

TDOT DESIGN DIVISION

DRAINAGE MANUAL

CHAPTER IX ENERGY DISSIPATORS

CHAPTER 9 – ENERGY DISSIPATORS

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SECTION 9.01 – INTRODUCTION

Erosive forces which can be at work in the natural drainage network are often increased by the construction of a highway. Interception and concentration of overland flow and constriction of natural waterways inevitably results in increased erosion potential. In fact, the failure of many highway culverts can be traced to unchecked erosion. To protect the highway and adjacent areas, it is sometimes necessary to employ an energy dissipating device. Throughout the process of selecting and designing an energy dissipator, the designer should keep in mind that the primary objective is to protect the highway structure and adjacent area from excessive damage due to erosion. An effective design will return the flow downstream of the dissipator to a condition which approximates the natural flow regime.

Energy dissipators may be used at a number of locations within a highway drainage system, including outfalls for culverts, storm sewers, detention ponds and steep ditches. However, the predominant use of energy dissipating structures will be at culvert outfalls. Thus, this chapter concentrates on the use of energy dissipators for culverts. The designer should be able to easily adapt the methods provided in this chapter to the design of dissipators for other drainage features.

Before specifying an energy dissipator for a culvert site, the designer may wish to investigate modifying the vertical alignment of the culvert to reduce the outlet velocity as described in Section 6.04.1.1.1.5 of this Manual. The choice between modifying the culvert alignment or providing an energy dissipator would normally be based on a site-specific consideration of the costs for construction and maintenance presented by each option. The designer should also be aware of the discussion of riprap aprons presented in Section 6.04.3.3 of this Manual. There may be situations where a riprap apron may be used in lieu of an energy dissipator, and the designer should be familiar with the criteria for the application of both options.

Although energy dissipators cover a wide range in complexity and cost, they can be grouped into two broad categories. One type of energy dissipator acts by forcing a hydraulic jump in the flow stream leaving the culvert. This is accomplished either by increasing the hydraulic roughness of a segment of the culvert or by directing flows into a basin located at the culvert outfall. The second group of energy dissipators is often referred to as impact basins, even though they are constructed at the stream bed level. Energy is dissipated in these basins as the concentrated flow jet from the culvert outlet impacts on blocks or baffles located on the basin floor. The selection of a particular type of dissipator should be based on consideration of the velocity of the culvert outflow, an assessment of the erosion hazard, and the amount of right-of-way available.

SECTION 9.02 – DOCUMENTATION PROCEDURES

The designer will be responsible for documenting the selection process and design computations for each energy dissipator included in the roadway project. In general, the documentation should be sufficient to answer any reasonable question that may be raised in the future regarding the proposed dissipator design. The documentation for each dissipator should be grouped together with the documentation for the individual drainage component that it will serve. For example, the documentation for a dissipator at a culvert outfall should be attached to the design documentation for that culvert.

As appropriate, the following materials should be included in the design documentation:

- the Energy Dissipator Worksheet, Figure 9A-1, which should be clearly labeled with the project description, project station, a description of the drainage feature being served, the date, and the initials of the designer
- documentation as to the need for an energy dissipator
- all of the design forms and computations generated in the design of the selected dissipator type
- documentation on the computations and assumptions used to design the riprap transition
- documentation on the review of the design as described in Step 10, Section 9.04.2.1

A number of the items in the above list may be completed simply by including the output reports from any software which may be used for energy dissipator design.

Each page of hand computation sheets and computer output reports should be clearly labeled with the project description, project station, a description of the drainage feature being served, the date, and the initials of the designer.

SECTION 9.03 – GUIDELINES AND CRITERIA

Design criteria form the basis for the final design configuration. This section presents design standards and guidance for determining the type of dissipator appropriate for a given site.

9.03.1 ENERGY DISSIPATOR USE

An energy dissipator should be considered for use where:

- the culvert outlet velocity computed for the design discharge is 15 feet per second or greater
- the required length of a riprap apron would be excessive or infeasible due to culvert outlet conditions (see Section 6.04.3.3 for additional information)
- erosion at the culvert outlet will pose an unacceptable risk to the roadway and downstream property (see Section 9.04.1.3 for the method that should be used to estimate this erosion)
- the need is apparent for any economically justifiable reason

An energy dissipator may not be necessary at sites where the natural stream slope is steep, resulting in a high flow velocity in the natural channel. Furthermore, energy dissipators will generally not be required at sites where the channel is lined with bedrock.

Any energy dissipation structure placed within the clear zone of a mainline roadway should be protected with the proper roadside safety appurtenances.

9.03.2 ENERGY DISSIPATOR DESIGN CRITERIA

An energy dissipator should be designed for the same storm frequency and discharge used to design the facility it serves.

Where practical, the velocity and depth of the flows leaving an energy dissipator should match the natural channel flow regime. Where this is not possible, the channel should be provided with a riprap apron of sufficient length to allow flows to return to the natural condition. See Section 6.04.3.3 for more information.

Energy dissipators should be designed according to the procedures provided in the FHWA publication HEC-14, *Hydraulic Design of Energy Dissipators for Culverts and Channels* and guidelines contained in this Manual. Section 9.05 describes software that may be used to apply these procedures.

9.03.3 ENERGY DISSIPATOR SELECTION

A wide variety of energy dissipation devices are available to the designer, each having different applications and limitations. Each culvert site presents a unique set of circumstances. The designer should exercise care when selecting the option which will best fit the culvert end treatment as well as the overall site. In general, the selection of the dissipation scheme should be determined based on the following parameters:

- **Culvert Outflow Froude Number:** The Froude Number represents the ratio of the inertial forces to the gravitational forces acting on a given flow. When inertial forces dominate the behavior of the flow, the Froude Number is greater than 1 and the flow is said to be supercritical. Because energy dissipation is normally required when the culvert outlet velocity is very high, the influence of inertial forces will far outweigh gravitational forces, resulting in Froude Numbers much greater than 1.
- **Velocity:** The velocity of flow at the structure outlet should often be evaluated along with the Froude Number when selecting an energy dissipator. In general, erosion protection would not be required where the outlet velocity is less than 5 feet per second. However, the designer may choose to provide some form of erosion protection where highly erodible soils may be present. Riprap linings should be used with caution where the outlet velocity exceeds 12 feet per second.
- **Debris:** For the purposes of designing an energy dissipator, debris is classified into three groups: silt/sand, gravel/boulders, and floating debris. Because of the high flow velocities and turbulence experienced in an energy dissipator, debris transported by the flows can cause abrasion or other damage. In addition, floating debris can be snagged in certain types of dissipators and cause clogging.
- **Tailwater Effects:** Many types of dissipators, particularly those that function by forcing a hydraulic jump, require the presence of a certain depth of tailwater to be effective.

Specific criteria for selecting the type of energy dissipator to be used at a site are provided in Table 9A-1 in the Appendix.

The use of an energy dissipator can represent a significant cost for both construction and for maintenance over the life of the structure. Therefore, the methods described below represent a progressive strategy to ensure the most economical means of erosion protection are provided. Each of the following sections generally represents strategies of increasing complexity and expense.

9.03.3.1 NATURAL SCOUR HOLE

This option consists of providing an area in which flows through the culvert will be allowed to form a natural scour hole. The designer should carefully estimate the size of the scour hole that will form using the method presented in Section 9.04.1.3 and line the channel and the overbanks over an area sufficient to cover the potential scour hole with the class of riprap appropriate for the culvert exit velocity (see Section 6.04.3.3 and Figure 9-1). In general, the size of the scour hole should be estimated assuming cohesionless material to provide a conservative estimate. The designer may, based on sound engineering judgment, choose to assume cohesive soils for this estimate and use the methodology provided in HEC-14.



Figure 9-1
Scour Hole at a Culvert Outlet with Deposited Material in the Foreground

When energy dissipation is to be provided by the natural scour hole, the designer should insure that the cut-off wall depth for the proposed culvert end treatment will be sufficient to prevent undermining of the end treatment. If the standard cut-off wall depth does not appear to provide adequate protection, it may be necessary to include a detailed endwall design with the plans. In such cases, the designer should coordinate the structural design of the endwall with the Structures Division.

Natural scour holes will be effective where the Froude Number of the culvert outflow is less than 3, and where the flow will carry heavy loads of any type of debris. Furthermore, it does not require a tailwater for efficient operation.

This method may be used where:

- right-of-way or drainage easements at the site are sufficient to encompass the entire scour hole, which may often be quite large
- environmental concerns due to sedimentation will not be a factor
- there are no aesthetic concerns or other nuisance effects, such as insect breeding

9.03.3.2 RIPRAP STILLING BASIN

Riprap stilling basins are similar to natural scour holes in that their design procedure is based on laboratory studies of the relationships between culvert flow properties and the dimensions of the scour holes that would form in riprap at the outfalls. These energy dissipators

consist of a pool at the culvert outfall, followed by an apron that rises to the channel flow line, and a transition to the natural channel cross section (see TDOT standard drawing EC-STR-21 and section 10.08.3 of this manual). Concentrated flow at the culvert outfall will plunge into one end of the pool and then form a hydraulic jump at the other end, against the apron. As a result, the flow will generally be well dispersed as it leaves the basin. In some situations, the design method provided in HEC-14 will require that the basin at the culvert outfall will be lined with a heavier class of Machined Riprap (Class B or C). Where this occurs, the apron and transition to the natural valley configuration may be constructed of a smaller class of riprap.

Riprap basins may be used where allowing a natural scour hole to form will not be acceptable. They will be effective when the Froude Number of the culvert outflow is less than 3. Although a riprap basin may be used where the tailwater depth is high, it is recommended that they be used only where the tailwater depth is less than 75% of the depth of flow at the culvert outfall. They are not affected by heavy debris loads.

For any site where a riprap basin is feasible, the designer should also check the design for a riprap apron (see Section 6.04.3) and select the structure type based on cost. Where the tailwater depth is sufficiently low, a riprap stilling basin can be shorter than a riprap apron. Thus, a basin can help to reduce the costs associated with obtaining a permanent drainage easement and environmental permits. In addition, a basin designed in accordance with HEC-14 can often be constructed using Machined Riprap (Class A1) instead of the heavier classes which would be required for an apron in the same setting. On the other hand, riprap aprons are more easily constructed and can be applied in a wider variety of situations. Section 9.04.2 provides additional information on the applicability of riprap stilling basins.

Typically, the standard cut-off wall depth for the culvert end treatment will be sufficient where a riprap stilling basin is employed.

9.03.3.3 INTERNAL ENERGY DISSIPATORS

In situations where there is limited right-of-way for an energy dissipator at a culvert outlet and where the culvert barrel is not used to capacity due to inlet control, metal or concrete roughness elements may be placed along a section of the downstream end of the culvert to control outlet velocities. These roughness elements are referred to as internal energy dissipators. Because the culvert is flowing partially full with inlet control, it is possible to increase the depth of flow near the culvert outlet without creating additional headwater.

Because internal energy dissipators may require regular maintenance, they should be used only in box culverts of sufficient size to allow for entry by maintenance personnel. They may be used where:

- moderate velocity reduction is required
- right-of-way is limited
- access for maintenance is available



Figure 9-2
Roughness Elements Inside of a Box Culvert

Roughness elements decrease flow velocities by either increasing the flow resistance of the culvert barrel or by a phenomenon known as tumbling flow.

Tumbling flow (Figure 9-3) is an excellent energy dissipator on steep slopes. It is essentially a series of hydraulic jumps and overfalls that maintain the flow approximately at critical velocity on slopes that would otherwise be characterized by high supercritical velocities. Use of tumbling flow is reasonable for slopes up to 10 or 15 percent. One of the major limitations of tumbling flow as an energy dissipator is that the required height of the roughness elements is closely related to the unit discharge (discharge divided by the width of the culvert). There may be situations where the element height would have to be half the culvert height in order to maintain tumbling flow. Thus, practical applications of tumbling flow are likely to be limited to low-discharge per unit width (i.e. shallow flow), high-velocity culverts.

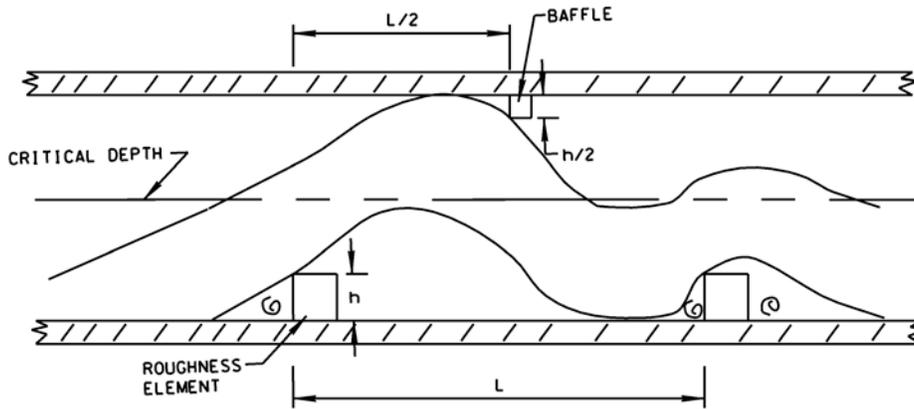


Figure 9-3
Typical Tumbling Flow Energy Dissipator

Tumbling flow can be established rather quickly by using either a very large leading element, or a smaller leading element and a baffle to reverse the flow jet between the first and second rows. The first alternative is not considered to be a practical solution since the element size is likely to be excessive. The baffle has merit since it deflects the so-called "rooster tail" jet back towards the culvert bottom and brings the flow under control very quickly without using a large leading roughness element.

