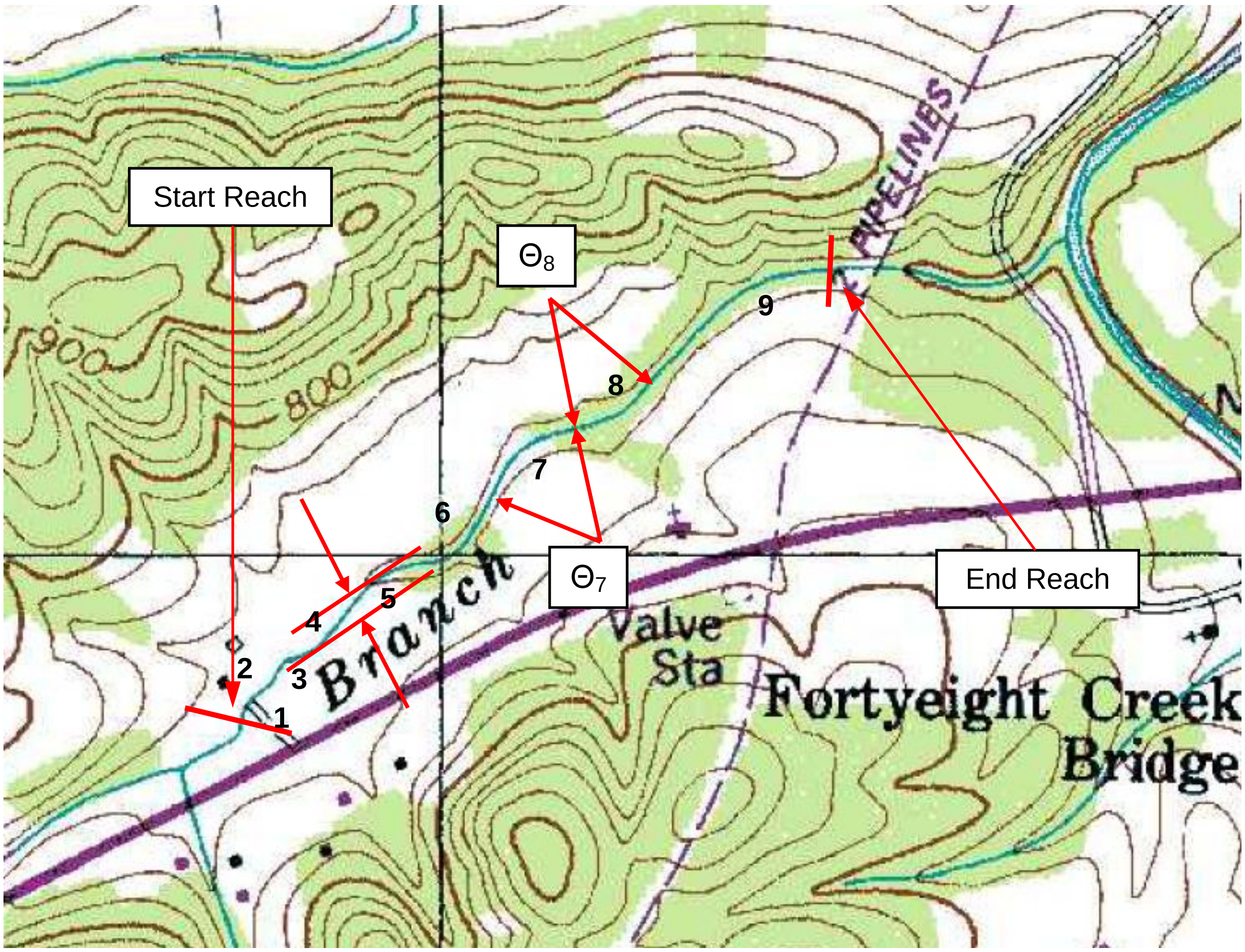


Figure 11A-9
Bends Used to Determine Furnace Branch Meander Characteristics
(Not to Scale)

Vertical Profile: Figure 11A-10 shows the flow line profile of the existing stream through the project reach based on the project survey data. The survey data seems to agree well with the visual observations of the site, in that it shows a series of horizontal shelves which end in steps or drops. Since the project site has been previously modified, it is not clear that the survey data will be a reliable indicator of the natural state of the steam. However, because detailed survey data is not available for stream reaches beyond the project reach, this data will be examined as the best available and Table 11A-6 provides a summary of the lengths and drop heights of each shelf.

Bend Number	Radius (feet)	Angle (degrees)	Arc Length (feet)	Amplitude (feet)
1	197	40.5	153	
2	191	30.0	97	
3	86	64.2	83	48
4	168	44.9	292	51
5	478	40.6	319	60
6	269	53.5	375	111
7	328	50.5	438	143
8	562	33.7	510	131
9	741	44.8	632	71
Average	336	44.7	322	88
Maximum	741	64.2	632	143
Minimum	86	30.0	83	48

Table 11A-5
Meander Characteristics Measured for the Representative Reach

	Shelf Lengths (feet)	Drop Heights (feet)
	46	1.00
	116	0.56
	87	0.25
	134	0.81
	56	0.11
	101	0.46
	23	0.45
	29	0.58
Average	74	0.53
Maximum	134	1.00
Minimum	23	0.11

Table 11A-6
Shelf Lengths and Drop Heights for the Existing Conditions Study Reach

Another important aspect of evaluating the existing vertical profile is to determine the slope of the existing stream bed. As described in Section 11.03, there are at least two different scales at which the slope should be determined. The first is a larger, more general scale which may be used to determine an overall valley slope for hydraulic analysis. To determine the slope at this scale, it usually sufficient for the designer to utilize the relevant USGS topographic quadrangle map to measure the distances between successive contour lines where they cross the stream channel. Table 11A-7 shows the distances measured between contours both upstream and downstream of the project reach.

Elevation Contour (feet)	Distance (feet)	Slope (ft/ft)	Comment
790			
	2189	0.00456	
780			
	1773	0.00564	Project reach
770			
	1938	0.00516	Project reach
760			
	2458	0.00407	
750			

Table 11A-7
Distances and Average Slope between Quadrangle Map Elevation Contours

It should be noted that the slope of the valley through the project reach is steeper than the slope of the valley upstream or downstream of the project site. It is not clear whether this increased slope is a result of the previous relocation of the channel or is the result of a natural variation in the stream slope.

The second scale at which the stream slope should be measured involves determining the local slope through the project reach. However, this determination is made somewhat more complicated by a 3.5 to 4-foot drop in the existing stream profile at the downstream end of the project reach (see Figure 11A-11). This is apparently not a natural feature, and may be the result of previous modifications of the channel alignment in the project area. The effect of this drop-off will be neglected in the determination of the local slope. Thus, based on the stream bottom profile presented in Figure 11A-10, the local slope of the channel is equal to approximately 0.0055 ft/ft. This appears to match well with the overall stream slope determined from the USGS topographic quadrangle map.

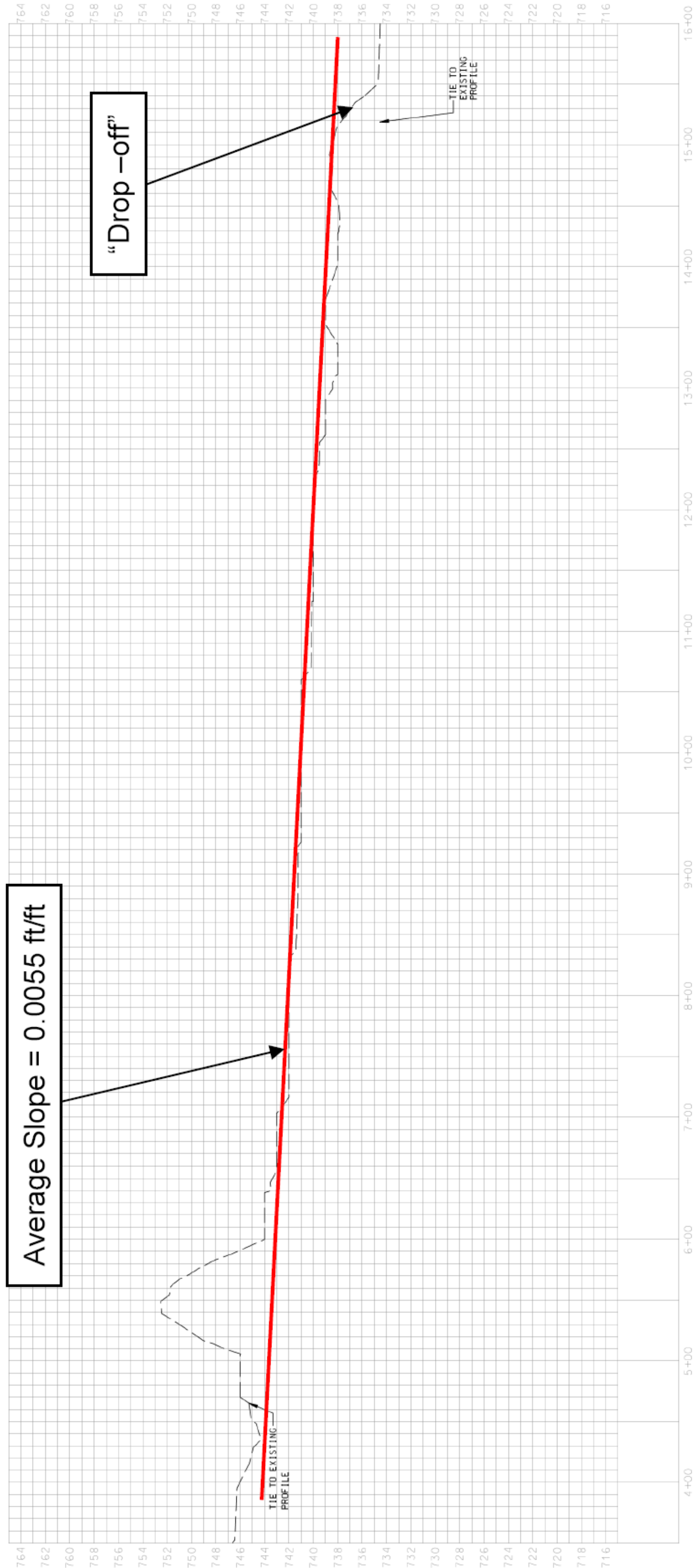


Figure 11A-10
Existing Streambed Profile with Average Slope and “Drop-Off” Noted

Figure 11A-11
Drop Off at the Downstream End of the Project Reach
Location: Furnace Branch, Wayne County, Tennessee (2010)

Stream Cross Sections: Because the project survey focused on the project reach which has already been previously modified, there is only a limited amount of detailed information available to describe the natural cross section of the existing stream. Based on survey data and a few measurements taken during a site visit, it appears that the existing natural cross section has the following general dimensions:

- bottom widths of approximately 20 at the upstream end of the project, and approximately 30 feet at the downstream end of the project
- where pools occur, the bottoms range from 0.75 to 1.5 feet below the normal water surface
- the tops of the low flow channel range from 1.5 to 2.0 feet above the normal water surface
- above the low flow channel, one side of the valley will continue up at an approximately 3H:1V slope, while the other side will provide a narrow flat overbank ranging from a few feet to roughly 30 feet wide

A typical natural stream cross section is illustrated in Figure 11A-12.