Increased resistance (Figure 9-4) involves using roughness elements to provide greater hydraulic roughness and thus, reduce velocity. Because increasing resistance will also increase the depth of flow, the designer should ensure that the proposed culvert height will be adequate in the roughened section.

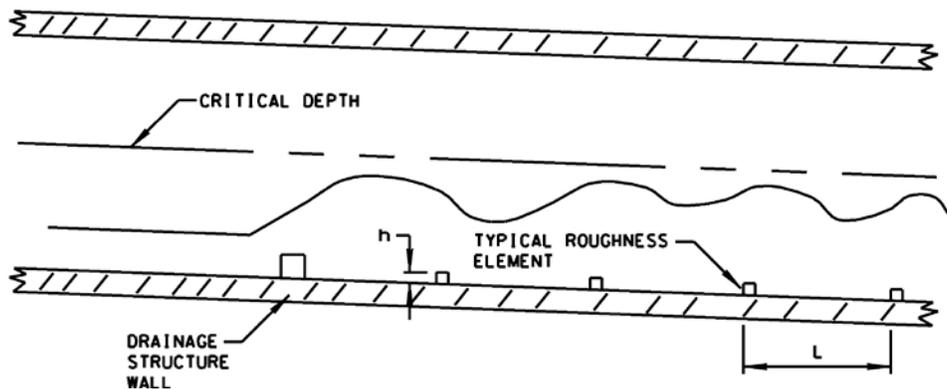


Figure 9-4
Increased Hydraulic Roughness

Whether roughness elements will represent increased resistance or create tumbling flow is largely dependent on the culvert slope. A roughness element on a steep slope may induce tumbling flow, whereas the same roughness element on a relatively flatter slope would represent increased resistance. Further, tumbling flow essentially delivers the outlet flow at critical velocity while increased resistance will deliver outlet velocities which are still in the supercritical flow regime. The designer should carefully evaluate the depth and velocity of the flows leaving the culvert and provide for any additional required erosion protection in the channel. Although internal energy dissipators may not completely eliminate the need for some form of erosion control at a culvert outlet, they may provide sufficient reduction in outlet velocity or Froude Number to allow a simpler, less expensive form of protection at the outlet.

Although internal energy dissipators will tolerate a moderate quantity of sand and silt, they should not be used in situations where the stream will transport cobbles and boulders or significant amounts of floating debris. These structures do not require a tailwater to operate efficiently.

9.03.3.4 EXTERNAL ENERGY DISSIPATORS

External energy dissipators are concrete structures placed at the culvert outfall as either stilling basins or impact basins. These structures may be used when:

- the presence of a scour hole at the culvert outlet would be unacceptable
- the Froude number of the culvert outflow exceeds the design limits for a riprap basin
- there is adequate right-of-way

Although the FHWA publication HEC-14 provides design information for a large number of these structures, the dissipators described in the following sections are the primary structures to be considered for use on TDOT designs.

The use of these structures will require an individual design be detailed in the plans. Required structural design should be coordinated with the Hydraulics Section in the Structures Division in the following manner:

- Following approval of the Grade Review Plans (Preliminary Plans), the designer should determine the required dimensions of the various elements of the structure using the equations and procedures provided in HEC-14. The designer should also use the equations provided in HEC-14 to estimate the hydrodynamic forces to be used in the structural design.
- This information would then be submitted to the Hydraulics Unit which would be responsible for the detailed structural design. The designer should allow sufficient time for the sizing and preliminary structural design to be completed prior to the Right-of-Way Plan submittal.

9.03.3.4.1 SAINT ANTHONY FALLS (SAF) STILLING BASIN

The Saint Anthony Falls or SAF stilling basin is a generalized and highly flexible design that uses a hydraulic jump to dissipate energy. From the culvert outlet, the design consists of a sloping chute with chute blocks at its base, followed by blocks on the floor of the basin. The basin floor also has a sill located at the downstream end. Usually, the floor of the stilling basin will be below grade. Thus, a backslope will be provided downstream of the sill to provide a

transition to the natural grade of the stream. The basin sidewalls may be parallel for a rectangular stilling basin or may diverge beginning at the downstream toe of the chute to create a flared stilling basin. A cut-off wall and wingwalls should be provided at the end of the stilling basin.

The SAF basin will accommodate culvert outflow Froude Numbers ranging from 1.7 to 17. Although it will tolerate moderate amounts of sand, silt and floating debris, it should not be used where the stream will transport more than small amounts of cobbles or boulders. As described in Section 9.04.2.2.3, the structure also requires a sufficient tailwater for proper and efficient operation.

9.03.3.4.2 USBR TYPE VI IMPACT BASIN

The USBR Type VI basin, as shown in Figures 9-5 and 9-6, is an impact-type energy dissipator which is contained in a relatively small box-like structure. Inside this box is a vertical baffle which is referred to as a hanging baffle because an opening is provided between the bottom of the baffle and the floor of the box. This type of energy dissipator is attached directly to the culvert outlet in place of a standard endwall.

Energy dissipation is initiated as flow strikes the vertical baffle and is deflected upstream by the horizontal portion of the baffle and by the floor, creating horizontal eddies. Despite its relatively small size, this impact basin yields greater energy dissipation than a hydraulic jump in the same setting.

The baffle is provided with notches which aid in cleaning the basin after prolonged non-use of the structure. If the basin should begin to collect sediment, the notches will provide concentrated jets of water for cleaning. The basin is designed so that the full design discharge can be passed over the top of the baffle should the space beneath it become completely clogged. Although this degrades the performance of the structure, it is acceptable for short periods of time. To provide structural support and aid in priming the device, a short support should be placed under the center of the baffle wall.



Figure 9-5
Typical USBR Type VI Baffled Dissipator

In situations where the culvert entering the basin has a slope greater than 27 percent, the basin should be constructed on a horizontal grade. In addition, the culvert should be provided with a horizontal section at least four culvert widths in length immediately upstream of the dissipator. Although the basin will operate effectively with entrance pipes on slopes up to 27 percent, experience has shown that it is more efficient when the flow jet entering the dissipator is horizontal.

The end of the basin should be provided with a low sill which, where feasible, should be set at the same elevation as the downstream channel. Where this is not possible, a slot should be placed in the end sill to provide for drainage during periods of low flow. Where needed to retain the roadway embankment, the end of the basin may be provided with an alternate end sill and 45° wingwalls as shown in Figure 9-13. It may also be necessary to provide a cut-off wall as described in Section 9.04.2.2.6. Where the velocities of flows exiting the basin exceed 5 ft/sec, the channel downstream of the basin should be provided with a riprap apron, as described in Section 6.04.3.3.

To prevent cavitation damage, use of the USBR Type VI basin is limited to installations where the discharge is less than 400 cfs. Although tailwater is not necessary for the successful operation of the basin, a moderate depth of tailwater will improve its performance. However, the tailwater depth should not be above half of the height of the baffle, or $h_3 + h_2/2$, as shown in Figure 9-13. This dissipator is not recommended where potential debris may cause substantial clogging.



Figure 9-6
Top of the Baffle in a USBR Type VI Energy Dissipator

9.03.3.4.3 HOOK TYPE IMPACT BASIN ENERGY DISSIPATOR

The hook energy dissipator is a type of impact basin that abates culvert outflow velocities by means of three hook-shaped blocks and an end sill in a uniform trapezoidal channel. The general layout of a hook energy dissipator is shown in Figure 9-15 and a detail of the hook-shaped block is provided in Figure 9-16. Although this type of dissipator was originally developed primarily for large arch culverts, it is also effective for box or circular culverts as shown in Figure 9-7.

Ideally, the width and shape of the uniform trapezoidal channel should generally resemble the natural channel cross section. However, for a given discharge condition, widening the basin and flattening the side slopes will tend to improve the performance of the basin. In practice, the side slopes of the basin should be between 1.5H:1V and 2H:1V, and the bottom width of the basin should be 1 to 2 times the effective opening width of the culvert.



Figure 9-7
Hook Type Energy Dissipator Basin

Depending on the final exit velocity and local soil conditions, some scour may occur downstream of the basin. Where this is possible, a riprap apron should be provided downstream of the basin according to the criteria presented in Section 6.04.3.3. In addition, the end of the basin should be provided with a cutoff wall as described in Section 9.04.2.2.6.

The hook energy dissipator should not be used where large amounts of debris are expected. Coarse sediments may abrade the upstream face of the hooks, while floating debris may catch on them, causing the basin to become choked. These basins may be used where the Froude number of the culvert outflow is between 1.8 and 3.0.

SECTION 9.04 – DESIGN PROCEDURES

9.04.1 COMPUTATIONS IN SUPPORT OF ENERGY DISSIPATOR DESIGN

A variety of background information is usually needed to properly design an energy dissipator. A portion of that information may be determined by means of computations that support the dissipator design. This section discusses the computations that should be completed prior to beginning the selection and design of an energy dissipation scheme.

9.04.1.1 CULVERT HYDRAULIC ANALYSIS

A significant portion of the data needed to design an energy dissipator will be obtained from the culvert design file. Detailed procedures for the design of a new culvert are described in Section 6.05.

9.04.1.2 COMPUTATION OF CULVERT OUTFLOW CONDITIONS

Although the culvert outflow conditions will likely be described in the culvert design file, a few parameters will require a more detailed analysis to support the energy dissipator design:

1. **Outlet Depth (d_o):** The outlet depth is often provided as a part of the hydraulic analysis of the culvert. Where this is not the case, the outlet depth may be determined using the guidance provided in Section 6.05.4 of this Manual.
2. **Area (A_o):** The cross sectional area of the flow at the culvert outlet should be determined using d_o . This determination may be aided by the use of Table 6A-11.
3. **Top width (T):** The top width of the flow at the culvert outlet may be determined using d_o . Table 6A-11 may also be used in determining this parameter.
4. **Velocity (V_o):** The culvert outlet velocity should be calculated as follows:

$$V_o = \frac{Q}{A_o} \tag{9-1}$$

Where: Q = culvert discharge, (ft³/s)

5. **Equivalent Depth (d_e):** The equivalent depth is used in a number of computations for non-rectangular culverts. It can be computed as follows:

$$d_e = \left(\frac{A_o}{2} \right)^{0.5} \tag{9-2}$$

6. **Froude Number (Fr):** This parameter is described in Section 9.03.3 and is an important factor in the design of energy dissipators. For rectangular shapes, it is calculated as follows:

$$Fr = \frac{V_o}{(g \times d_o)^{0.5}} \quad (9-3)$$

Where: g = acceleration due to gravity, (32.2 ft/sec²)
 d_o = depth of flow at outlet, (ft)
 V_o = culvert outlet velocity, (ft/s)

For non-rectangular shapes, the term d_o may be substituted with the equivalent depth, d_e.

9.04.1.3 SCOUR HOLE ESTIMATION

The estimate of the scour hole size is an essential part of the energy dissipator design procedure. Together with the maintenance history and site reconnaissance information, this estimate can serve to assist in determining an appropriate energy dissipation design.

This section presents a procedure for estimating scour holes in cohesionless materials for the maximum or extreme scour case. The designer may refer to HEC-14, Chapter 5 for detailed information on estimating scour holes in cohesive soils. HEC-14 recommends that soil testing be done at a site where cohesive soils are present to determine the plasticity index and saturated shear strength, which are necessary for the HEC-14 procedure. However, unless the dimensions of the scour hole are critical to the overall design, sufficient accuracy may be obtained by looking up average values of these parameters in a soil mechanics textbook for the general soil classification at a site.

Results of tests by the U.S. Army Waterways Experiment Station in Vicksburg, Mississippi indicate that scour hole geometry varies with the tailwater conditions. The maximum scour geometry occurs for tailwater depths less than half the culvert height. As shown in Figure 9-8, the maximum depth of scour, d_s, occurs at a location equal to approximately 40% of the length of the scour hole, L_s, measured downstream from the culvert.

Equation 9-4 is an empirical equation that may be used to compute the three dimensions (length, width and depth) of the scour hole. The equation is applied using three coefficients termed α, β, and θ. The value of these coefficients will vary depending on which dimension of the scour hole is being computed. Thus, to compute all three dimensions of the scour hole, the equation would be applied three times. Each time, a different set of values are assigned to α, β, and θ as determined from Table 9-1.

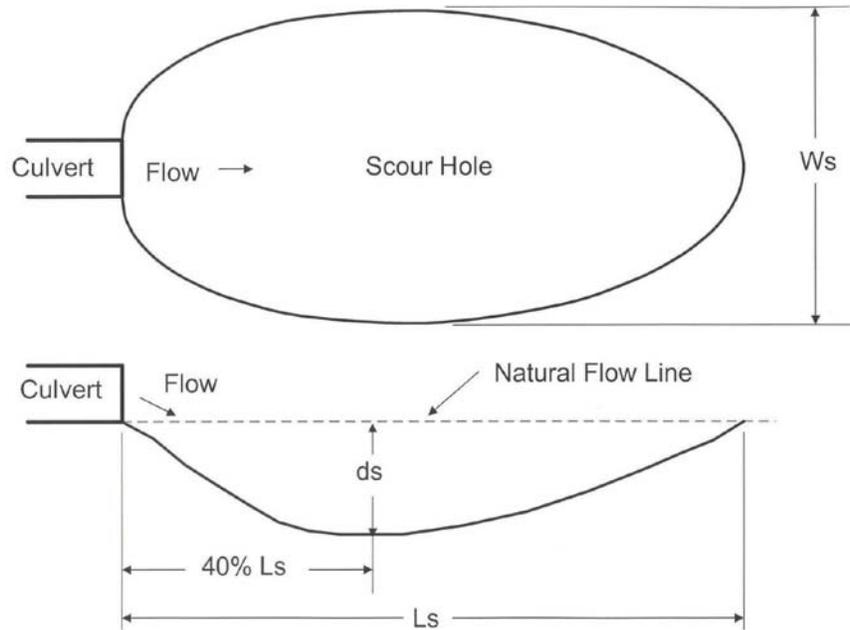


Figure 9-8
Scour Hole at Culvert Outlet

The dimensions of the scour hole will be affected by the slope of the culvert and whether or not a drop exists between the culvert invert and the channel bed. Therefore, two adjustment factors, C_s and C_h , are included in Equation 9-4. C_s is used to account for the slope of the culvert. Values for this factor may be obtained or interpolated from Table 9-2 based on the culvert slope in percent. Values for C_h may be obtained or interpolated from Table 9-3 using the drop height, H_d , expressed in culvert diameters. To use the table, the distance from the culvert invert to the channel bed should be determined and then divided by the culvert diameter to determine H_d . If the culvert is non-circular, the rise of the structure should be used to compute the drop height.

The dimensions of a scour hole will also be affected by the length of time over which flows will occur at the site. The term F_3 in Equation 9-7 is used to account for the duration of the peak flow at the culvert site as compared to the time base of 316 minutes used in the tests by the U.S. Army Waterways Experiment Station. The duration of the peak flow may be estimated if a stream flow hydrograph is available. Lacking this information, it is recommended that a time of 30 minutes be used. It has been found that approximately $\frac{2}{3}$ to $\frac{3}{4}$ of the maximum scour will occur in the first 30 minutes of the flow duration.

$$d_s, w_s, L_s = C_s C_h F_1 F_2 F_3 R_o \tag{9-4}$$

and,

$$F_1 = \frac{\alpha}{\sigma^{1/3}} \tag{9-5}$$

$$F_2 = \left(\frac{Q}{g^{0.5} R_o^{2.5}} \right)^\beta \tag{9-6}$$

$$F_3 = \left(\frac{t}{316} \right)^\theta \tag{9-7}$$

Where: d_s = maximum depth of the scour hole, (ft)
 L_s = length of the scour hole, (ft)
 w_s = width of the scour hole, (ft)
 Q = design discharge, (ft³/s)
 g = acceleration due to gravity, (32.2 ft/sec²)
 t = duration of the peak flow, (minutes), Use 30 minutes if unknown
 R_o = hydraulic radius of the cross-sectional flow, (ft)
 σ = material standard deviation (see following discussion)
 α , β , θ , C_s and C_h are coefficients, as shown in Tables 9-1 through 9-3

The material standard deviation, σ , is a measure of the grain size distribution of the bed material in the channel. When a sieve analysis is available from a geotechnical investigation, the standard deviation may be computed as:

$$\sigma = \left(\frac{d_{84}}{d_{16}} \right)^{0.5} \tag{9-8}$$

Where: d_{84} = mean particle diameter at the 84th percentile of the distribution
 d_{16} = mean particle diameter at the 16th percentile of the distribution

When a sieve analysis is not available, an approximate value of 2.10 may be used for gravel and an approximate value of 1.87 may be used for sand. An average value of σ is not available for non-cohesive silts; however, a conservative estimate may be obtained by assuming a value of 1.0.

	α	β	θ
Depth (d_s)	2.27	0.39	0.06
Width (W_s)	6.94	0.53	0.08
Length (L_s)	17.10	0.47	0.10

Table 9-1
 Coefficients for Computing Scour Hole Dimensions Using Equation 9-4

Culvert Slope (%)	Depth	Width	Length
0	1.00	1.00	1.00
2	1.03	1.28	1.17
5	1.08	1.28	1.17
≥ 7	1.12	1.28	1.17

Table 9-2
Coefficients, C_s , for Culvert Slope Using Equation 9-4

Drop Height (H_d)*	Depth	Width	Length
0	1.00	1.00	1.00
1	1.22	1.51	0.73
2	1.26	1.54	0.73
4	1.34	1.66	0.73

* Height in pipe diameters

Table 9-3
Coefficients, C_h , for Culvert Outlets Above the Stream Bed¹ Using Equation 9-4
¹Coefficients have been derived from experiments with sand bed materials

9.04.2 DESIGN PROCEDURES

Detailed design procedures for the energy dissipator types described in this Manual are provided in the FHWA document HEC-14, *Hydraulic Design of Energy Dissipators for Culverts and Channels*. This document is available on the Internet from the Federal Highway Administration hydraulics home page. This Manual provides a general procedure for determining whether an energy dissipator is needed and for selecting the type of dissipator, as well as detailed design procedures for the Saint Anthony Falls Stilling Basin and the USBR Type VI Impact Basin. When it becomes necessary to perform a design for other types of dissipators, the designer should refer to HEC-14 for detailed guidance and computational procedures. Specific comments and notes helpful in the application of the HEC-14 procedures are provided in the second half of this section.

9.04.2.1 GENERAL DESIGN PROCEDURE

The following design procedure is intended to provide a convenient and organized procedure for manually designing energy dissipators. The designer should be familiar with all of the equations in Section 9.04.1 before using this procedure. In addition, application of the following design method without an understanding of the applicable hydraulic principals can result in an inadequate, unsafe or costly structure.

Step 1: Obtain the culvert design file and assemble the required data. This should include:

- Survey data as defined in the TDOT Survey Manual and other site information
- Design storm frequency and discharge (will be the same as used for the culvert design)
- Tailwater information, including the channel slope, cross section, normal depth and velocity
- Information on the composition of the downstream bed and bank materials
- Information on the proposed culvert design, including the culvert type (size, shape and roughness), outlet flow conditions (see Section 9.04.1.2), culvert slope, and the culvert performance curve

Step 2: Enter the data from Step 1 onto the Energy Dissipator Worksheet provided in the chapter Appendix as Figure 9A-1.

Step 3: Estimate the scour hole size. Enter the required data onto the Energy Dissipator Worksheet and compute d_s , W_s , and L_s using Equations 9-4 through 9-7.

Step 4: Determine the need for an energy dissipator using the criteria presented in Section 9.03.1.

Step 5: Select dissipator design alternatives based on Section 9.03.3. More than one alternate may be possible. The alternate that provides the best overall fit for the site may become apparent as detailed designs are developed for each one.

Step 6: Develop designs for each of the alternates identified in Step 5. Design procedures and forms for each dissipator type are presented in the chapter Appendix.

Step 7: Design the riprap apron. Many dissipators may require a riprap apron between the outlet of the dissipator and the natural channel. This provides for a smooth flow pattern between the dissipator and the channel and provides any final erosion protection that may be required. The length and class of riprap for the apron should be determined based on the procedure provided in Section 6.05.5.

Step 8: Select the cut-off wall depth. Where necessary, energy dissipation structures that are constructed of reinforced concrete should be provided with a cut-off wall of sufficient depth to protect the basin outfall. The cut-off wall depth may be selected based on the criteria provided in Section 9.04.2.2.6.

Step 9: The need for any structural design of a reinforced concrete energy dissipator should be coordinated with the Hydraulics Unit in the Structures Division. In areas which may be subject to a high water table the Hydraulics Section should also be consulted with regard to the buoyancy of the structure. If the ground is saturated, and tailwater conditions exist, the structure may be subject to buoyant forces that are relative in strength to the volume of water displaced by the structure. Flotation of the structure will occur when its weight is equal to or less than the uplift force exerted by the water. Buoyancy analysis should be performed if the possibility of flotation exists.

Step 10: Review the results. At a minimum, the following items should be addressed:

- If the downstream channel conditions (velocity, depth, or stability) are exceeded, provide a riprap apron designed according to Section 6.05.5 or select another type of dissipator.
- If the preferred dissipator affects the hydraulic performance of the proposed culvert, re-compute the culvert performance and insure that the selected dissipator design will still be adequate. Once any needed adjustments are made to the dissipator design, it is not necessary to check the culvert hydraulics any further.
- Ensure that the proposed dissipator will adequately pass debris expected at the site, or that it will not require excessive maintenance.
- Check whether the proposed energy dissipator, and any needed riprap apron, will be contained within the proposed right-of-way. If not, it may be necessary to obtain a permanent drainage easement to accommodate the structure.

9.04.2.2 NOTES ON HEC-14 PROCEDURES

Although the FHWA HEC-14 document provides detailed procedures for the design of the energy dissipators discussed in this Manual, there are points at which specific comments may be helpful in applying these procedures. This section provides suggestions and other guidance information intended to aid the designer in developing energy dissipator designs that are consistent with the guidelines set forth in this chapter.

The only dissipator designs for which a detailed procedure is provided in this Manual are the Saint Anthony Falls stilling basin and the USBR Type VI impact basin.

9.04.2.2.1 HEC-14 PROCEDURE FOR RIPRAP BASINS

The TDOT Standard Drawing EC-STR-21 and section 10.08.3 of this manual provide design details for a permanent riprap basin energy dissipator. The procedure provided in HEC-14 should be used to design a riprap basin. The designer should carefully note the differences between the Standard Drawings and HEC-14 in regard to the variable names assigned to the various dimensions of the basin.

Equation 10.1 in HEC-14 may be used to compute the required depth of a riprap basin (H_1 in the Standard Drawings or h_s in HEC-14) in a ratio with the equivalent depth (d_e) at the culvert outfall. This equation contains a correction factor, C_o , which varies with the tailwater depth. This correction factor is computed by one of two sets of equations (10.2 or 10.3) depending on whether a more conservative design is desired. In general Equation 10.2 will result in basin depths 1 to 2 feet greater than will Equation 10.3; however, it will also allow a basin to be used in a greater number of situations and is therefore recommended for use.

The application of Equation 10.1 is based on assuming a value for the D_{50} of the riprap and then back-checking to ensure that the resulting value for H_1 meets the following criteria:

$$\frac{H_1}{D_{50}} \geq 2 \tag{9-9}$$

Theoretically, the most efficient design would be to find select a rock gradation such that the value of this ratio is as close to 2 as possible. In practice, the design should be based on one of the standard TDOT classes of machined riprap. D_{50} values for TDOT machined riprap may be found in Section 5.04.7. For the great majority of situations where a riprap stilling basin will be feasible, the value of H_1 determined by Equation 10.1 will be between 1.5 and 2.5 feet, even with using Equation 10.2 to determine C_o . Thus, Machined Riprap (Class B or C) will be used to construct the basin only for comparatively large culvert installations. For many smaller culverts, the value of H_1 determined by Equation 10.1 will be zero or negative, especially where the tailwater depth is more than approximately 85% of the equivalent depth at the culvert outfall. It is recommended that a riprap apron be considered for these situations.

NOTE A - IF EXIT VELOCITY OF BASIN IS SPECIFIED, EXTEND BASIN AS REQUIRED TO OBTAIN SUFFICIENT CROSS-SECTIONAL AREA AT SECTION A-A SUCH THAT $Q_{des}/(\text{CROSS SECTION AREA AT SEC. A-A}) = \text{SPECIFIED EXIT VELOCITY}$.

NOTE B - WARP BASIN TO CONFORM TO NATURAL STREAM CHANNEL. TOP OF RIPRAP IN FLOOR OF BASIN SHOULD BE AT THE SAME ELEVATION OR LOWER THAN NATURAL CHANNEL BOTTOM AT SEC. A-A.