Step 3: Hydraulic Analysis of Existing Stream

Once the characteristics of the existing stream have been determined, it is possible to conduct the hydraulic analysis of the existing stream reach. Because Furnace Branch is a threshold stream, the hydraulic analysis will include the 50-year and 100-year peak flood discharges and will provide the base information needed to evaluate the hydraulic analysis of the proposed stream as the design progresses. This analysis may also provide insights on the existing erosion problems along the stream.

Figure 11A-12
Photograph Illustrating a Typical Natural Stream Cross Section
Location: Furnace Branch, Wayne County, Tennessee (2010)

Determine the Input Data for the Hydraulic Analysis: Flood discharges for the hydraulic analysis are determined using the on-line *StreamStats* application provided by the USGS. As shown in Figure 11A-13, the drainage area is delineated by choosing a point near the downstream limit of the project. Based on the results provided by *StreamStats*, the drainage area at the project site is 2.75 mi^2, and the 50-year and 100-year peak flood discharges are 1490 cfs and 1720 cfs, respectively.

The hydraulic roughness of the existing channel is evaluated using the Cowan method, as described in Section 11.03.4. The individual parameters for the Cowan method are determined as shown in Table 11A-8 and the resulting channel n-value is calculated as:

$$n=(n_0+n_1+n_2+n_3+n_4)m_5=(0.025+0.010+0.005+0.005+0.010)1.00=0.055$$

Based on an evaluation of field conditions, an n-value of 0.075 was selected for the overbank areas (See Chapter 5 Appendix).

Another important input to the hydraulic model is the valley slope which will be used to determine the starting condition for the hydraulic analysis. Based on the slopes determined in Table 11A-7, the starting slope is set at 0.0041 ft/ft.

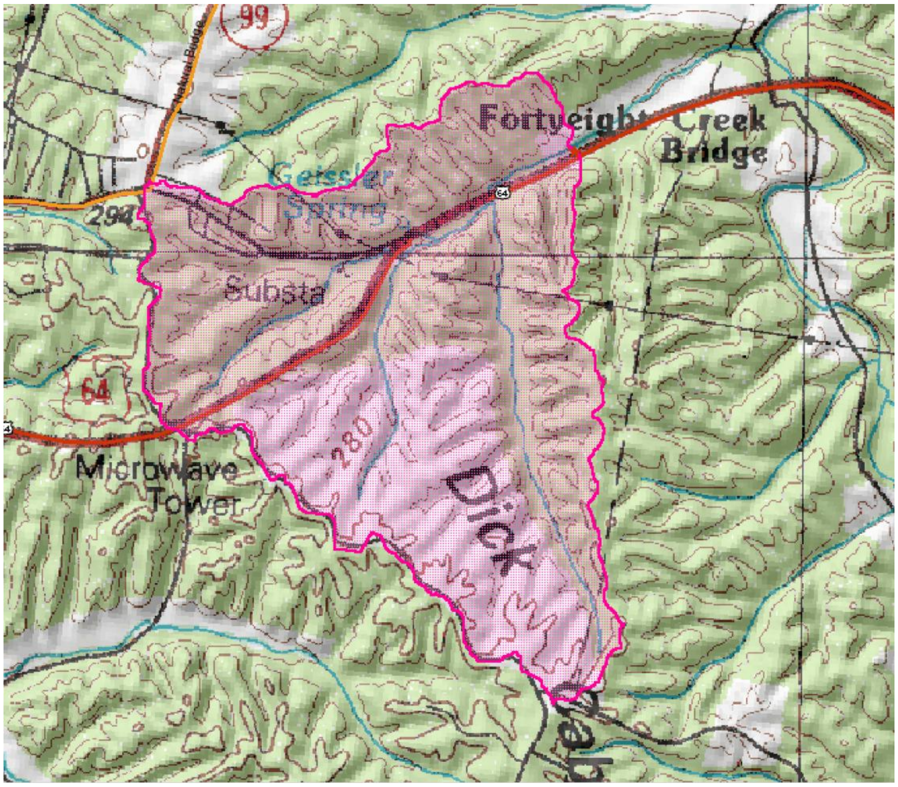


Figure 11A-13
Drainage Area of Furnace Branch as Delineated by *StreamStats*

Variable	Criteria	Value
Base value, n_0	Rock cut / fine gravel	0.025
Irregularity, n_1	Moderate (natural stream)	+0.010
Variation, n_2	Occasional (rock shelves)	+0.005
Obstructions, n_3	Minor / negligible	+0.005
Vegetation, n_4	Medium, moderate brush	+0.010
Sinuosity, m_5	Minor (< 1.2)	1.00

Table 11A-8
Parameter Values for Cowan's Method

Cross sectional data for the hydraulic model were extracted from the project survey data at several locations along the project reach. Once the data for each of the cross sections are placed into the model, the top of the channel banks are determined based on the configuration of the cross section as well as the top of channel bank heights observed during the field visit. Figures 11A-14a and 11A-14b provide examples of the cross sectional data used in the model.

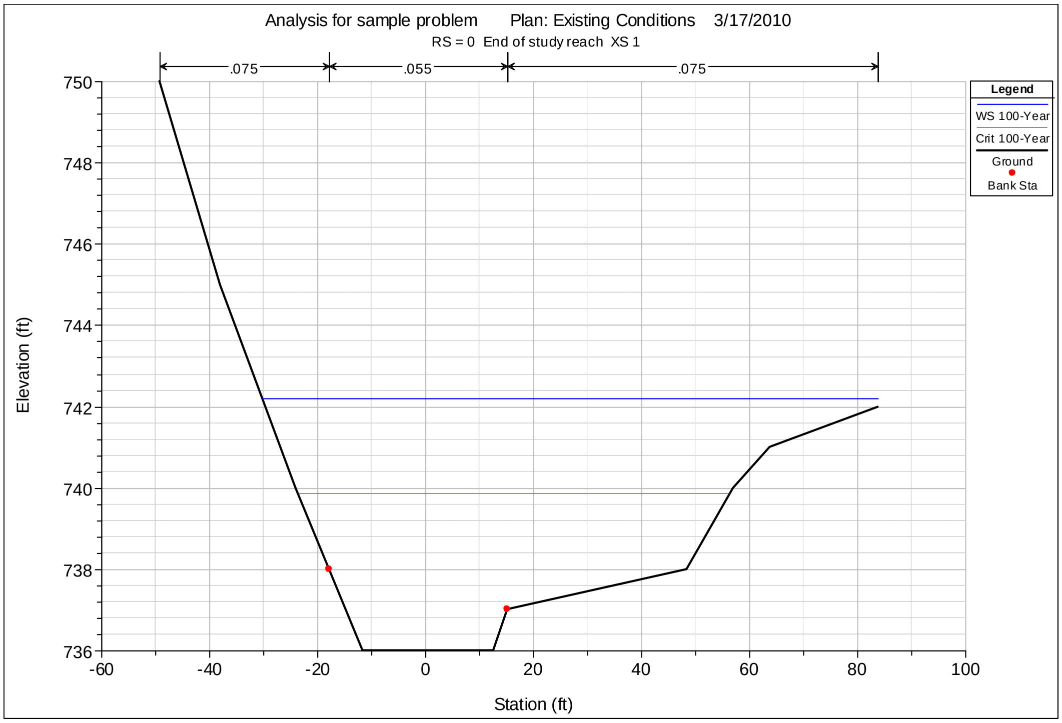


Figure 11A-14a
Cross Section at Downstream Limit of Study Reach

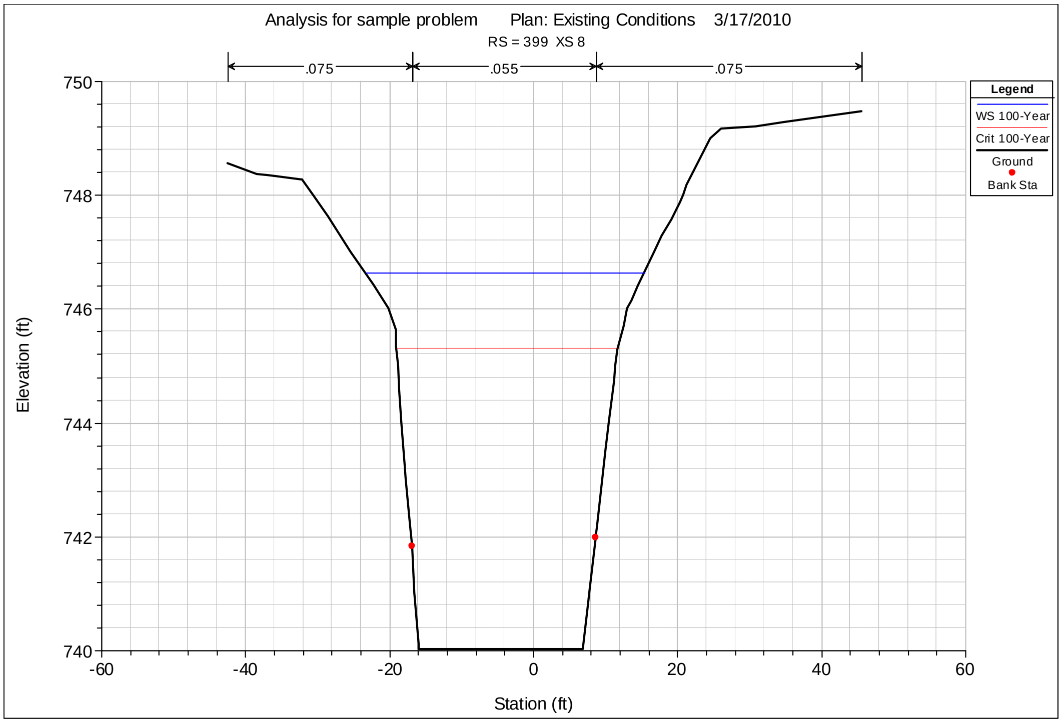


Figure 11A-14b
Typical Cross Section through the Existing Rock Cut

Results of the Hydraulic Analysis: The input data for the hydraulic analysis is placed into the computer program HEC-RAS to calculate water surface profiles for the 50 and 100-year events, and the resulting profiles are shown in Figure 11A-15. Although the existing culvert crossing creates a significant increase in the water surface elevation, this effect is quickly attenuated due to the comparatively steep slope of the stream.