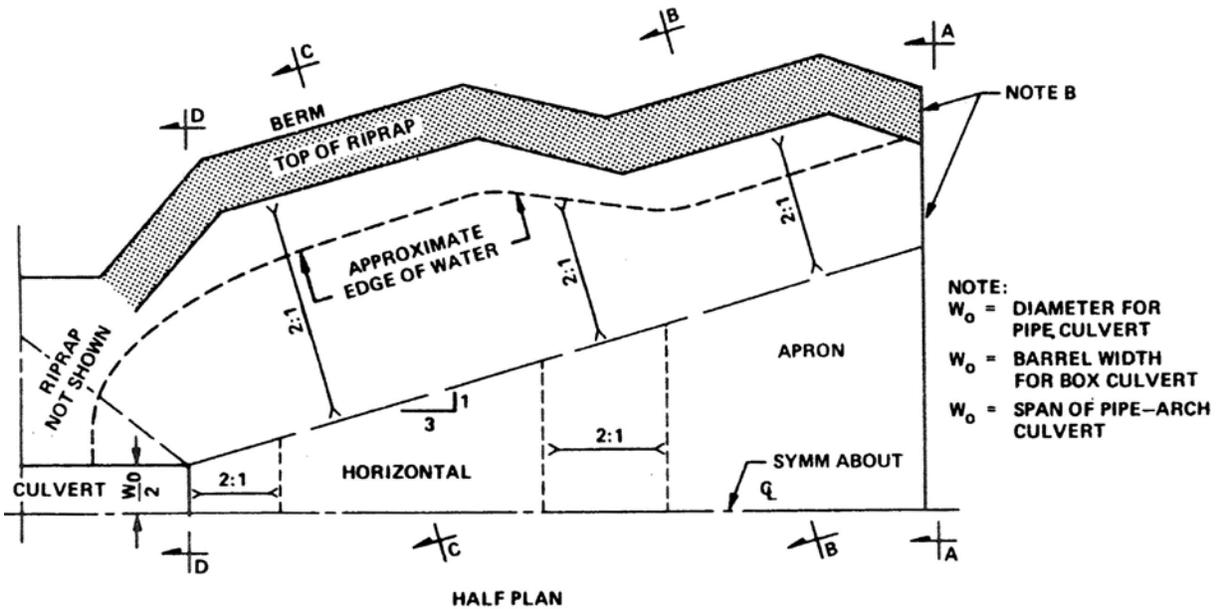
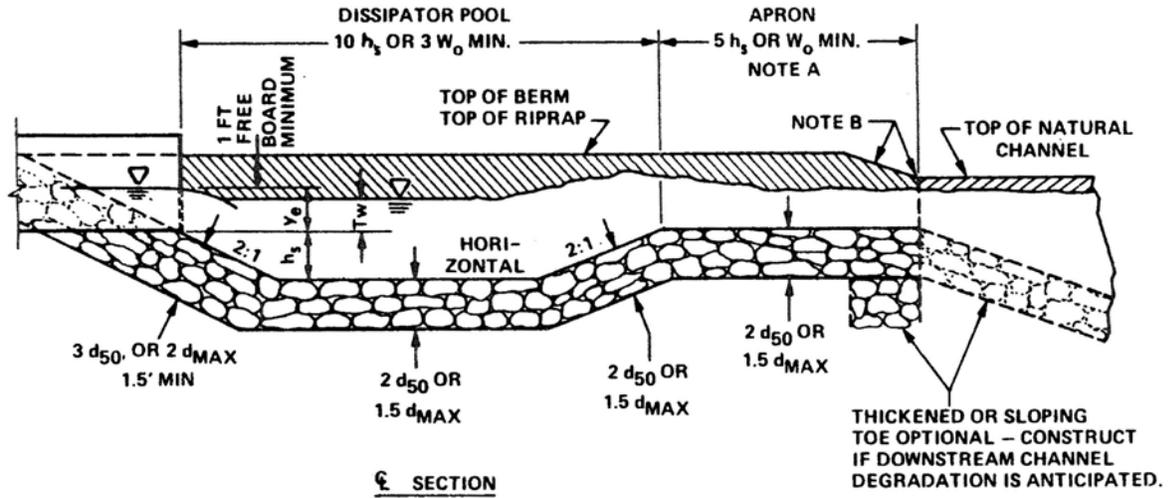


Figure 9-9
 Typical Riprap Stilling Basin
 Reference: USDOT, FHWA, HEC-14 (1983)

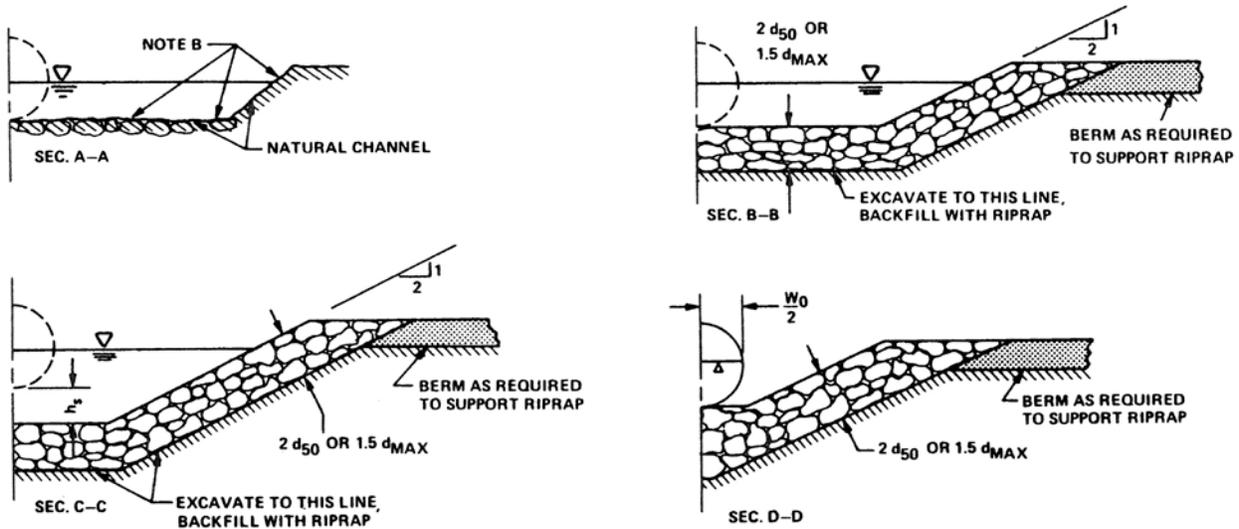


Figure 9-10
 Typical Riprap Stilling Basin
 Reference: USDOT, FHWA, HEC-14 (1983)

9.04.2.2.2 HEC-14 PROCEDURES FOR INTERNAL ENERGY DISSIPATORS

The FHWA publication HEC-14 provides design procedures for internal roughness elements which serve to dissipate energy either by producing tumbling flow or by presenting increased roughness. The Appendix to this chapter provides design computation worksheets for both types of flow in box culverts. Although HEC-14 includes procedures for tumbling flow or increased roughness in round pipes as well as box culverts, the use of roughness elements in round pipe is not recommended due to concerns regarding the maintenance of such structures.

9.04.2.2.3 SAINT ANTHONY FALLS STILLING BASIN DESIGN PROCEDURE

As described in Section 9.03.3.4.1, the Saint Anthony Falls (SAF) stilling basin consists of a concrete basin, typically constructed below grade, which forces a hydraulic jump in supercritical flows leaving a culvert outfall. The sidewalls of the basin may be either parallel or flared to provide a transition between the width of the chute and the width of the stream cross section at the basin outfall. As shown in Figure 9-11, the degree of flare is measured by the parameter z , which is the longitudinal distance needed to widen one side of the flare by 1 foot. The minimum allowable value for z should be 2.0.

In general, the design of an SAF basin should consist of the following parts:

- determine the culvert outlet flow characteristics
- compare the sequent depth of the culvert outflow to the tailwater depth in order to estimate the required basin depth
- determine the dimensions of the basin
- select the sidewall configuration (parallel or flared) and z -value based on local conditions

- based on the dimensions determined in the previous step, evaluate whether the design should be modified to better fit the site

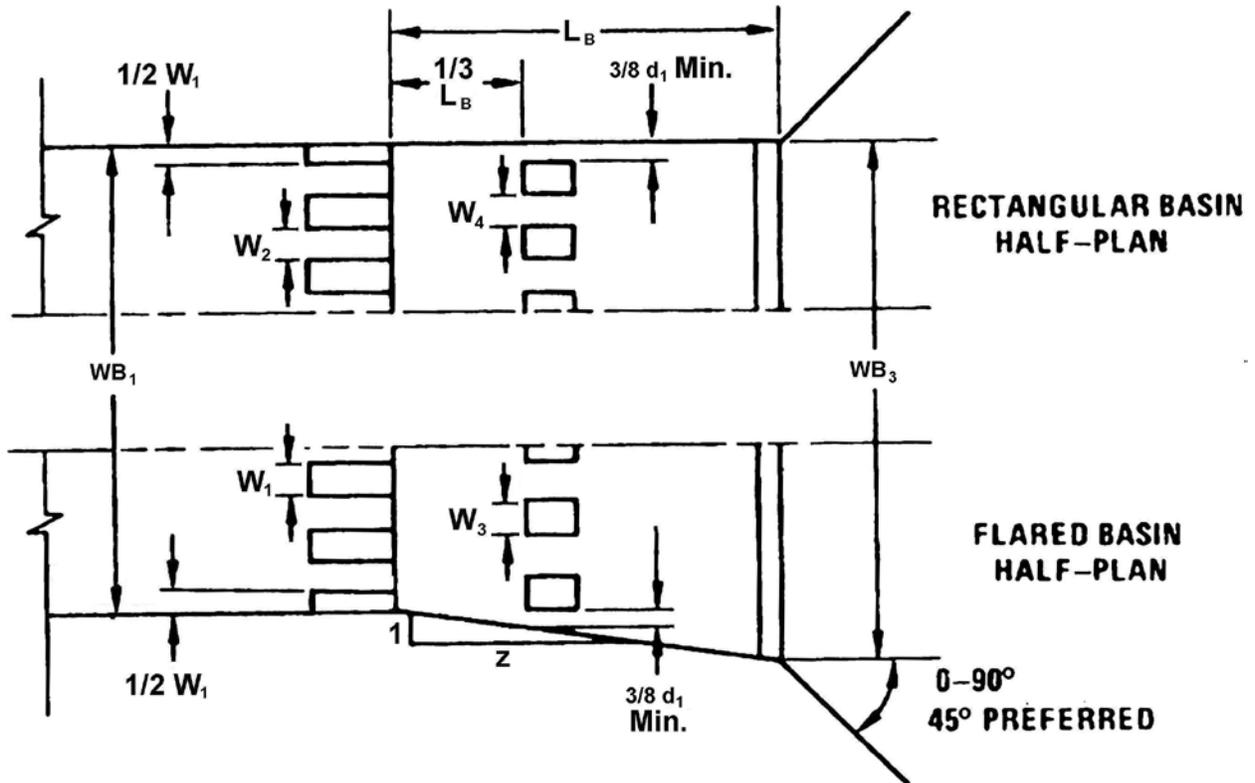


Figure 9-11
 Saint Anthony Falls (SAF) Stilling Basin Plan
 Reference: USDOT, FHWA, HEC-14 (1983)

A complete diagram of the design dimensions for a Saint Anthony Fall Basin may be found in Figure 9A-5.

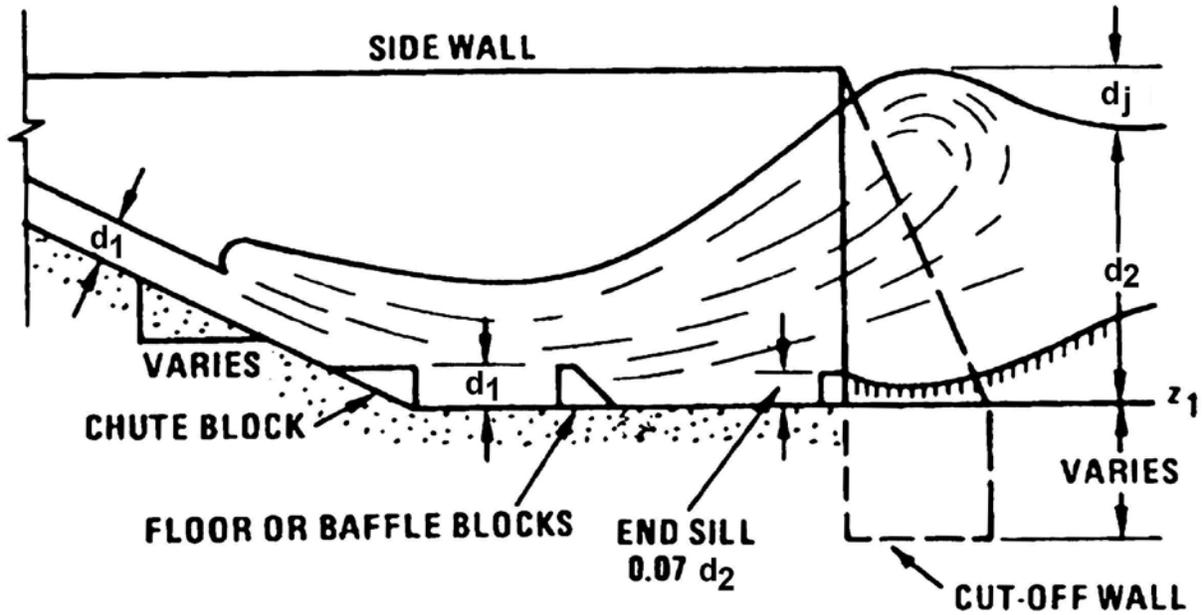


Figure 9-12
 Saint Anthony Falls (SAF) Stilling Basin Profile
 Reference: USDOT, FHWA, HEC-14 (1983)

The specific design procedure should be as follows:

Step 1: Using the procedures outlined in Section 9.04.1.2, determine the culvert brink depth, d_o , outlet flow velocity, V_o , and the Froude Number of the outlet flow, Fr_o .

Step 2: Determine the depth of flow in the channel cross section downstream of the culvert, TW , based on the procedure provided in Section 5.06.1.3.4.

Step 3: Determine the width of the basin, WB_1 (if the basin is flared, this width would be applied to the chute), the slope of the chute, and backslope of the basin. If the culvert is a concrete box, WB_1 will be equal to the span of the culvert. If the culvert is not rectangular, W_B would be the greater of:

$$WB_1 = D_o \tag{9-10}$$

or:

$$WB_1 = 0.3D_o \frac{Q}{D_o^{2.5}} \tag{9-11}$$

Where: WB_1 = width of the basin, (ft)
 D_o = diameter of the culvert, (ft)
 Q = design flow rate, (ft³/s)

The chute of the basin is described by the parameter X_f such that the slope (expressed as the ratio H:V) would be $X_f:1$. Similarly, the backslope X_s of the basin is described as $X_s:1$. Values for X_f and X_s should normally be either 2 or 3.

Step 4: Compute the theoretical sequent depth d_{jo} for the culvert outflow as:

$$d_{jo} = d_o \frac{(1 + 8Fr_o^2)^{0.5} - 1}{2} \quad (9-12)$$

Where: d_{jo} = sequent depth, (ft)
 d_o = culvert brink depth, (ft)
 Fr_o = Froude Number of the outlet flow

Step 5: Based on the Froude Number of the culvert outflow, Fr_o , compute the actual hydraulic jump height, d_2 , from one of the following equations.

- For $1.7 \leq Fr_o < 5.5$ use:

$$d_2 = (1.1 - \frac{Fr_o^2}{120})d_{jo} \quad (9-13)$$

- For $5.5 \leq Fr_o < 11$ use:

$$d_2 = 0.85d_{jo} \quad (9-14)$$

- For $11 \leq Fr_o < 17$ use:

$$d_2 = (1.0 - \frac{Fr_o^2}{800})d_{jo} \quad (9-15)$$

Step 6: Compare the jump height, d_2 , with the tailwater depth, TW, computed in Step 2. In most situations, the jump height will be greater than the tailwater depth. Where this is not the case, another type of dissipator may need to be selected. Otherwise, the elevation of the floor of the basin should be lowered, such that the water surface at a depth of d_2 on the basin floor is below the water surface at a depth of TW in the natural channel.

Because the chute of the stilling basin will be steeper than the culvert slope, water on the chute will flow at a much higher velocity and lower depth than in the culvert. This serves to increase the strength of the hydraulic jump on the basin floor, which will, in turn, increase its height. This will result in a greater value for d_2 than what was computed in Step 5. Thus, the determination of the elevation of the basin floor, z_1 becomes a trial and error process. The elevation of the floor should be varied until the computed value of d_2 results in a water level in the basin that is below the water surface elevation at the depth TW downstream of the basin.

A first estimate of the floor elevation may be obtained from:

$$z_1 = z_o - 1.5(d_2 - TW) \quad (9-16)$$

Where: z_1 = elevation of the basin floor, (ft)
 z_o = elevation of the culvert outfall, (ft)
 d_2 = jump height, as computed in Step 5, (ft)
 TW = downstream tailwater depth, (ft)

Step 7: The depth of flow, d_1 , on the chute just upstream of the chute blocks may be computed from Equation 9-17, as follows:

$$Q = d_1 WB_1 \left[2g(z_o - z_1 + d_o - d_1) + V_o^2 \right]^{0.5} \quad (9-17)$$

Where: Q = design discharge, (ft³/s)
 d_1 = flow depth on chute upstream of chute blocks, (ft)
 WB_1 = width of the basin, (ft)
 g = acceleration due to gravity, (32.2 ft/sec²)
 z_o = elevation of the culvert outfall, (ft)
 z_1 = elevation of the basin floor, (ft)
 d_o = depth of flow at outlet, (ft)
 V_o = culvert outlet velocity, (ft/s)

Since there is no direct solution for d_1 in Equation 9-17, d_1 must be determined by trial and error.

Step 8: Compute the velocity of flow V_1 on the chute as:

$$V_1 = \frac{Q}{WB_1 d_1} \quad (9-18)$$

The Froude Number of the chute flow would then be computed as:

$$Fr_1 = \frac{V_1}{(g \times d_1)^{0.5}} \quad (9-19)$$

Where: Fr_1 = Froude Number of the flow just upstream of the chute blocks
 V_1 = flow velocity on the chute, (ft/s)
 g = acceleration due to gravity, (32.2 ft/sec²)
 d_1 = flow depth on foreslope upstream of chute blocks, (ft)

Step 9: Compute the hydraulic jump sequent depth and jump height for the flow on the basin chute. Equation 9-12 would be used to compute the sequent depth, and either Equation 9-13, 9-14, or 9-15 would be selected to compute the jump height depending on Fr_1 . However, when these equations are applied for this step:

- the jump height on the basin floor, d_j , would be substituted for the jump height at the outlet, d_{j_o}
- the depth of flow on the basin chute, d_1 , would be substituted for the flow depth at the culvert outlet, d_o , and
- the Froude Number, Fr_1 , on the basin chute would be substituted for the Froude Number at the culvert outfall, Fr_o

Step 10: Determine the total length of the basin, L , so that a value can be determined for z_3 . The length of the chute, L_f , may be computed using Equation 9-20:

$$L_f = X_f (z_o - z_1) \quad (9-20)$$

Where: L_f = chute length, (ft)
 X_f = horizontal component of chute H:V ratio (when 2H:1V, $X_f = 2$)
 z_o = elevation of the culvert outfall, (ft)
 z_1 = elevation of the basin floor, (ft)

The length of the basin floor, L_B , may be computed from Equation 9-21:

$$L_B = \frac{4.5d_j}{Fr_1^{0.76}} \quad (9-21)$$

Where d_j and Fr_1 are the hydraulic jump sequent depth and Froude Number computed in Step 9.

Using Equation 9-22, the length of the basin backslope, L_s , may be computed as:

$$L_s = \frac{z_o - z_1 - (L_f + L_B)S_n}{\frac{1}{X_s} + S_n} \quad (9-22)$$

Where: L_s = basin backslope length, (ft)
 L_f = basin chute length, (ft)
 L_B = length of basin floor, (ft)
 X_s = horizontal component of backslope H:V ratio (when 3H:1V, $X_s = 3$)
 z_o = elevation of the culvert outfall, (ft)
 z_1 = elevation of the basin floor, (ft)
 S_n = slope of the natural stream downstream of culvert, (ft/ft)

The length of the basin can now be computed using Equation 9-23:

$$L = L_f + L_B + L_s \quad (9-23)$$

and, z_3 , the elevation at the downstream end of the basin, is computed by solving Equation 9-24:

$$z_3 = z_1 + \frac{L_s}{X_s} \quad (9-24)$$

Check the value of d_2 computed in Step 9 by the following expression:

$$z_1 + d_2 \leq z_3 + TW \quad (9-25)$$

If this expression is found not to be true, a new value for z_1 would be selected and the process would return to Step 7.

Step 11: Based on the channel configuration at the stilling basin outlet, determine whether a straight or a flared basin will best fit the site. If a flared basin is selected, the width of the basin at the outlet, WB_4 , should be determined based on the channel bottom width and the degree of flare, z , and should be computed from Equation 9-26:

$$z = \frac{2(L_B + L_s)}{WB_4 - WB_1} \quad (9-26)$$

Where:
 z = degree of flare
 L_B = length of the basin floor, (ft)
 L_s = length of the backslope, (ft)
 WB_1 = width of the chute, (ft)
 WB_4 = width of the basin at the downstream end, (ft)

The computed value of z should be 2.0 or greater. If not, the designer should return to Step 3 and modify the basin so that it will be longer.

Step 12: Determine the dimensions and spacing of the chute blocks. As shown in Figure 9-12, the height of the chute blocks, h_1 , above the basin floor should be approximately equal to the approach depth, d_1 . If necessary, h_1 may be rounded somewhat to simplify construction. The width of each block, W_1 , should be equal to the spacing between each block, W_2 , such that:

$$W_1 = W_2 = 0.75d_1 \quad (9-27)$$

Where:
 W_1 = width of the blocks on the chute
 W_2 = width of the spaces between the blocks
 d_1 = flow depth on the chute

The number of chute blocks, N_b , may then be determined from Equation 9-28:

$$N_b = \frac{WB_1}{2W_1} \quad (9-28)$$

Where: WB_1 is the width of the basin and the other parameters are as previously defined.

The result of this equation should be rounded to the nearest whole number. W_1 and W_2 should then be adjusted such that:

$$N_b(W_1 + W_2) = WB_1 \quad (9-29)$$

The chute blocks should be arranged at the toe of the chute as depicted in Figure 9-11. Half-blocks, with a width of $\frac{1}{2} W_1$ are attached to each side wall, with the other blocks spaced evenly in between.

Step 13: The floor (or baffle) blocks should be arranged on the basin floor such that the leading edge of the blocks is a distance equal to $L_B/3$ from the end of the chute blocks. In a basin with parallel walls, the floor blocks would have the same width and spacing as the chute blocks. However, they would be staggered with respect to the chute blocks such that each floor block is directly in front of a space between the chute blocks. In a flared basin, the width and spacing of the floor blocks, W_3 and W_4 respectively, may be increased so that the number of floor blocks is still the same as the number of chute blocks. However, the distance from the basin sidewall to the nearest floor block should be no less than $\frac{3}{8} d_1$, and W_3 should be equal to W_4 .

WB_2 , the width of the basin at the leading edge of the floor blocks, may be computed from:

$$WB_2 = WB_1 + \frac{2L_B}{3z} \quad (9-30)$$

Where: WB_1 = width of the chute, (ft)
 L_B = length of the basin floor, (ft)
 z = degree of flare

The total width of the floor blocks, $N_b W_3$, should be such that:

$$0.40WB_2 \leq N_b W_3 \leq 0.55WB_2 \quad (9-31)$$

Where this is not true, it will be necessary to adjust the block width and spacing.

The height of the floor blocks, h_2 , should be equal to the height of the chute blocks, h_1 , determined in the previous step.

Step 14: Even where the basin is a number of feet below grade, it should be provided with an end sill at the downstream end of the floor. The height of this sill, h_3 , should be equal to $0.07d_j$, where d_j is the hydraulic jump sequent depth computed in Step 9. The width of a flared basin at the sill, WB_3 , may be computed from:

$$WB_3 = WB_1 + \frac{2L_B}{z} \quad (9-32)$$

Where: WB_1 = width of the chute, (ft)
 L_B = length of the basin floor, (ft)
 z = degree of flare

Step 15: The height of the basin sidewalls, with respect to the basin floor should be equal to $d_2 + d_i/3$. In addition, these walls should extend the full length of the basin, L , from the culvert outfall. As depicted in Figure 9-12, the sidewalls should be provided with wingwalls at the downstream end of the basin. The angle of the wingwalls with respect to the basin should be as close as possible to 45° .

Step 16: Design any additional erosion protection that may be needed at the basin outfall. This might include a cut-off wall with a depth consistent with Section 9.04.2.2.6, as well as a riprap apron.

The approximate average flow velocity at the downstream end of the basin may be computed by using Equation 9-33 as follows:

$$V_2 = \frac{Q}{(z_1 + d_2 - z_3)WB_4} \quad (9-33)$$

Where: V_2 = average velocity at the downstream end of the basin, (ft/s)
 Q = design flow rate, (ft³/s)
 z_1 = elevation of the basin floor, (ft)
 d_2 = jump height, as computed in Step 5, (ft)
 z_3 = elevation of the basin at downstream end, (ft)
 WB_4 = width of the basin at the downstream end, (ft)

When V_2 is significantly greater than the natural stream flow velocity, erosion protection should be provided in the form of a riprap apron designed in accordance with Section 6.05.5.

9.04.2.2.4 USBR TYPE VI IMPACT BASIN DESIGN PROCEDURE

The FHWA publication HEC-14 provides a very simple procedure for selecting the dimensions of a USBR Type VI impact basin. However, it does not include detailed instructions for estimating the total energy loss through the structure, nor does it provide specific guidance on the design of any riprap apron that may be required at the outlet. This section presents the HEC-14 method for determining the dimensions of the basin (see Figures 9-5, 9-6, and 9-13) as well as a few additional steps which may be helpful in completing the design.

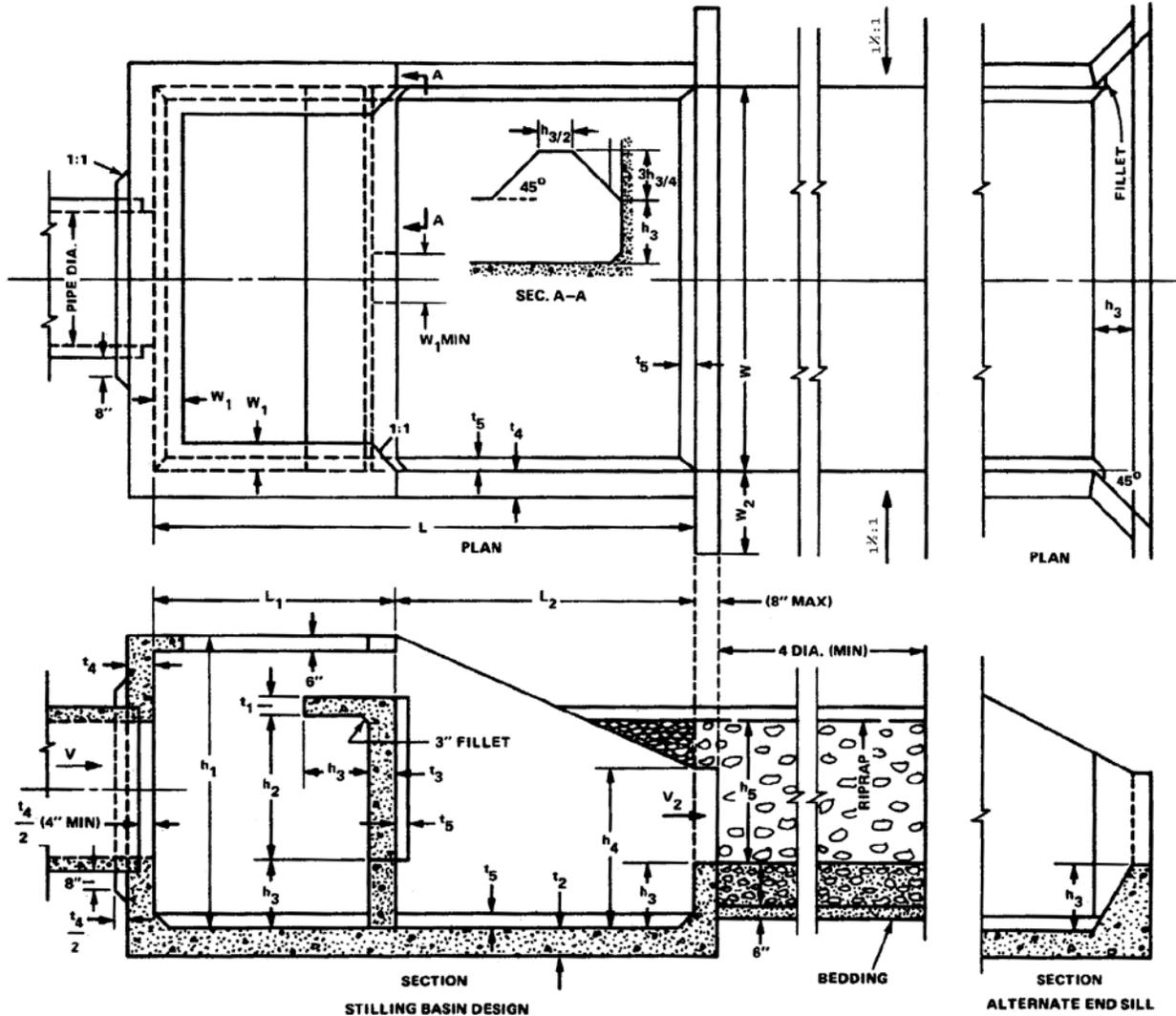


Figure 9-13
 Typical USBR Type VI Baffled Dissipator
 Reference: USDOT, FHWA, HEC-14 (1983)