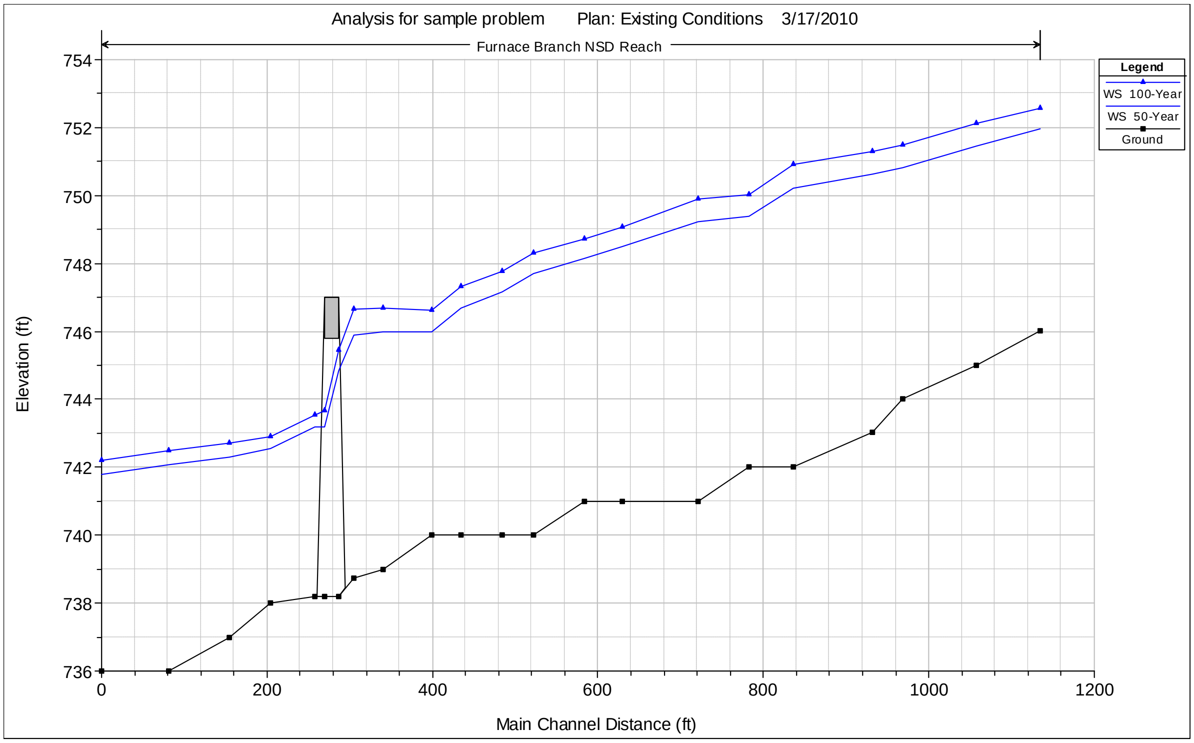


Figure 11A-15
50 and 100-Year Profile for the Existing Conditions

Figure 11A-16 shows a perspective plot of the stream for the 100-year profile. Although this plot does not reflect the curved planform of the stream, it does illustrate the relative size, shape, and spacing of the cross sections used in the existing conditions analysis. In general, the first two cross sections at the upstream end of the model and the last two cross sections at the downstream end reflect natural conditions while the cross sections in between reflect the modification to the channel which may have occurred as the result of a prior roadway construction project.

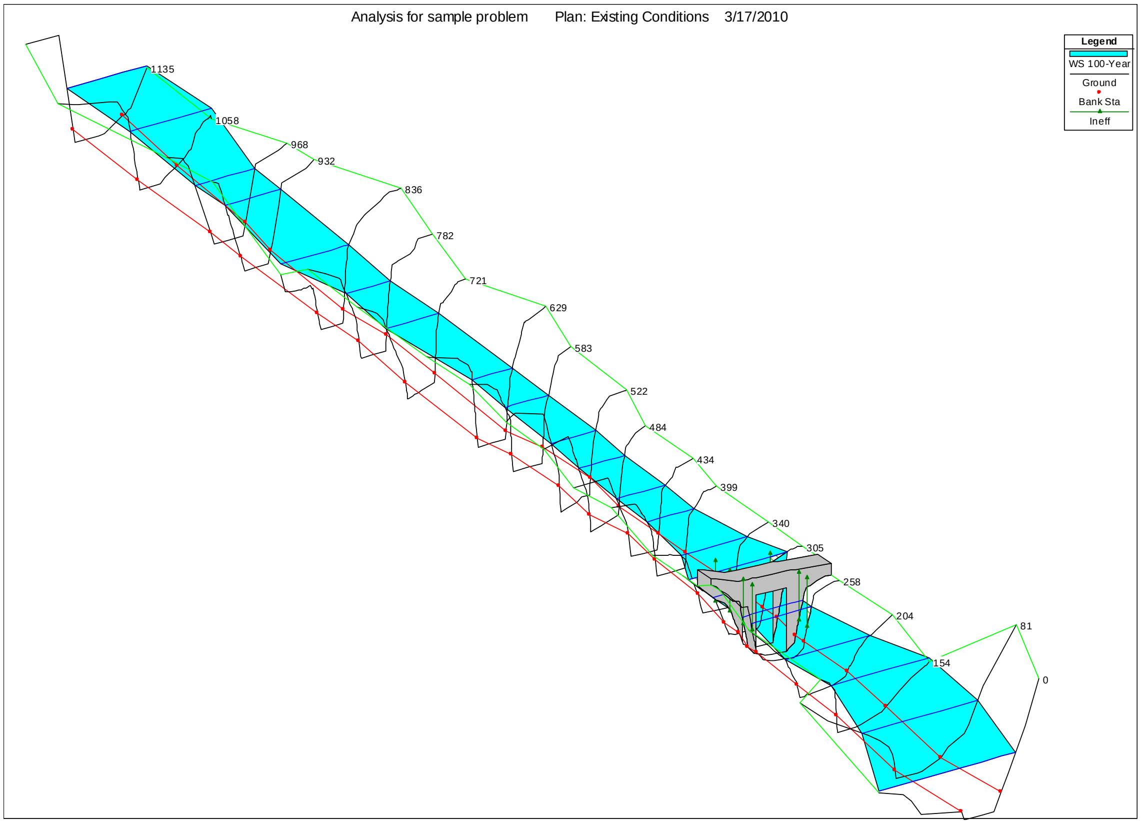


Figure 11A-16
Perspective Plot of the Existing 100-Year Flood Profile

Examination of the existing conditions along the stream indicate that the right (south) bank of the channel is subject to erosion from stream station 4+50 to station 6+00, and from station 14+00 to station 15+50. Some of this bank instability can be seen in Figure 11A-11. The results of the hydraulic analysis may be examined to better understand the causes of this bank instability. Since the design storm frequency for threshold channels is the 50-year event, the results from that run of the hydraulic model are chosen for this analysis. The hydraulic analysis indicates that the flow velocity in the channel for the 50-year event will range from 5.38 to 8.80 ft/sec and that shear stresses in the channel will range from 1.39 to 4.61 lb/ft^2.

However, it is noted that the highest velocity and shear values occur within the portion of the project reach that is currently in a rock cut and thus, very little erosion is taking place in these areas. At the upstream end of the project reach (stations 4+50 through 6+00), the channel flow velocity and shear stress are relatively moderate, ranging from 5.5 to 6.5 ft/sec and from 1.6 to 2.3 lb/ft^2, respectively. It appears that the bank instability in this area is primarily due to the loose, un-compacted nature of the soils, the relatively steep slope of the bank and the increased shear stress that would occur on the outside of a bend. All of these factors are present, as well where the bank is failing at the downstream end of the project. However, in this case, the instability of the bank may be exacerbated by the high flow velocities (up to 12.3 ft/sec) which occur at the outfall of the existing box culvert. The results of the hydraulic analysis are summarized in Table 11A-9.

Stream Station	Q (cfs)	Channel Bottom Elev. (ft)	Water Surface Elev. (ft)	Energy Grade Line Elev. (ft)	Channel Velocity (ft/sec)	Flow Area (ft^2)	Channel Shear (lb/ft^2)
1135	1490.00	746.01	751.96	752.43	5.76	293.22	1.60
1058	1490.00	745.00	751.46	752.04	6.47	281.28	1.98
968	1490.00	744.00	750.82	751.53	7.04	242.82	2.27
932	1490.00	743.02	750.63	751.34	7.08	247.54	2.22
836	1490.00	742.00	750.20	750.86	7.07	274.50	2.19
782	1490.00	742.00	749.39	750.49	8.59	192.08	3.36
721	1490.00	741.00	749.24	750.00	7.22	235.44	2.31
629	1490.00	741.00	748.48	749.45	8.03	203.13	2.87
583	1490.00	741.00	748.14	749.13	8.03	195.40	2.96
522	1490.00	740.01	747.71	748.67	7.95	199.58	2.94
484	1490.00	740.00	747.17	748.33	8.80	185.63	3.61
434	1490.00	740.00	746.69	747.85	8.77	184.91	3.64
399	1490.00	740.01	745.98	747.42	9.74	162.73	4.61
340	1490.00	739.00	745.98	746.70	6.97	234.18	2.26
305	1490.00	738.72	745.90	746.45	6.14	268.28	1.71
282	Box Culvert						
258	1490.00	738.19	743.20	744.17	7.99	194.10	3.31
204	1490.00	738.00	742.56	743.47	7.88	210.09	3.32
154	1490.00	737.00	742.30	742.90	6.53	270.19	2.17
81	1490.00	736.00	742.08	742.46	5.39	349.32	1.39
0	1490.00	736.00	741.79	742.12	5.38	387.18	1.41

Table 11A-9
Results of Existing Conditions Hydraulic Analysis

Step 4: Determine Proposed Natural Stream Design

At this point in the process, it is possible to begin to develop the actual natural stream design for the proposed channel. This particular design problem is complicated by the fact that a portion of the existing stream is contained within a rock cut. Thus, significant changes to the horizontal and vertical profiles of the stream would require large amounts of rock excavation and possibly the placement of backfill in an existing rock cut area. This would not only significantly increase the cost of the project, but could also create slope stability problems at the interface between the existing rock face and proposed soil backfill. Because of these issues, it may be necessary for the actual proposed design to deviate somewhat from an ideal design in order to accommodate some of these concerns. Since the purpose of this sample problem is to illustrate the natural stream design process for a threshold channel, the proposed design will be initially developed as if these concerns do not exist. Where necessary, the reasoning for deviating from this ideal design will be explained.

Determine Proposed Stream Length: In the proposed condition, the project reach should ideally have sinuosity equal to 1.043, which is what was computed for the representative reach downstream of the project. In the pre-project condition, the project reach has a channel length of 1067 feet between the project tie-in points, and an overall valley length of 1051 feet, which yields a sinuosity of 1.015. To achieve the desired value of sinuosity, it will be necessary to add curves to the proposed channel alignment in order to increase its length and the total desired length is calculated as:

$$L_{Chan(\Pr oposed)} = L_v \times Sin = 1051 \times 1.043 = 1096 \text{ feet}$$

Determine Proposed Channel Planform: Ideally, the objective for determining the proposed channel alignment for the stream will be to extend the length of the channel to the distance computed in the previous step by introducing meanders that will match the average, minimum and maximum meander parameters provided in Table 11A-5. In addition, these meanders should be located on the north side of the current alignment as much as possible to minimize interference with the proposed roadway project.

The first step in achieving this objective is to examine the suitability of the current tie-in points. To simplify the process of matching the proposed channel with the existing channel, it is decided to adjust the tie-in points so that the transitions between the proposed and existing channels will be located on a tangent section rather than in the middle of an existing bend. Based on an examination of the project survey and site photographs, it appears that the upstream tie-in point is already located on a tangent alignment (see Figure 11A-6). Thus, no adjustment is needed, and the upstream tie-in point will remain at station 4+50. However, the initial tie-in point at the downstream end is located on a curved section of the channel (see Figure 11A-7). Thus, this tie-in point is moved downstream about 41.7 feet to station 15+60.5. Because of this adjustment, the total desired length for the proposed channel reach is increased to 1138 feet.

To properly align the proposed channel with the existing channel, it is necessary for the designer to determine the bearing of the existing channel at the adjusted tie-in points. For the purpose of this example problem, the flow direction at these points will be based on a compass bearing, with zero degrees equal to due north, 90° equal to east, 180° equal to south, and 270° equal to west. Based on an examination of the survey data, the flow at the upstream tie-in point is determined to be on a compass bearing of 121.11°, while a compass bearing of 88.54° is measured for the flow at the adjusted downstream tie-in point.

Based on judgment, it decided that the proposed channel alignment should consist of six horizontal curves, with a short tangent reach to accommodate the box culvert. Working from the upstream end of the project reach towards the downstream end, the procedure for locating the proposed horizontal curves is as follows:

- Assume a radius of curvature (Rc1) for the first curve. Beginning at the upstream tie-in point, extend a line equal to Rc1 and perpendicular to the flow direction in order to determine the center of the circle on which the curve would lie.
- Assume a deflection angle (θ1) for the first curve. Based on the center point of the circle determined in the previous step, lay out a circular arc from the upstream tie-in point to the point defined by the values assumed for Rc1 and θ1. Note the location and compass bearing of the flow at the downstream end of the arc.
- Assume a radius of curvature (Rc2) and deflection angle (θ2) for the second arc. Working from the downstream end of the first arc, create the second arc by finding the center of the second circle and laying out a circular arc with an internal angle of θ2.
- Continue the steps above in the downstream direction until the last curve is reached.
- The internal angle for the final curve will not be assumed. Rather it is calculated by subtracting the bearing at the end of the previous curve from the bearing of the channel at the downstream tie-in point. This will allow the flow in the proposed channel to be aligned with the existing channel at the downstream end of the project reach.

To determine the proposed channel alignment, the radius of curvature and internal angle for each curve are varied by trial and error until the downstream end of the proposed channel alignment connects to the existing channel in both location and alignment.

Following the procedure described above, the curve data for this proposed alignment are shown in Table 11A-10, along with the corresponding values measured for the representative stream reach as shown in Table 11A-5.

Curve #	**Radius (feet)**	**Start Bearing (degrees)**	**End Bearing (degrees)**	**Internal Angle (degrees)**	**Length (feet)**
1	270	121.11	59.11	62.0	292.2
2	150	59.11	112.11	53.0	138.8
3	560	112.11	76.11	36.0	351.9
4	170	76.11	102.11	26.0	77.1
tangent					60.0
5	153	102.11	51.11	51.0	136.2
6	108.43	51.11	88.54	37.43	70.8
Total					1126.9 *(1138)*
Average	235 *(336)*			44.2 *(44.7)*	178 *(322)*
Maximum	560 *(741)*			62.0 *(64.2)*	352 *(632)*
Minimum	108 *(86)*			26.0 *(30.0)*	71 *(83)*

Table 11A-10
Meander Characteristics for the "Ideal" Proposed Channel Alignment
(Target values based on the downstream representative reach are shown in parentheses)

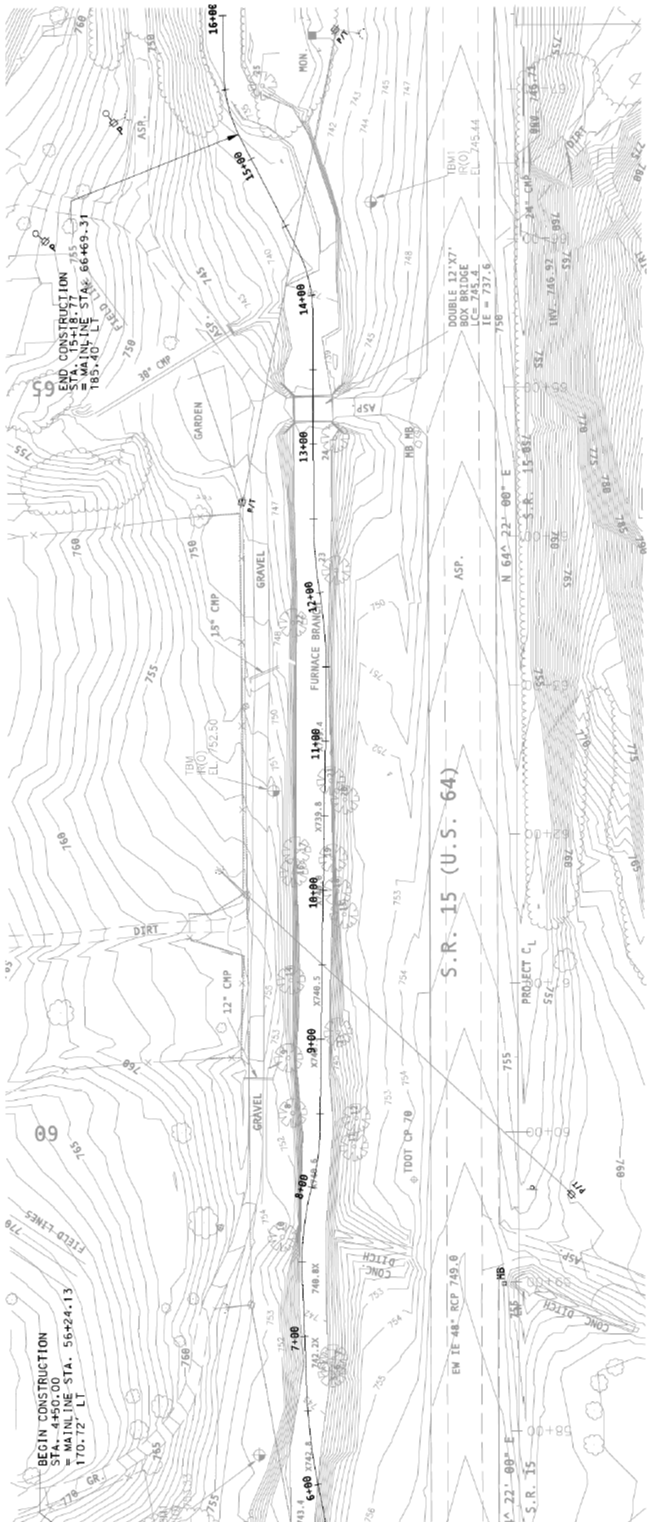


Figure 11A-17
"Practical" Alignment for Proposed Channel

As can be seen in Table 11A-10, the meander characteristics of the proposed channel do not match well with the characteristics of the representative reach. In particular, the average radius of curvature is 235 feet, which is much less than the desired value of 336 feet. However, using longer radii of curvature would tend to result in a straighter alignment and thus a shorter reach length. Since the proposed reach length of 1127 feet is already less than the desired length of 1138 feet, it is judged that the shorter radii of curvature represent an acceptable compromise between the two competing goals. The shorter reach length also results in a proposed sinuosity value of 1.032, which is less than the desired value of 1.043.

It appears that the ideal proposed channel alignment would require a considerable amount of new rock excavation as well as backfill in areas of existing rock cut. After careful evaluation, it is decided to modify the ideal alignment to the channel centerline. Not only will this result in a more efficient design, but it will also help to prevent future maintenance issues. In addition, it will allow the re-use of the existing box culvert, which based on field inspection, appears to be in good condition. Thus, the actual alignment will be as shown in Figure 11A-17.

Determine Proposed Vertical Profile: The vertical profile of the proposed stream channel will be established based on a number of criteria, including:

- Matching the existing pattern of bedrock shelves and drops-off that are evident in the natural sections of the stream. This will require setting up a vertical profile that reflects the average, maximum and minimum values for shelf length and drop height shown in Table 11A-6
- Recreating the pools that were observed in the field check (but did not appear in the survey)
- Maintaining the flow line of the existing box culvert crossing
- Minimizing rock excavation

As illustrated in Figure 11A-10, the general slope of existing stream appears to be about 0.0055 ft/ft. However, there is also a large drop off of 3 to 4 feet at the downstream end of the project reach (see Figure 11A-11). Because it seems unlikely that this drop-off is a natural feature, the proposed vertical profile will be set up to follow a slope of 0.0055 ft/ft with the large drop off distributed into a series of smaller drops throughout the project reach.

The establishment of the vertical profile is accomplished in two steps. First, a base profile consisting of a series of horizontal shelves and drops is established. This base profile is set up to reflect the average shelf lengths and drop heights measured in the project survey. The second step is to add pools to each of the steps, based on the depths and length of the pools observed in the natural stream during the field check. The pools observed in the field ranged from 9 to 18 inches deep below normal water. In adding pools to the profile, the pool depths were varied within this range, and the lengths of the pools were assumed to be between 35% and 45% of the length of each shelf. The resulting profile is shown in Figure 11A-18, and Table 11A-11 provides a listing of the data used to describe the proposed vertical profile.

Station	Elevation (feet)	Shelf Length (feet)	Step Height[1] (feet)	Pool Depth[2] (feet)	Total Drop (feet)	Pool Length (feet)	Comments
4+50.	745.0	90					Start of project
5+40.	745.0		0.6	1.1	1.7		
5+40.	743.3	90				40	Begin pool
5+80.	743.3						
5+85.1	744.4						End pool
6+30.	744.4		0.4		0.4		Rock vane required
6+30.	744.0	8					
6+38.	744.0		1.0		1.0		
6+38.	743.0	72					
7+10.	743.0		0.4	0.4	0.8		
7+10.	742.2	90				40	Begin pool
7+50.	742.2						
7+52.4	742.6						End pool
8+00.	742.6		0.6	0.6	1.2		Rock vane required
8+00.	741.4	33				12	Begin pool
8+12.	741.4						
8+15.6	742.0						
8+33.	742.0		0.7	0.6	1.3		
8+33.	740.7	91				40	Begin pool
8+73.	740.7						
8+76.9	741.3						End pool
9+24.	741.3		0.9	0.8	1.7		
9+24.	739.6	136				50	Begin pool
9+74.	739.6						
9+79.1	740.4						
10+60.	740.4		0.6	0.6	1.2		
10+60.	739.2	63				25	Begin pool
10+85.	739.2						
10+88.6	739.8						End pool
11+23.	739.8		0.5	0.5	1.0		
11+23.	738.8	88				40	Begin pool
11+63.	738.8						
11+66.	739.3						End pool
12+11.	739.3		0.8	0.7	1.5		
12+11.	737.8	88				40	Begin pool
12+51.	737.8						
12+55.5	738.5						End pool
12+99.	738.5		0.5		0.5		
12+99.	738.0	51					
13+12.	738.0						Box culvert

Station	Elevation (feet)	Shelf Length (feet)	Step Height[1] (feet)	Pool Depth[2] (feet)	Total Drop (feet)	Pool Length (feet)	Comments
13+30.	738.0						Box culvert
13+50.	738.0		1.0	0.9	1.9		
13+50.	736.1	61				28	Begin pool
13+78.	736.1						
13+83.7	737.0						End pool
14+11.	737.0		1.0	0.9	1.9		
14+11.	735.1	39				18	Begin pool
14+29.	735.1						
14+34.7	736.0						End pool
14+50.	736.0		0.5		0.5		
14+50.	735.5	51					
15+01.	735.5		0.3		0.3		
15+01.	735.2	25					
15+26.	735.2		0.63		0.63		
15+26.	734.57	34.5					
15+60.5	734.57						End of project
	Average	65	0.7				
	Maximum	136	1				
	Minimum	8	0.3				

Table 11A-11
Data for Proposed Vertical Profile of Stream

[1] Drop Height is the height of the drop that necessary to reach the level of the next downstream shelf
[2] Pool Depth is an additional depth below the shelf level to create a pool in the profile.