Step 1: Determine the depth, d_o , equivalent depth, d_e , velocity, V_o , and Froude Number, Fr_o of the flow at the culvert outlet using the procedures provided in Section 9.04.1.2. In addition, determine the depth of flow (tailwater) in the stream cross section downstream of the basin. This may be computed using the procedure provided in Section 5.06.1.3.4.

Step 2: Compute the specific energy, H_o , of the culvert outflow using Equation 9-34:

$$H_o = d_o + \frac{V_o^2}{2g} \tag{9-34}$$

Where: H_o = specific energy of culvert outflow, (ft)
 d_o = depth of flow at the outlet, (ft)
 V_o = velocity of flow at the outlet, (ft/s)
 g = acceleration due to gravity, (32.2 ft/sec²)

Step 3: Compute a value for the ratio of the outlet specific energy, H_o , to the width of the basin, W , from Equation 9-35:

$$\frac{H_o}{W} = 0.0348Fr_o^2 + 0.1343Fr_o + 0.1128 \quad (9-35)$$

Where: H_o = specific energy of the culvert outflow, (ft)
 W = width of the impact basin, (ft)
 Fr_o = Froude Number of the culvert outflow

Determine the required width, W , of the basin by dividing the specific energy computed in Step 2 by the value for H_o / W determined by Equation 9-35. The result should be rounded to the nearest foot.

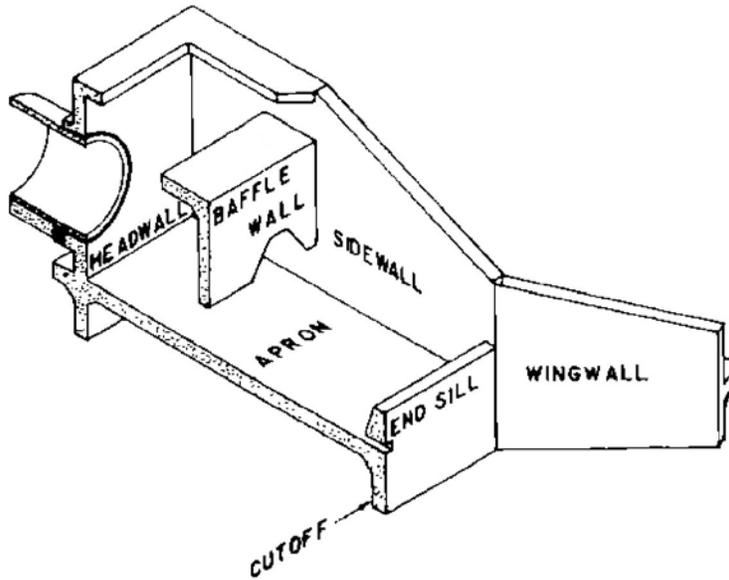


Figure 9-14
 “Cut-Away” Isometric View of a Typical USBR Type VI Baffled Dissipator
 Reference: USDA, NRCS, TR-49 (1971)

Step 4: Based on the computed value of W in Step 3, obtain values for h_2 and h_3 from Table 9A-2 in the Appendix and verify that Equation 9-36 is true.

$$TW \leq h_3 + \frac{h_2}{2} \quad (9-36)$$

Where: TW = tailwater depth computed in Step 1, (ft)

If Equation 9-36 is not true, the culvert outlet and the basin should be raised such that the height of the tailwater surface above the end sill will make the expression true. This will have the effect of changing the slope of the culvert. Usually, this will require the culvert performance be reanalyzed and the procedure would begin again from Step 1.

Step 5: The remaining dimensions of the basin should be determined from Table 9A-2 in the Appendix.

Step 6: Compute a value for the ratio of the head lost, H_L , in the impact basin to the specific energy, H_o , at the culvert outlet from Equation 9-37. Equation 9-37 utilizes the natural log of the Froude Number at the culvert outlet.

$$\frac{H_L}{H_o} = 0.2718 \ln(Fr) + 0.2328 \quad (9-37)$$

Where: H_L = head lost in the impact basin, (ft)
 H_o = specific energy at the culvert outlet, (ft)
 Fr = Froude Number of the culvert outflow

The ratio computed above may then be multiplied by H_o to estimate the total energy lost in the basin.

Step 7: Compute the energy, H_E , at the basin outlet as:

$$H_E = H_o - H_L \quad (9-38)$$

Step 8: Determine the depth of flow, d_E , at the basin outlet. There are three possible values for this depth. The first possible value is based on the energy at the basin outlet and may be estimated from Equation 9-39:

$$H_E = d_E + \frac{\left[\frac{Q}{W \times d_E} \right]^2}{2g} \quad (9-39)$$

Where: H_E = energy at the basin outlet
 d_E = depth of flow over end sill, (ft)
 Q = design discharge, (ft³/s)
 W = basin width at the end sill, (ft)
 g = acceleration due to gravity, (32.2 ft/sec²)

This equation should be solved for d_E using trial and error. Typically, two values for d_E will be possible from this expression, one in the supercritical regime and the other in the subcritical regime. The subcritical solution, which will involve the greater value of d_E , should be considered for use.

The second possible value for d_E is the critical depth of flow across the end sill at the design discharge. This may be computed from the equation:

$$d_{Ec} = \left[\frac{Q}{W\sqrt{g}} \right]^{0.667} \quad (9-40)$$

Where: d_{Ec} = critical depth at the end sill, (ft)
 Q = design discharge, (ft³/s)
 W = basin width at the end sill, (ft)
 g = acceleration due to gravity, (32.2 ft/sec²)

The third possible value for d_E is the depth of flow (tailwater) in the channel cross section downstream of the basin, which was determined in Step 1.

The value to be used for the depth of flow at the end sill may be determined by comparing the tailwater depth with the other possible values for d_E . Where the tailwater depth is greater than d_E , as computed from the energy at the basin outlet, d_E will be equal to TW. Where TW is less than the critical depth, d_{Ec} , the outlet depth will be equal to d_{Ec} . Where TW is between the two values, d_E may be assumed to be equal to the value computed based on energy loss.

Step 9: The flow velocity, V_E , across the basin sill can be computed using Equation 9-41:

$$V_E = \frac{Q}{W \times d_E} \quad (9-41)$$

When V_E is significantly greater than the natural stream flow velocity, erosion protection should be provided in the form of a riprap apron designed in accordance with Section 6.05.5.

Step 10: It is recommended that the basin outlet be provided with a cut-off wall. The depth of this wall may be determined based on Section 9.04.2.2.6.

9.04.2.2.5 HEC-14 PROCEDURE FOR HOOK IMPACT BASINS

HEC-14 provides design information on hook impact basins, which may be constructed as either straight or flared trapezoidal basins. In general, the straight trapezoidal basin is recommended for use. The following comments, as well as the design form provided in the Appendix (Figure 9A-7), are based on that assumption.

The dimensions of a hook type impact basin (see Figure 9-15) may be selected using the procedure provided in HEC-14 for straight trapezoidal basins, taking into account the following notes:

1. The trapezoidal shape of the basin should be modified to fit the downstream channel as well as possible. Once the effective width of the culvert cross section, W_o in HEC-14, has been determined, the width of the trapezoid floor, W_6 in HEC-14, may be any width between W_o and 2 times W_o , to match the existing channel bottom width as closely as possible.

2. All three hooks should have the same width, W_4 , which is equal to 0.16 times the effective culvert width, W_o . Other dimensions necessary for the proper design of the hooks can be determined from Figure 9-16.

3. When the guidance provided in HEC-14 is followed, the width between the two upstream hooks, W_2 , plus the width of the two hooks, should be approximately equal to the effective culvert width. This spacing will not change when the floor width, W_6 , is greater than W_o .

4. Further, when the HEC-14 procedure is followed, the ratio of the spacing between the upstream and downstream hooks, W_3 , to the hook width, W_4 , will always be about 1.6. Therefore, it should not be necessary to check that the ratio is greater than one.

5. HEC-14 provides a graph which may be used to determine the reduction in flow velocity that will be provided by the proposed basin as a function of the Froude Number of the culvert outflow. This graph provides two efficiency curves, one for $W_6 = W_o$ and one for $W_6 = 2W_o$. Where the width of the basin floor, W_6 , is equal to one of these two values, the curves may be used directly to determine the ratio of the culvert outlet velocity, V_o , to the velocity at the basin outlet, V_B . When the floor width falls between these two values, the designer should interpolate between these two curves. A copy of these curves has been reproduced as Figure 9A-8 in the Appendix. As an alternative to using the curves, the designer may choose to interpolate a value for the ratio of the culvert outlet velocity to the basin outlet velocity (V_o / V_B) from Table 9-5.

Culvert Outlet Froude Number	Floor Width = W_o	Floor Width = 2 times W_o
1.8	1.469	1.352
1.9	1.491	1.429
2	1.519	1.528
2.1	1.550	1.646
2.2	1.585	1.792
2.3	1.633	1.899
2.4	1.701	1.970
2.5	1.773	2.013
2.6	1.858	2.051
2.7	1.949	2.089
2.8	2.031	2.122
2.9	2.110	2.164
3	2.180	2.218

Table 9-5
 V_o / V_B versus Culvert Outlet Froude Number for Various Floor Widths
 Reference: Adapted from HEC-14

A value for V_o / V_B may be interpolated from both columns in the table based on a given culvert outlet Froude Number. Based on the proposed basin floor width, the final value would then be interpolated from the two values taken from the table.

6. Where V_B is significantly greater than the natural stream flow velocity, erosion protection should be provided in the form of a riprap apron designed in accordance with Section 6.05.5.

7. It is recommended that the basin outlet be provided with a cut-off wall with a depth as determined based on Section 9.04.2.2.6.

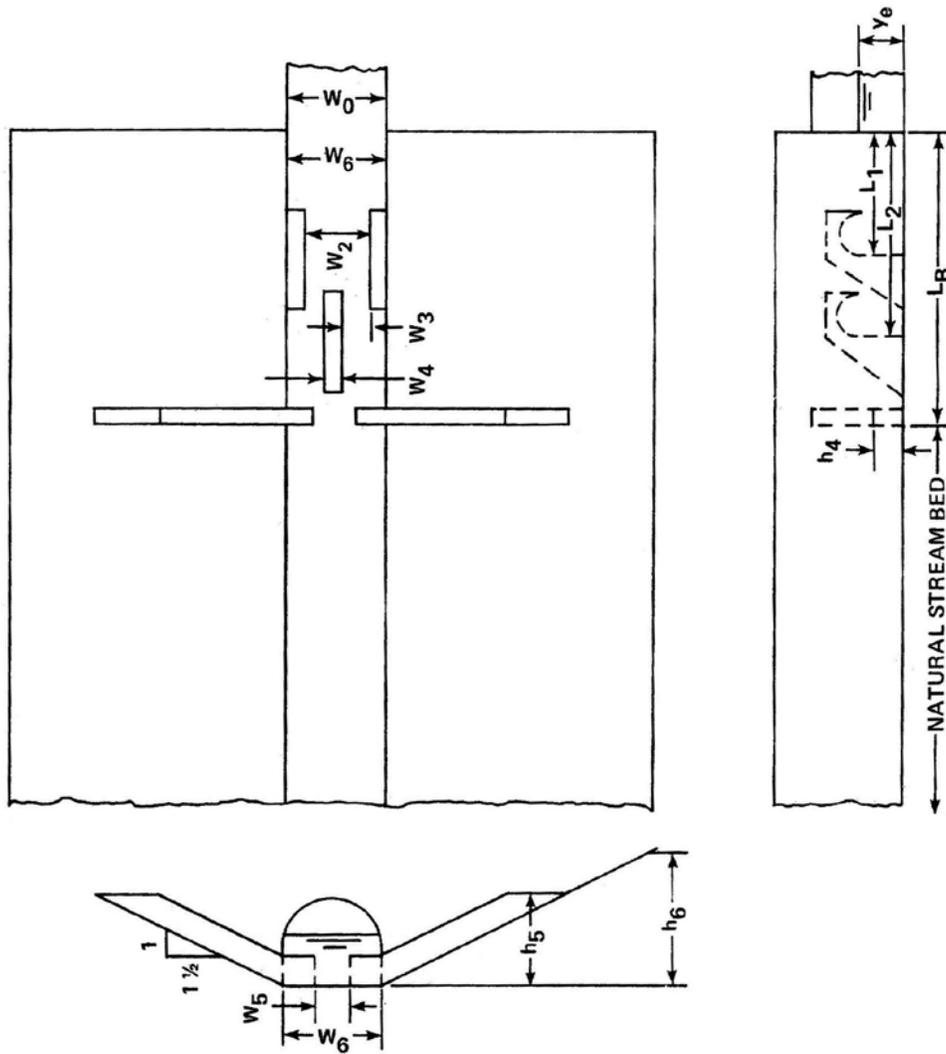
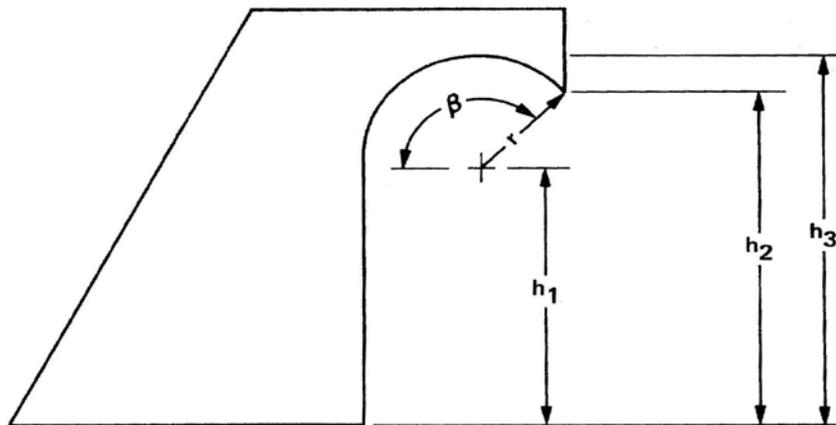


Figure 9-15
 Hook Type Energy Dissipator Basin
 Reference: USDOT, FHWA, HEC-14 (1983)



$$h_2 = v_e$$

$$h_1 = 0.78 v_e$$

$$h_3 = 1.4 h_1$$

$$r = 0.4 h_1$$

$$\beta = 135^\circ$$

Figure 9-16
Hook Detail

Reference: USDOT, FHWA, HEC-14 (1983)

9.04.2.2.6 CUT-OFF WALL DEPTHS

Except in areas where the stream bed is composed of competent bed rock, a cut-off wall should be provided at the outfall of the stilling basin. The cutoff wall should be a minimum of 3 feet deep, unless site-specific conditions require a greater depth.

SECTION 9.05 – ACCEPTABLE SOFTWARE

The software discussed in the following sections should be used for the design of an energy dissipator unless special circumstances on the project require other software. The TDOT design manager should approve the use of any other software for these special circumstances.

9.05.1 COMPUTER PROGRAM HY-8

HY-8 is a Windows™ based computer program developed by the FHWA for culvert design. Energy dissipator design computations using the methods prescribed in HEC-14 are available as a module within HY-8. The program is capable of providing design information for all of the dissipator options described in this chapter as well as a number of other dissipator types discussed in HEC-14. Features of the computer program include:

- scour hole estimation
- design of internal energy dissipators
- design of external energy dissipators
- automatic evaluation of the feasibility of the available dissipator types
- the ability to move seamlessly between the culvert design and energy dissipator design modules
- a convenient means of quickly analyzing a number of dissipator design alternatives for a given site
- output of results to different file formats (.pdf, .rtf or .xls)

The program is available in the Public Domain from the FHWA Hydraulics internet web page.

TDOT DESIGN DIVISION

DRAINAGE MANUAL

CHAPTER IX APPENDIX 9A

SECTION 9.06 – APPENDIX

9.06.1 FIGURES AND TABLES

ENERGY DISSIPATOR WORKSHEET										
Project _____										
Station _____					Structure Type _____					
Design Frequency _____					Discharge (cfs) _____					
Designer _____					Date _____					
CULVERT DATA (See TDOT Drainage Manual, Section 9.04.1.2)										
Type	Size	n-value	Length (feet)	Slope (%)	d _o (feet)	A _o (sf)	V _o (fps)	T (feet)	Fr	End Treatment
TAILWATER SECTION (See TDOT Drainage Manual, Section 5.03.4.1)										
Bottom Width (feet)	Side Slope (X:1)	n-value	Slope (%)	Depth (feet)	Flow Area (sf)	Velocity (fps)	Type of materials in channel			
SCOUR HOLE COMPUTATIONS (See TDOT Drainage Manual, Section 9.04.1.3)										
Time (min)	d _s (feet)	W _s (feet)	L _s (feet)	(Attach Scour Hole Computation Worksheet, TDOT Drainage Manual, Section 9.06.1)						
SITE CONSTRAINTS										
Allowable Outlet Velocity (fps)		Allowable Scour Dimensions			Other Restrictions					
		Width (feet)	Length (feet)	Depth (feet)						
Comments										

Figure 9A-1
Energy Dissipator Worksheet

NATURAL SCOUR HOLE COMPUTATION WORKSHEET				
Project _____				
Station _____		Designer _____		Date _____
BACKGROUND AND DESIGN DATA				
Discharge (cfs)	Culvert Diameter (in)	Culvert Slope (%)	Drop Height (feet)	Peak Flow Duration (min)
MATERIAL STANDARD DEVIATION				
Material Type	<i>(Enter if known)</i>		σ	Note: Use σ = 1.87 for sand or σ = 2.10 for gravel
	d ₁₆ (mm)	d ₈₄ (mm)		
CULVERT HYDRAULIC RADIUS				
Flow Area (square feet)	Wetted Perimeter (feet)	Hydraulic Radius, R _o (feet)		
SCOUR HOLE DIMENSIONS				
	Depth	Width	Length	$\alpha/\sigma^{0.333}$ $[Q / (g^{0.5}R_o^{2.5})]^\beta$ $(t / 316)^\theta$
α	2.27	6.94	17.10	
β	0.39	0.53	0.47	
θ	0.06	0.08	0.10	
F ₁				
F ₂				
F ₃				
C _h				
C _s				
	d _s (feet)	W _s (feet)	L _s (feet)	
C _s C _h F ₁ F ₂ F ₃ R _o				
Comments:				

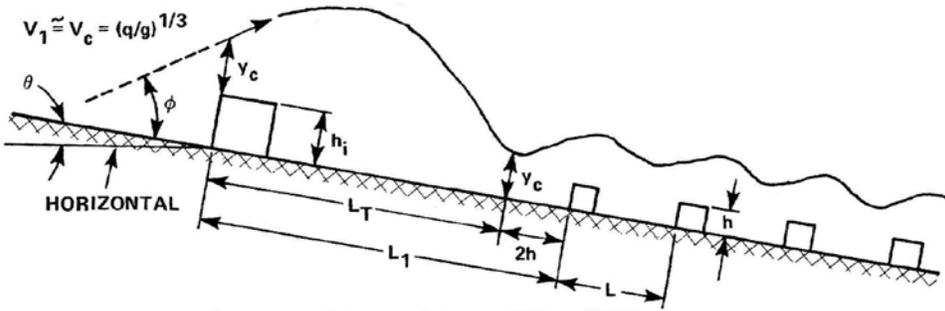
Figure 9A-2
Natural Scour Hole Computation Worksheet

TUMBLING FLOW COMPUTATION WORKSHEET (See notes, following page)

Page 1 of 2

Project _____

Station _____ Designer _____ Date _____



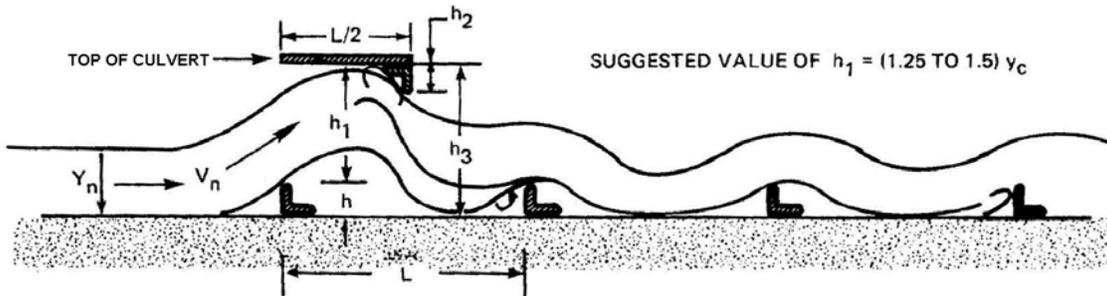
Large Leading Element Configuration

Design Data:

Design Q: _____ (cfs)

Slope: _____ (%)¹

Span (W): _____ (ft)

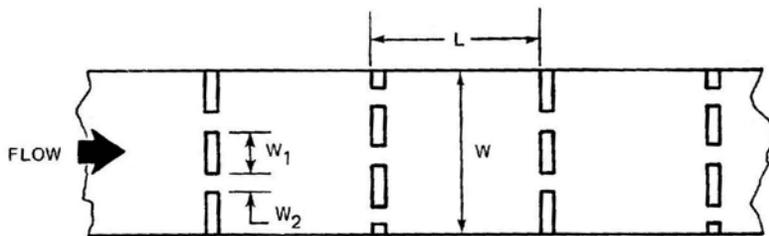


Uniform Element Configuration

Proposed element configuration (check one): Large Leading Uniform

Conditions before Tumbling Flow	$q = Q / W$	d_c (ft)	V_c (fps) ²	d_n (ft)	V_n (fps)	If $d_n > d_c$, method cannot be used

Element Spacing	h (ft)	L / h	L (ft)	d_2 (ft) *	h_i (ft) *	L_1 (ft) *	* Large leading element only



Element Width

$W_2 =$ _____ (ft)

Row #	N_s	W_1
1	2	
2	3	
3	2	
4	3	
5	2	

TUMBLING FLOW COMPUTATION WORKSHEET				
				Page 2 of 2
Baffle & Culvert Rise ³	h_1 (ft)	Height of Jet (ft) ⁴	h_2 (ft)	Culvert rise must be greater than or equal to height of jet

NOTES:

- ¹ If greater than 15% tumbling flow should not be used.
- ² Outlet velocity after tumbling flow will be approximately equal to the critical velocity.
- ³ A top baffle is not required for the large leading element configuration.
- ⁴ Height of jet = h_1+h for uniform elements; d_2 for the large leading element.

Figure 9A-3
Tumbling Flow Computation Worksheet

INCREASED RESISTANCE COMPUTATION WORKSHEET					
Project _____					
Station _____		Designer _____		Date _____	
Initial Culvert Design Data					
Q (cfs)	"Smooth" n^1	Width (ft)	Length (ft)	Slope (%)	If slope > 6%, do not use method
<p>The diagram shows a cross-section of a culvert. A solid line represents the 'Top of Culvert'. A dashed line represents the 'Critical Depth'. Below the culvert, a roughened section is shown with a length 'L'. The depth of the roughened section is 'h'. The roughness height is 'h_r'. The water depth in the roughened section is 'y_i'. The depth of the culvert is 'd_n'. The critical depth is 'd_c'.</p>				Smooth Flow	
				d_n (ft)	
				V_n (fps)	
				d_c (ft)	
				If $d_n > d_c$, do not use	
				Roughened Section ²	
L_r (ft)					
P (ft)					
h / R_i^3					
h (ft) ⁴					
Compute Final Outlet Velocity					
n_r (low)	Y_i (trial)	A_i (sf)	R_i (ft) ⁵	Q (cfs) ⁶	$V_i = Q / A_i$
Compute Required Number of Rows of Elements					
A_f	V_w	N	$L = 10 * h$	Total = N*L	Total length must be < culvert length
Check Height of Culvert for Capacity					
n_r (high)	Y_i (trial)	A_i (sf)	R_i (ft) ⁴	Q (cfs) ⁷	Rise $\geq y_i + h$

NOTES:

- ¹ If culvert actual n-value exceeds 0.015, use 0.015.
- ² P and R_i should be computed assuming that the culvert is flowing full.
- ³ Select a value between 0.1 and 0.4.
- ⁴ Should be $\leq 10\%$ of the depth in the roughened section. If not, select a smaller h / R_i .
- ⁵ Assume that R_i for part full flow is approximately equal to R_i for full flow.
- ⁶ Using Manning's equation with n_r (low), adjust y_i until computed Q matches design Q.
- ⁷ Using Manning's equation with n_r (high), adjust y_i until computed Q matches design Q.