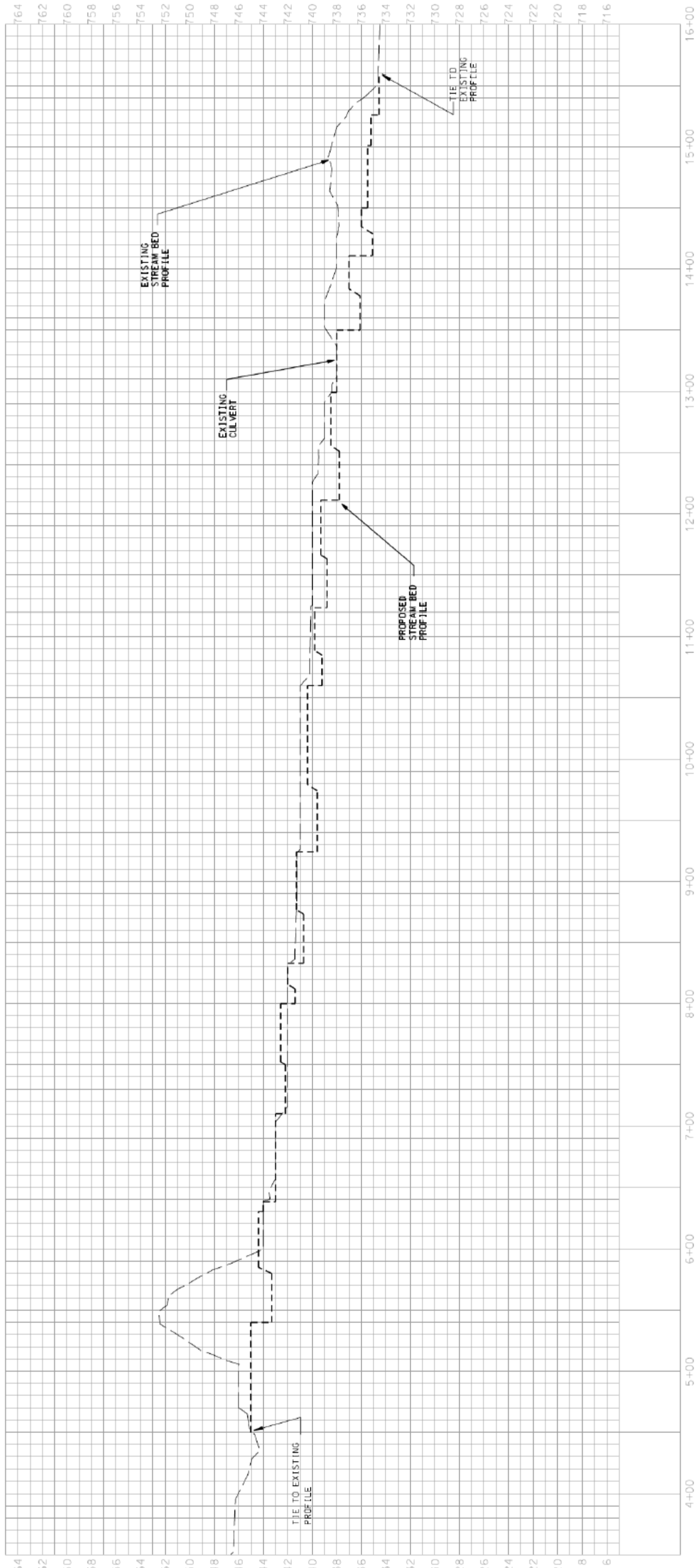


Figure 11A-18
Proposed Vertical Channel Profile

Determine Proposed Stream Cross Sections: Typically, the two main objectives for determining the proposed channel cross sections are providing sufficient hydraulic capacity and ensuring that the proposed channel will remain stable for the design discharge. For an alluvial stream, ensuring the stability of the proposed channel involves finding the channel forming discharge, evaluating sediment transport and developing stability curves. However, since this stream is a threshold stream, ensuring channel stability will only require that the selected channel lining materials will resist erosion during the design discharge flood event. The actual configuration of the proposed channel cross section will reflect the natural channel configuration of the stream.

As described in the previous sections, the natural stream has a channel bottom width ranging from 20 to 30 feet, a low-flow channel 1.5 to 2 feet deep, and a narrow flat overbank. As illustrated in Figures 11A-19a through 11A-19d, this pattern is reproduced to the extent allowed by the site conditions. In particular, where the overbank is located on the right side of the stream, its width has been limited to avoid interfering with the proposed roadway project. Once the proposed channel cross sections have been evaluated with the proposed conditions hydraulic analysis, the stability of the proposed channel will be ensured by specifying appropriate stream mitigation measures.

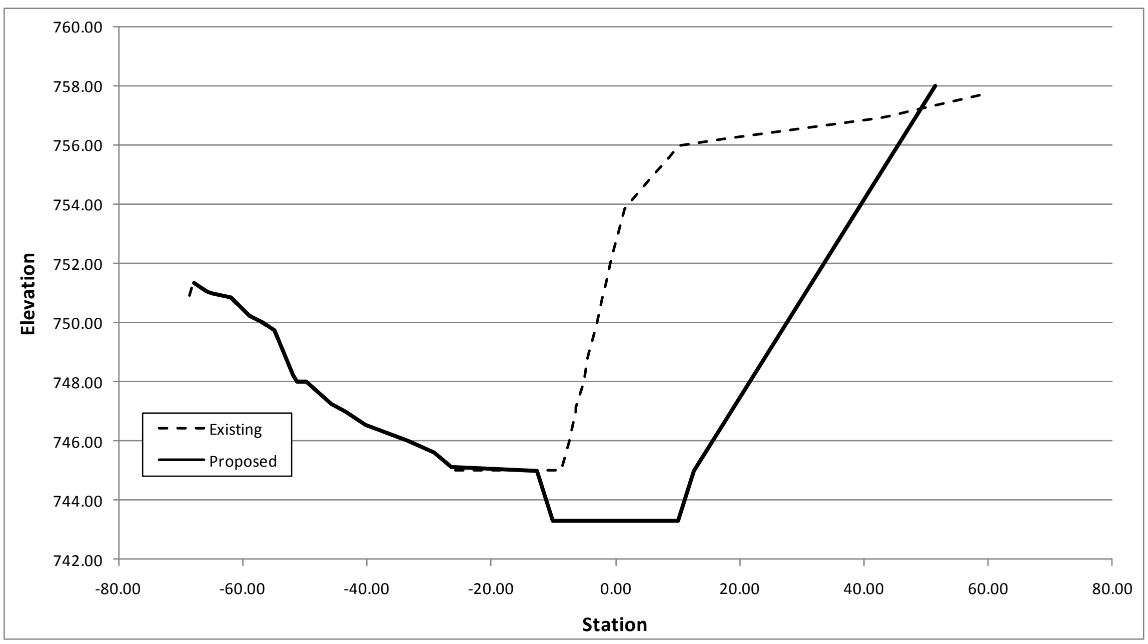


Figure 11A-19a
Existing and Proposed Cross Sections, Station 5+42

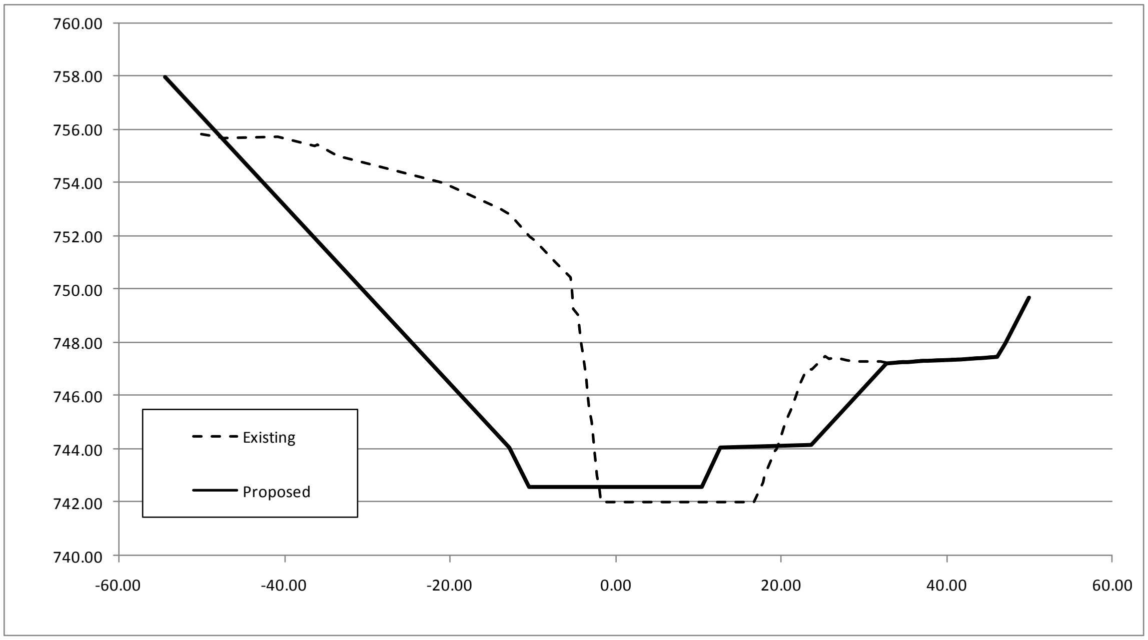


Figure 11A-19b
Existing and Proposed Cross Sections, Station 7+64

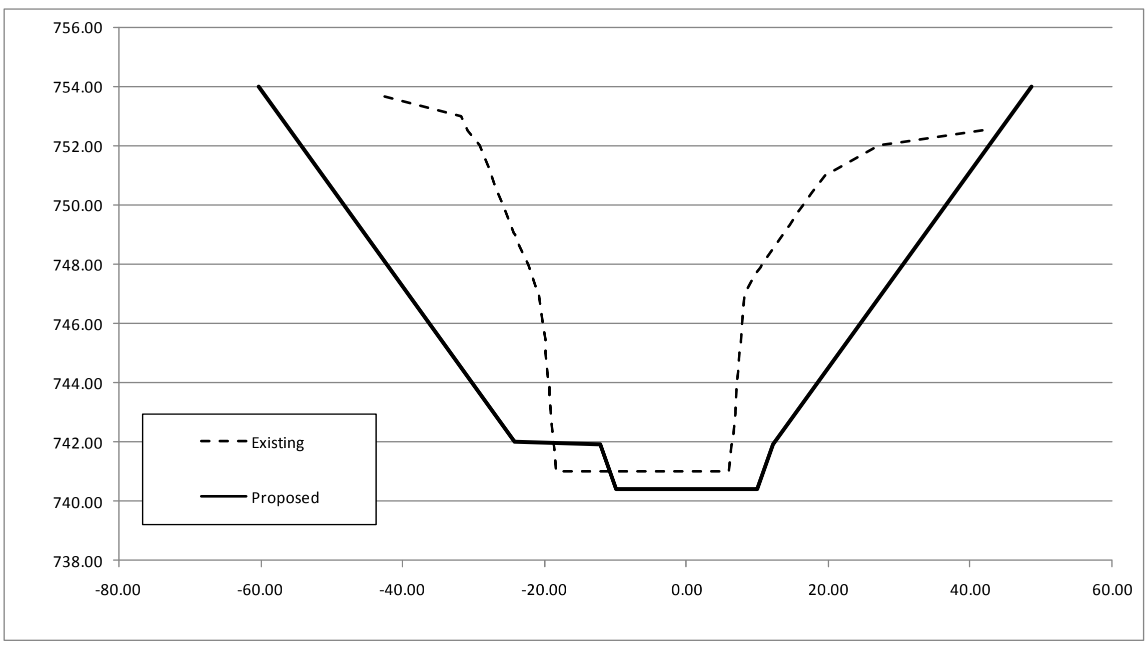


Figure 11A-19c
Existing and Proposed Cross Sections, Station 10+17

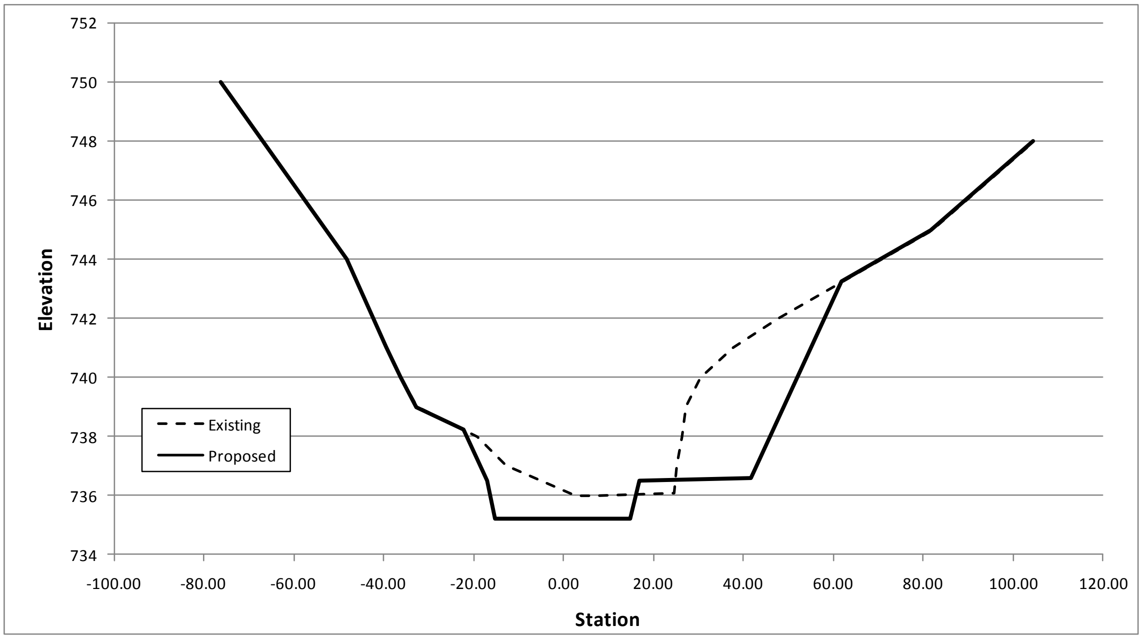


Figure 11A-19d
Existing and Proposed Cross Sections, Station 15+19

Step 5: Proposed Conditions Hydraulic Analysis

Once the proposed channel profile and cross sections have been determined, data representing the proposed natural stream design are used to create a proposed conditions plan in HEC-RAS. Like the existing conditions analysis, the proposed conditions model will be run for both the 50 and the 100-year events. The results of the 50-year analysis will be used to evaluate flow velocities and shear values for the design of the proposed stream mitigation measures. The results of the 100-year analysis will be compared to the existing conditions 100-year profile to ensure that flood elevations will not be increased in the proposed design.

Figure 11A-20 shows the 100-year profiles computed by HEC-RAS for the existing and proposed conditions analyses. For most of the project reach, the proposed conditions 100-year profile will be significantly lower than the existing 100-year profile, due to the fact that the proposed conditions cross sections are generally significantly larger than the existing conditions cross sections. The exception to this is the area just upstream of the box culvert. The 100-year flood elevations in this area apparently are determined mostly by the pressure flow condition which occurs at the culvert inlet. Since the flood discharges are the same for both conditions, the elevations for the two profiles are very similar in this area. Based on these results, it may be concluded that the proposed natural stream design will not have an adverse impact on flood elevations.

A perspective plot of the proposed conditions 100-year profile is provided in Figure 11A-21. While this plot does not account for the curvature of the proposed stream alignment, it does indicate the relative sizes and configurations of the cross sections.

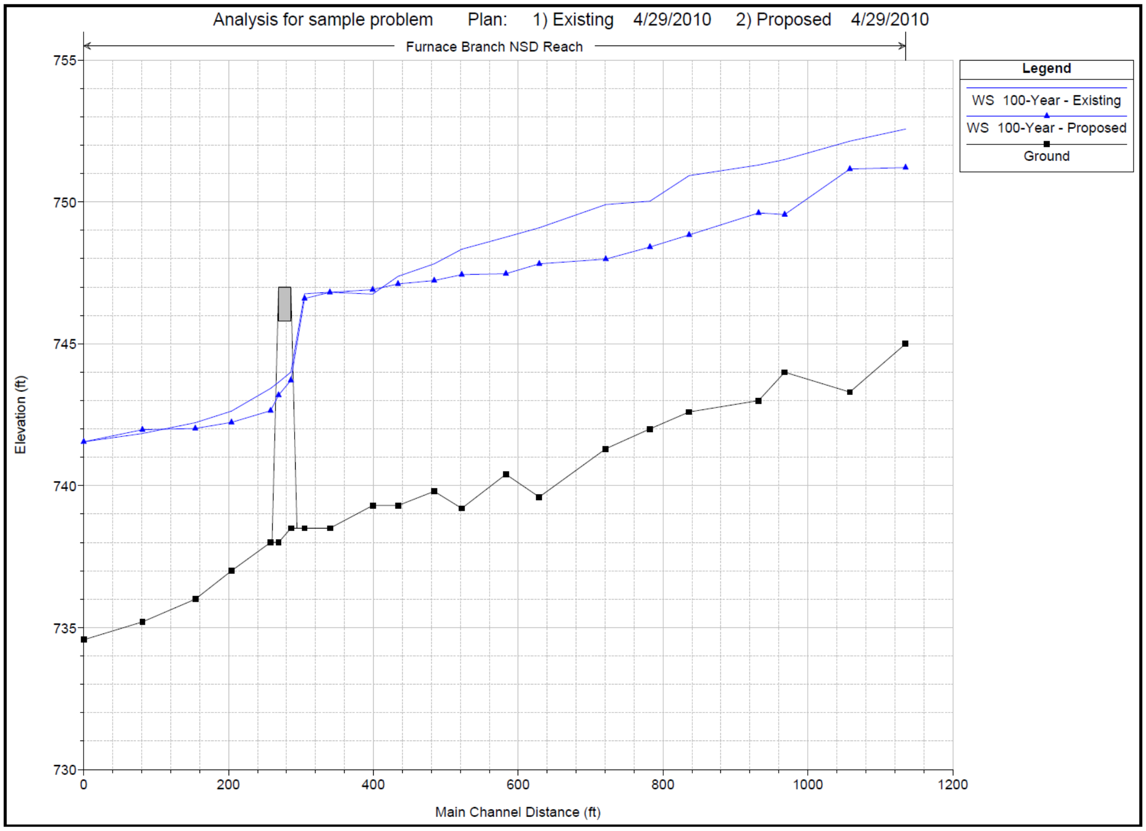


Figure 11A-20
Existing and Proposed 100-Year Profiles

The results of the 50-year proposed conditions analysis as determined by the computer program HEC-RAS are summarized in Table 11A-12. These results represent both pool and riffle sections of the proposed stream. Thus, these results may not be consistent in terms of flow velocity and computed shear, since these parameters will tend to be less in pool sections but have greater values in riffle sections. Therefore, these results should be evaluated carefully before they are applied to the design of best management practices for stream mitigation.

Step 6: Select Mitigation Measures

Although it might be possible to utilize a number of different stream mitigation measures for this project, the actual selection of the measures used is based on a consideration of the conditions in the relatively non-impacted reaches upstream and downstream of the project reach and the following general criteria:

- As described earlier, the proposed channel bottom profile will consist of a series of relatively horizontal shelves followed by drop-off's into shallow pools. For most of the project reach, the proposed channel bottom elevation will be at or below the elevation of the existing channel bottom. Where necessary, the drop-off's and pools will be constructed by excavating the existing channel bottom.

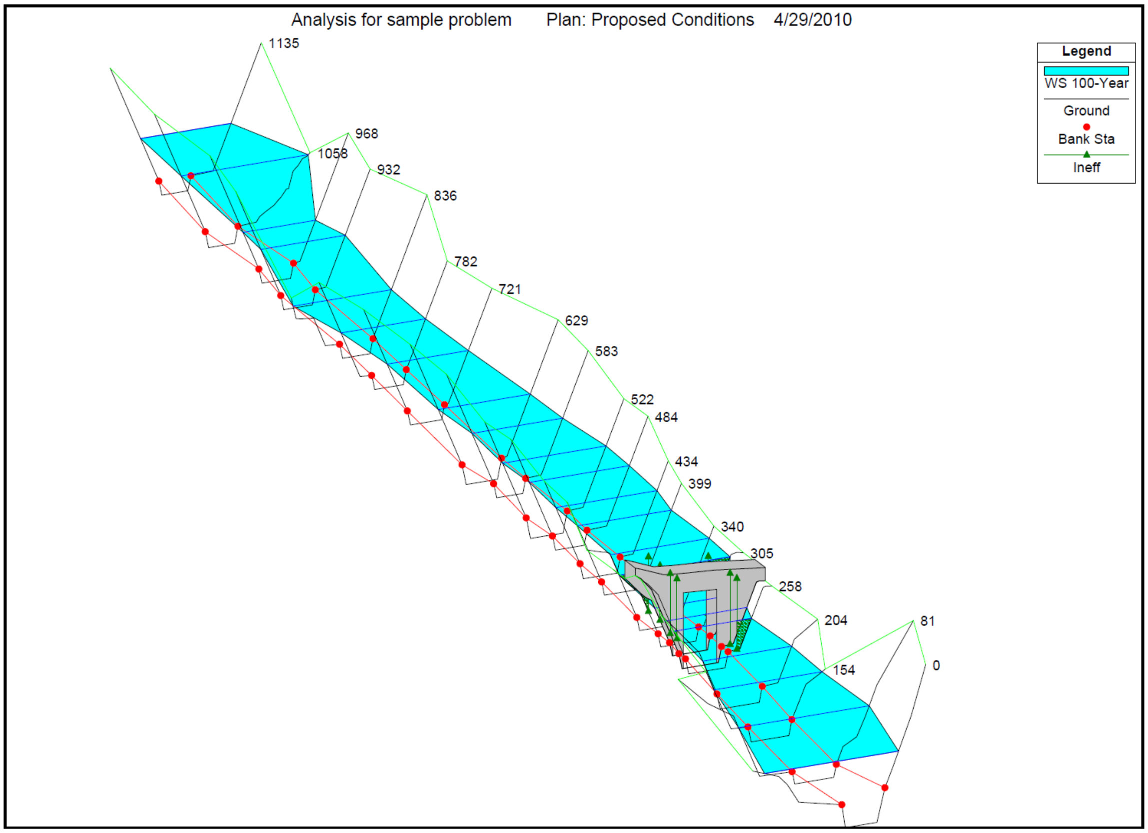


Figure 11A-21
Perspective Plot of the Proposed 100-Year Flood Profile

- At a few locations, the proposed channel bottom elevation will be above the existing channel bottom. Step pool structures will be used at these locations to appropriately control the proposed grade. It should be possible to construct these step pools using slabs of rock excavated from other locations in the stream bed.

- Boulder clusters will be used to duplicate similar features noted in other segments of the stream. It should be possible to also utilize material excavated from the channel bed to construct these clusters.

- Along a significant portion of the project reach, the proposed cross sections will be constructed by excavating into existing rock. However, at a number of other locations, the 3H:1V slopes will be constructed from soil. Although erosion protection will not be needed in rock cut areas, the soil slopes will be protected by means of longitudinal stone toe protection up to the level of the bank full flow, and above that by means of either erosion control blanket or turf reinforcement mats.

- Selection of vegetation for the stream mitigation plan will be coordinated with the Environmental Division.

Detailed discussion of the design considerations for each of these mitigation measures is presented in the following sections.

Stream Station	Q (cfs)	Channel Bottom Elev. (ft)	Water Surface Elev. (ft)	Energy Grade Line Elev. (ft)	Channel Velocity (ft/sec)	Flow Area (ft^2)	Channel Shear (lb/ft^2)
1135	1490.00	745.00	750.71	751.40	7.56	259.85	2.79
1058	1490.00	743.30	750.66	750.94	5.07	418.60	1.15
968	1490.00	744.00	749.15	750.37	9.48	190.33	4.54
932	1490.00	743.00	749.19	749.86	7.22	262.71	2.47
836	1490.00	742.60	748.28	749.08	8.03	249.14	3.16
782	1490.00	742.00	747.83	748.59	7.69	245.42	2.86
721	1490.00	741.30	747.36	748.11	7.44	244.44	2.64
629	1490.00	739.60	747.18	747.59	5.56	333.35	1.38
583	1490.00	740.40	746.79	747.38	6.97	281.87	2.28
522	1490.00	739.20	746.74	747.07	5.02	378.74	1.13
484	1490.00	739.80	746.51	746.93	5.93	332.56	1.63
434	1490.00	739.30	746.38	746.74	5.34	356.90	1.29
399	1490.00	739.30	746.16	746.61	5.87	319.18	1.57
340	1490.00	738.50	746.05	746.40	5.13	367.86	1.16
305	1490.00	738.50	745.86	746.28	5.49	303.31	1.34
282	Box Culvert						
258	1490.00	738.00	742.26	743.71	9.97	163.62	5.34
204	1490.00	737.00	741.77	742.59	7.75	228.94	3.11
154	1490.00	736.00	741.53	742.10	6.57	281.92	2.12
81	1490.00	735.20	741.47	741.72	4.61	430.98	1.00
0	1490.00	734.57	741.06	741.44	5.56	354.68	1.47

Table 11A-12
Results of Proposed Conditions Hydraulic Analysis

Step Pools: As indicated in Figure 11A-18, step pools will be required at stations 6+30 and 8+00. The step at Station 6+30 will be 5 inches high, while the step at Station 8+00 will be 12 inches high. To ensure that these step pools remain stable, it will likely be necessary to roughen the surface of the existing bedrock shelves at these locations.

Boulder Clusters: These measures will be utilized to create complexity in the flow at locations on the proposed profile where the spacing between the proposed drop-off's is the longest. These clusters will consist of 10 to 12 larger boulders placed along one side of the stream and extending no more than half way across the channel bottom width. The individual boulders will be placed at a relatively close spacing – no more than 6 inches apart – so that they will serve as collection points for coarse substrate particles transported by the stream during high flows.

The size of the boulders to be utilized in each cluster will be determined based on the hydraulic parameters computed by the proposed conditions HEC-RAS analysis and Equation 11-35 in Section 11.08.1.1. The locations selected for boulder clusters and the initial evaluation of the required stone size are summarized in Table 11A-13.

Cluster Location (Station)	Depth (feet)	Energy Slope	Computed Diameter (in)	Comments
5+00 – 5+06 Right	5.71	0.00831	11	
9+00 – 9+06 Right	6.06	0.00735	10	
10+30 – 10+36 Left	6.39	0.00606	9	
10+70 – 10+76 Left	7.55	0.00257	4	Affected by culvert backwater
14+70 – 14+76 Left	5.53	0.00644	8	May also be affected by backwater

Table 11A-13
Summary of Boulder Cluster Design

The results in Table 11A-13 indicate that stones ranging in diameter from 9 to 11 inches should remain stable for the 50-year event. Because the designer wants to provide a conservative standardized design, it is decided that all of the boulder clusters should be constructed from 12 inch diameter stones.

Erosion Protection: Based on a consideration of the nature of the channel substrate materials, it is determined that the proposed channel banks should be protected by longitudinal stone toe protection up to the approximate top of bank, then by some type of rolled erosion control product – either an erosion control blanket or turf reinforcement mats – with seeded vegetation. To determine the proposed design, the shear values computed by HEC-RAS for the proposed conditions 50-year event were compared with the permissible shear values provided in Table 5A-7 for various types of products. This allows a determination of the class of machines riprap to be used in the longitudinal stone protection as well as a selection of the class of erosion control blanket or turf reinforcement mat to be selected for a give location. In doing this analysis, the procedures discussed in Section 11.04.5 were carried out to determine the increase shear values that would result from the proposed curved alignments. The results of these computations are summarized in Table 11A-14.

Figure 11A-22
Boulders in the Stream near the Project Reach

After careful evaluation of the results presented in Table 11A-14, it is concluded that:

- In the straight reaches of the proposed stream, the computed shear values are sufficiently low that longitudinal stone protection composed of Machined Riprap Class A1 and seeded slopes with erosion control blanket would provide sufficient protection. However, from approximately Station 7+50 through Station 13+00, the proposed channel will be excavated from rock and no additional erosion protection would be required.

- The areas immediately downstream of the box culvert crossing will require heavier protection due to the high outflow velocities which occur at the culvert. During field inspection, the presence of significant channel scour was noted in this area.

- The shear values computed by HEC-RAS for cross sections which are located in pools may be artificially low due to the reduced flow velocities which occur in these areas. Thus, the results for these areas were ignored in selecting the required class of erosion protection.

Based on these conclusions, appropriate classes of machined riprap and turf reinforcement mats were selected for various reaches of the stream and this final design is summarized in Table 11A-15. At all of the location where longitudinal stone protection is required, the height of the stone will be 1.5 feet, except in the area downstream from the box culvert where the required height will be 2.0 feet. Turf reinforcement mats will be placed above the longitudinal stone toe protection up to the total bank height of 8 feet.

Stream Station	Computed Shear	Channel Bottom Width	Radius of Curva-ture	Kb	Final Shear Value	Riprap Class Req'd	TRM Class Req'd	ECB Class Req'd*
4+65	2.79	20	-	1.00	2.79	A1	II	too high
5+42	1.15	20	130	1.38	1.59	A1	I	II
6+32	4.54	22	400	1.00	4.54	B	II	too high
6+68	2.47	22	-	1.00	2.47	A1	II	too high
7+64	3.16	21	190	1.12	3.55	B	II	too high
8+18	2.86	22	168	1.26	3.61	B	II	too high
8+79	2.64	24	-	1.00	2.64	A1	II	too high
9+71	1.38	24	-	1.00	1.38	A1	I	I
10+17	2.28	20	-	1.00	2.28	A1	II	too high
10+78	1.13	25	-	1.00	1.13	A1	I	I
11+16	1.63	22	-	1.00	1.63	A1	I	II
11+66	1.29	26	300	1.00	1.29	A1	I	I
12+01	1.57	26	344	1.00	1.57	A1	I	II
12+60	1.16	27	-	1.00	1.16	A1	I	I
12+95	1.34	27	-	1.00	1.34	A1	I	I
13+42	5.34	28	-	1.00	5.34	C	III	too high
13+96	3.11	30	96	1.82	5.65	C	III	too high
14+46	2.12	29	-	1.00	2.12	A1	II	IV
15+19	1.00	30	120	1.70	1.70	A1	I	II
16+00	1.47	25	-	1.00	1.47	A1	I	I

Table 11A-14
Analysis of Required Erosion Protection
* “Too high” indicates that the final shear value was too great for any class of ECB

LEFT				RIGHT			
From Station	To Station	Class of Riprap	Class of TRM	From Station	To Station	Class of Riprap	Class of TRM
4+50	6+75	A1	II	4+50	5+25	A1	II
6+75	7+50	B	II	5+25	8+00	B	II
7+50	13+10	n/a	n/a	8+00	13+10	n/a	n/a
13+30	14+00	C	III	13+30	14+00	C	III
14+00	15+35	A1	II	14+00	15+35	A1	II

Table 11A-15
Summary of Final Erosion Protection Design
"n/a" indicates that the proposed channel will be excavated from bedrock so that no erosion protection is required

CONCLUSION:

The threshold stream design presented in this example problem discusses the basic responsibilities that the designer will have with the design of a stream relocation project. These responsibilities include design of the vertical and horizontal planform, design of the proposed stream cross section, and selection and design of mitigation measures. The design will be completed by selection of the species of vegetation to be included in the project and this should be provided by the Environmental Division in the form of the Planting Schedule and Plant List.

11.09.3 GLOSSARY

The following list of terms is representative of those used in natural stream relocation planning and design. The terms may not all be used in the chapter text; but rather are commonly used by engineers, scientists, and planners involved with stream relocations.

AGGRADATION – The excessive accumulation of material and sediment eroded and transported from other areas resulting in a rise of the natural stream bed elevation. Aggradation is generally considered to be the opposite of degradation.

ALLUVIAL CHANNEL – A channel developed in sediment transported and deposited by a stream.

BACKWATER – The rise of water surface elevation upstream due to a downstream obstruction, channel constriction, or other flow impediment.

BASE FLOW– sustained stream or channel low flow that in typically present year-round and is normally generated by moisture in the soil or groundwater rather than storm water runoff.

BANK FULL DISCHARGE – stream or channel flow that transports the majority of a streams sediment load over a given period of time and whereby leads to forming of the channel. This discharge occurs when water just begins to leave the channel and spread out into the floodplain.

BED FORMS – Irregularities found on the bed of a stream related to flow characteristics such as dunes, ripples, and anti-dunes.

BED LOAD – The amount and size of sediment or other channel material which is mobilized by tractive or other erosive forces and transported by flowing water along the bed of a waterway, by sliding, rolling, or jumping, but not in suspension. Measured, quantified, or calculated at a specified discharge.

BEST MANAGEMENT PRACTICES (BMP’s) – The application of appropriate control measures or mitigation practices, project scheduling, construction methods, post construction monitoring, and maintenance activities to prevent negative impacts to a natural stream or the habitat within.

BOUNDARY ROUGHNESS – The roughness of the stream bed and banks. The greater the roughness, the greater the frictional resistance to flow; and thus, the grater the water surface elevation for a given discharge.

CHANNEL FORMING DISCHARGE – Discharge that, if maintained indefinitely, would produce the same channel geometry as the natural long term hydrograph.

CONTINUITY EQUATION – A simplified expression of the conservation of mass for the flow of a non-compressible fluid, such as water. The equation states that the mass flow rate through a given flow cross section is equal to the area of the cross section times the average velocity of the flow.

CONVEYANCE – A measure of the capacity of an open channel or pipe to pass water based on its geometric and flow resistance properties.

CROSS VANE – an in-stream hydraulic control mitigation measure constructed from rock or boulders that extends across a stream from bank to bank, and normally keyed into the bank at bankfull elevation to control channel carving (forming) flow.

CUT BANK – The outside and often eroding bank in a channel bend. Generally considered opposite to that of a point bar.

DEGRADATION – the removal of streambed materials and subsequent lowering of a natural streambed caused by scour and channel erosion. Generally considered to be the opposite of aggradation and often may be an indicator that a stream's discharge or sediment load is changing.

DEPOSITION – The settlement of materials out of moving water onto the stream bed, banks, and/or floodplain. Occurs when flowing water is unable to transport the sediment load.

DESIGN DISCHARGE (or FLOW RATE) – The quantity of flow, usually expressed as the number of cubic feet of water passing a given point in one second (cfs), to accommodated by the proposed drainage facility.

EFFECTIVE DISCHARGE – The discharge in a channel that transports the largest fraction of the bed-material load over the long-term and, therefore is considered a good estimator for the channel-forming discharge.

EROSION – The process or group of processes by which the ground surface is loosened, dissolved, or worn away due to the detachment of soil particles by external forces such as rain or wind.

EXCEPTIONAL TENNESSEE WATERS – Surface waters of the State of Tennessee which are: a.) designated by the Water Quality Control Board as Outstanding National Resource Waters; b.) waters that provide habitat for ecologically significant populations of certain aquatic or semi-aquatic plants or animals; c.) waters that provide specialized recreational opportunities; d.) waters that possess outstanding scenic or geologic value; or e.) waters where existing conditions are better than current water quality standards.

FLOW DURATION CURVE – a plot that shows the percentage of time that flow in a stream is likely to equal or exceed some specified value of interest.

GRADATION – The proportion of material of each particle size constituting a particulate material such as sediment or soil. Significant gradations in stream relocations are gradations of suspended load, bed load, material of the bed surface, and material below the channel bed.

HEADCUTTING – the erosion of the channel bed progressing in an upstream direction through a basin characterized by small drops or waterfalls or abnormally steepened channel segments indicating that a readjustment of the basin's profile slope, channel discharge, and sediment load characteristics is taking place. Often an indicator of major disturbances in a stream system.

HYDRAULIC JUMP – A flow discontinuity occurring at an abrupt transition from subcritical to supercritical flow, usually dissipating a significant amount of energy.

HYDRAULIC RADIUS – A parameter used in the analysis of uniform flow and which is computed as the flow area divided by the wetted perimeter.

HYDROGRAPH – A graphic representation showing variation in discharge or depth (stage) of a stream of water over a specified period of time. May be defined in terms of discharge from a basin or runoff from a watershed.

INEFFECTIVE FLOW – Water in a channel that is not actively being conveyed in the downstream direction due to some type of blockage (building, bridge, etc…). The velocity of ineffective flow is close to zero due to the blockage, and typically not included as part of the active flow area in a hydraulic analysis.

INCISED STREAM – A stream in which scouring has caused the channel to down-cut, deepen, or degrade to a point where the stream is no longer connected to its floodplain. The channel has "cut" into the floor of the valley.

LARGE WOODY DEBRIS – Large pieces of natural woody material that are embedded in a stream channel or banks, typically several inches in diameter and equal to or greater in length to the average bankfull width.

MANNING'S EQUATION – An empirical formula used to analyze flow conditions for a steady, uniform flow.

MANNING'S N-VALUE – An empirical number assigned to a given material as a gage of its frictional resistance to the flow of water.

MEANDER – a circuitous winding or bend in a stream or channel. The shape and existence of meanders in a stream are a result of the natural alluvial process, and not determined by the terrain through which the channel flows.

MORPHOLOGY – The science which deals with the form of the earth, the general configuration of its surface, and the changes that take place due to erosion and sediment deposition. With regard to streams and channels, morphology examines the processes of meandering and bed material transport, as well as the geometry of the channel cross-section.

NATURAL STREAM CHANNEL DESIGN – the fluvial, geomorphic based relocation and restoration method that uses field data collection, hydraulic modeling, and stable channels in the design of an ideal channel configuration.

NICKPOINT – An location in a stream or channel where there is a sharp change or abrupt discontinuity in the channel slope resulting from differential rates of erosion above and below the nickpoint indicating the upper limit of channel incision. A nickpoint usually occurs at a hard point in the stream bed, such as a geologic formation, natural debris jams, and at natural or artificial grade control structures.

PERENNIAL STREAM – A stream that flows continuously throughout the year.

PLANFORM – The characteristics of a stream as viewed from above which are normally expressed in terms of sinuosity, pattern, and meandering attributes such as wavelength, amplitude, and radius of curvature.

POINT BAR – An alluvial deposit of sand or gravel lacking permanent vegetal cover occurring in a channel at the inside of a meander loop (river bend), usually somewhat downstream from the apex of the loop. An actively mobile river feature.

POOL – A natural stream reach where the water is typically deeper and more tranquil that reaches above and below the subject reach. Pools typically form in the thalweg of a channel near the outside bank of bends and typically contain fine-grained sediments.

REACH – A segment of stream length that is arbitrarily bounded for the purposes of a study.

REGIME – The condition of a stream or its channel with regard to stability. Considered the general pattern of variation around a mean condition such as in flow regime.

REVETMENT – A structural measure, such as riprap, gabions, boulders, etc…, placed on a slope to stabilize that slope against erosion or slippage caused by wave action and/or currents.

RIFFLE – A topographic high area in a channel in which the water flow is shallower and more rapid than the reaches above and below the subject reach. Riffle areas usually form between two bends at the point where the thalweg crosses over from one side of the channel to the other and is created by the accumulation of coarse-grained sediment. Average riffle spacing is often (but not always) half the meander length since riffles tend to occur at meander inflection points or crossovers.

RIPARIAN – Pertaining to anything connected with or adjacent to the banks of a stream (e.g. corridor, vegetation, zone, etc.). Generally referred to vegetation that is tolerant of, or more dependent on, water than other vegetation further upland.

ROUGHNESS COEFFICIENT – A numerical measure of the frictional resistance to flow in a channel, such as the Manning's coefficient.

RUN – A straight relatively fast-moving section of a stream between two riffles.

SEDIMENTATION – The gravity-induced settling of soil or other particles which have been transported by water or wind.

SEDIMENTS – Fragments of soil which come have been eroded from the ground surface or from rock and are transported by water, wind or other means.

SHEAR STRESS – A force exerted by the flow of water on the wetted area of the channel, acting in the direction of the flow; expressed as force per unit wetted area. The “pull” on a bank or other surface that may cause it to slide.

SINUOSITY – The ratio between the thalweg length (actual channel length) and the valley length of a stream from the same two fixed points at each end of a studied reach of stream. A straight channel has a sinuosity of 1.0; whereas, a fully meandering channel has a sinuosity of 2.0 or greater.

SLOUGHING – The downward sliding, slipping, or collapse of a mass of material from an earthen slope such as an embankment or stream bank. Sloughing usually occurs when the material in the slope or an underlying stratum is saturated.

SPIRAL VORTEX – A turbulent zone in a flow field characterized by a circular motion running longitudinally with the overall stream flow and is often associated with a curved stream alignment or an obstruction that forces flows toward the center of the channel.
STABLE (CHANNEL) – A ditch or stream channel for which the shape of the cross section is not significantly affected by sediment transport, either by erosion or by deposition. A channel that does not change in plan form or profile over a given time period.

STANDARD STEP BACKWATER METHOD – A process by which the water surface profile is computed for gradually varied flow, based on the conservation of energy and computed head losses between successive cross sections a given distance apart.

STREAMBED DEGREDATION – A general lowering, due to erosion, of the bottom of a channel across a given reach of a ditch or stream.

SUBCRITICAL FLOW – A flow condition where the behavior of the flow is determined more by gravitational forces than by inertial forces.

SUPERCRITICAL FLOW – A flow condition where the behavior of the flow is determined more by inertial forces than by gravitational forces.

SUPERELEVATION – An increase in water surface elevation above the natural depth of a flow occurring on the outside of a curved channel alignment due to centrifugal and other forces.

SUSPENDED LOAD – The part of the total sediment load that is carried by water for a considerable time period at a velocity in sync with the flow velocity in the channel; free from contact with the stream bed.

TAILWATER – Either the elevation or the depth of the water surface at the downstream end of a drainage structure, usually equivalent to the natural depth of flow in the waterway.

THALWEG – The main flow path of a stream. Usually follows the deepest path in the channel.

THRESHOLD CHANNEL – A stream of channel where the bed and bank material (boundary material) has no significant movement during a discharge event because the shear forces acting on the boundary material is below the amount required to cause movement of the material.

WASH LOAD – The part of a streams sediment load composed of material sizes smaller than those found in appreciable quantities in the shifting portions of the stream bed, originating from sources such as bank failure, gully erosion, and sheet erosion and not related to discharge. Typically NOT considered part of the bed material or sediment load of a stability analysis.

WATERSHED – An area of land surface defined by a distinguishable topographic divide that collects precipitation into a stream.

11.09.4 REFERENCES

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11.09.5 ABBREVIATIONS

AASHTO – American Association of State Highway and Transportation Officials
ARAP – Aquatic Resource Alteration Permit
ARS – Agricultural Research Service
ASCE – American Society of Civil Engineers
BAGS – Bedload Assessment for Gravel-bed Streams
EBMM – Ecological Boundary and Mitigation Memo
EB – Environmental Boundaries
EPA – Environmental Protection Agency
EPSC – Erosion Prevention and Sediment Control
FEMA – Federal Emergency Management Agency
FHWA – Federal Highway Administration
FISRWG - Federal Interagency Stream Restoration Working Group
HEC – Hydraulic Engineering Circular
HMS – Hydrologic Modeling System (i.e. HEC-HMS)
MSE – Mechanically Stabilized Earth
NEH – National Engineering Handbook
NEPA – National Environmental Policy Act
NRCS – Natural Resource Conservation Service
PPM – Parts Per Million
RAS – River Analysis System (i.e. HEC-RAS)
SCS – Soil Conservation Service
SIAM – Sediment Impact Analysis Method
SSWMP – Statewide Storm Water Management Program
SWPPP – Stormwater Pollution Prevention Plan
TDOT – Tennessee Department of Transportation
TDEC – Tennessee Department of Environment and Conservation
TSMP – Tennessee Stream Mitigation Program
USACE – United States Army Corps of Engineers
USDA – United States Department of Agriculture
USDOT – United States Department of Transportation
USGS – United States Geological Survey
WES – Waterways Experiment Station