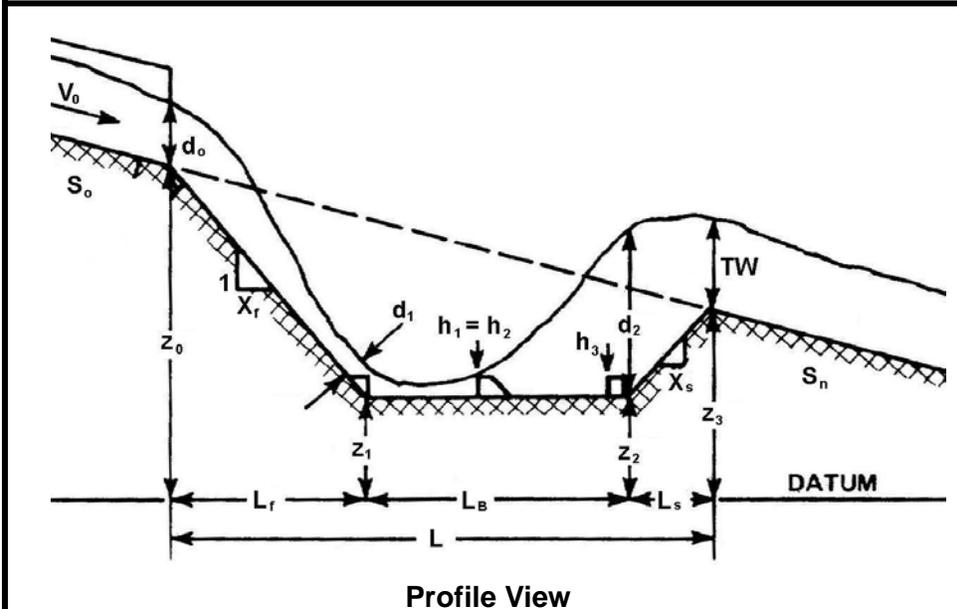
Figure 9A-4
Increase Resistance Computation Worksheet

SAINT ANTHONY FALLS STILLING BASIN DESIGN WORKSHEET

Page 1 of 2

Project _____

Station _____ Designer _____ Date _____



Profile View

Background Information:

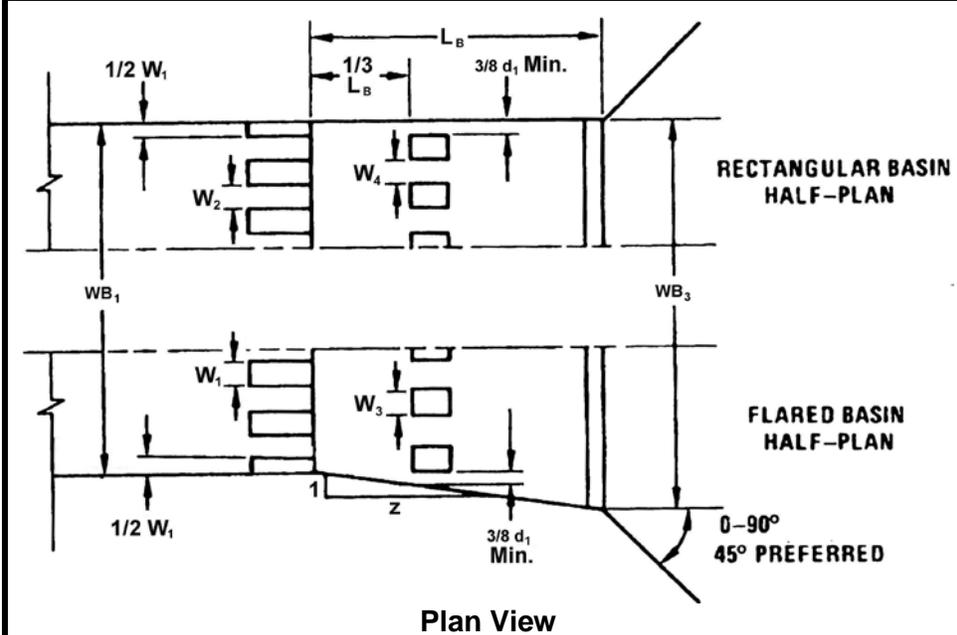
Q = _____
(cfs)

S₀ = _____
(%)

d₀ = _____
(ft)

V₀ = _____
(fps)

Fr = _____



Plan View

Z₀ = _____
(ft)

S_n = _____
(%)

TW = _____
(ft)

d_{jo} = _____
(ft)

d₂ (initial) = _____
(ft)

Initial Basin Parameters

BASIN TYPE (check)	Rect- angular		z (flare)	D _o (ft) ¹	WB ₁ (ft)	X _r	X _s
		Flared					

(Continued next page)

SAINT ANTHONY FALLS STILLING BASIN DESIGN WORKSHEET					
					Page 2 of 2
Basin Dimensions					
z ₁ (trial) (ft)	d ₁ (ft)	V ₁ (fps)	Fr ₁	d _j (ft)	d ₂ (ft)
L _f (ft)	L _B (ft)	L _s (ft)	L (ft)	z ₃ (ft)	
z ₁ + d ₂ (ft)	z ₃ + TW (ft)	[z ₁ + d ₂] must be ≤ [z ₃ + TW]			
Chute Blocks					
h ₁ (ft)	0.75 d ₁ (ft)	N _b	W ₁ (= W ₂) (ft)		
Floor (Baffle) Blocks					
h ₂ (ft)	WB ₂ (ft)	W ₃ (= W ₄)	(N _b W ₃)	(N _b W ₃) / WB ₂ [*]	
Other Basin Details					
End Sill, h ₃ (ft)	Sidewall Height d ₂ + (d _j / 3)	Cutoff Wall Depth (ft)	V ₂ (fps)	Riprap Apron Length (ft)	

NOTES:

¹ Enter diameter for a pipe culvert or span for a box culvert.

^{*} This value should be between 0.40 and 0.55

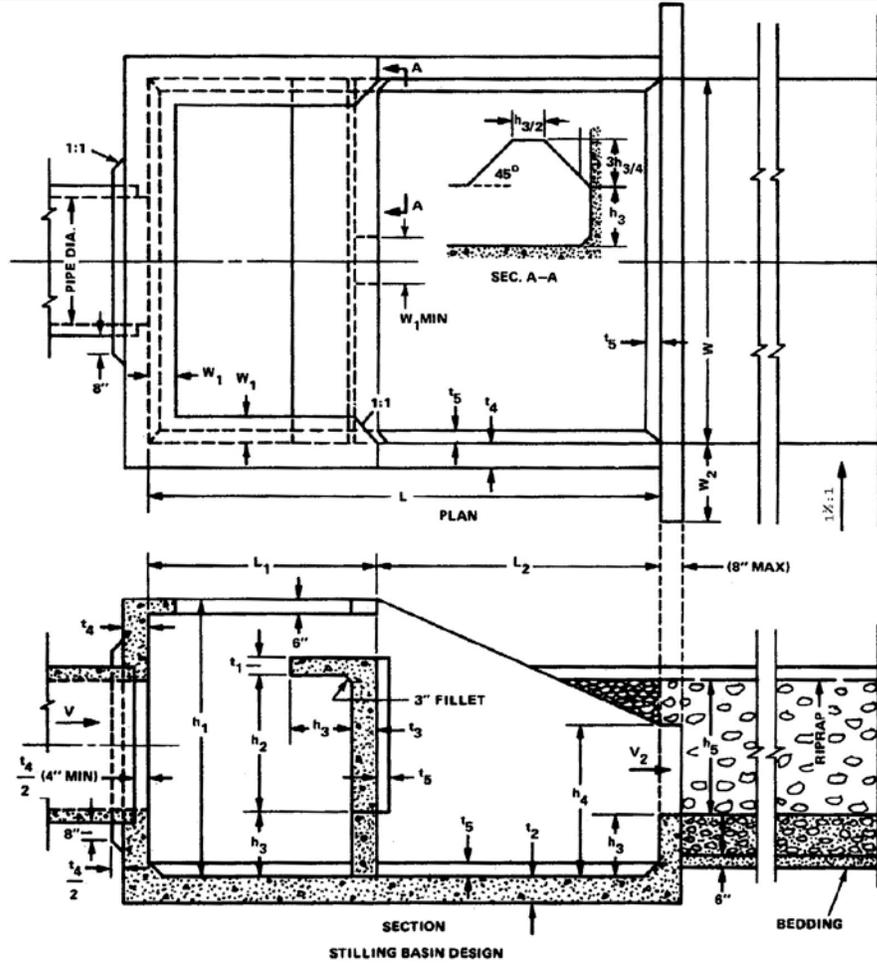
Figure 9A-5
Saint Anthony Falls Stilling Basin Computation Worksheet

USBR TYPE VI IMPACT BASIN DESIGN WORKSHEET

Sheet 1 of 2

Project _____

Station _____ Designer _____ Date _____



Design Information:

Q = _____
(cfs)

TW = _____
(ft)

d_o = _____
(ft)

A_o = _____
(sf)

V_o = _____
(fps)

d_e = _____
(ft)

Fr = _____

H_o = _____
(ft)

Basin Width and Baffle Height

H _o / W	W (ft)	h ₂ (ft)	h ₃ (ft)	h ₂ + (h ₃ /2)	If TW is not ≤ h ₂ +(h ₃ /2), raise the basin

Other Basin Parameters

h ₁ (ft-in)	L (ft-in)	L ₁ (ft-in)	L ₂ (ft-in)	h ₄ (ft-in)	W ₁ (ft-in)
W ₂ (ft-in)	t ₃ (ft-in)	t ₂ (ft-in)	t ₁ (ft-in)	t ₄ (ft-in)	t ₅ (ft-in)

USBR TYPE VI IMPACT BASIN DESIGN WORKSHEET			
			Sheet 2 of 2
Estimate Energy Loss			
H_L / H_o	H_L (ft)	H_E (ft)	
Outlet Depth			
d_E (by energy)	d_{EC} (ft)	d_E (actual) (ft)	d_E (actual) = max of d_E (by energy) and TW if $TW > d_{EC}$. If $TW < d_{EC}$, d_E (actual) = d_{EC}
Other Basin Design Elements			
V_E (fps)	Riprap Apron Length (ft)	Cutoff Wall Depth (ft)	

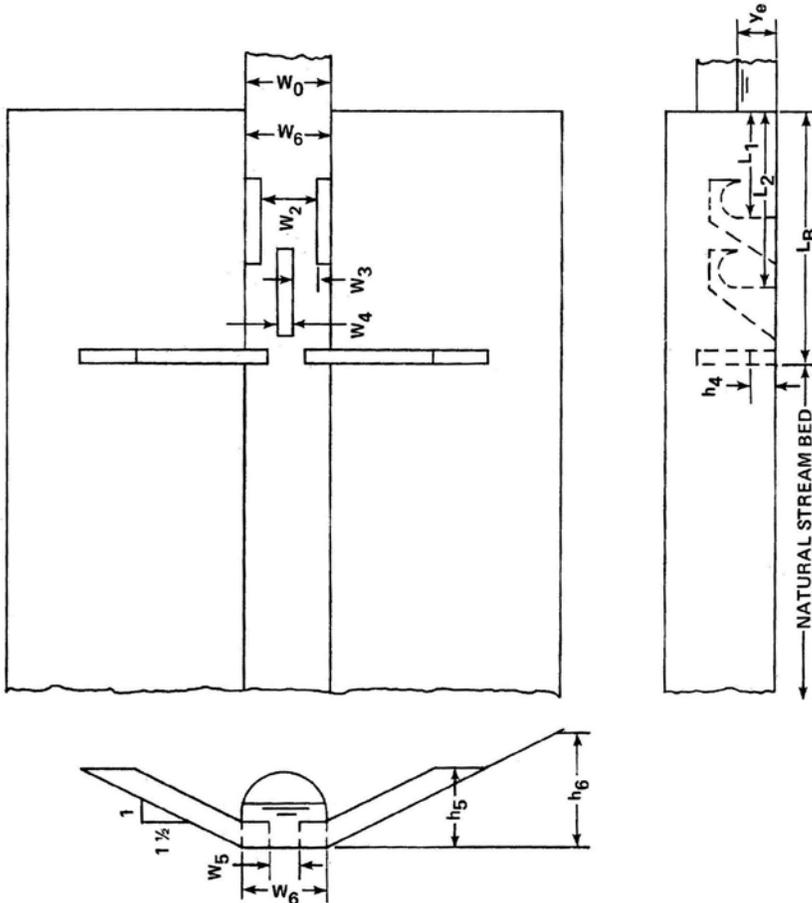
Figure 9A-6
USBR Type VI Impact Basin Design Worksheet

HOOK TYPE IMPACT BASIN DESIGN WORKSHEET

Sheet 1 of 2

Project _____

Station _____ Designer _____ Date _____



Design Information:

Q = _____
(cfs)

TW = _____
(ft)

V_n = _____
(fps)

d_o = _____
(ft)

V_o = _____
(fps)

d_e = _____
(ft)

Fr = _____
(between 1.8 and 3.0 only)

Basin Dimensions

W _o ¹ (ft)		2 x W _o (ft)		W ₆ (ft)		Side Slope		Side slope should be 1½ :1 or 2:1
L ₁ (ft)	L ₂ (ft)	W ₂ (ft)	W ₄ (ft)	W ₅ (ft)	h ₄ (ft)	h ₅ (ft)	h ₆ (ft)	

Continued on following sheet

HOOK TYPE IMPACT BASIN DESIGN WORKSHEET				
<div style="margin-top: 10px;"> $h_2 = d_e$ $h_1 = 0.78d_e$ $h_3 = 1.4 h_1$ $r = 0.4 h_1$ $\beta = 135^\circ$ </div>				<p style="text-align: right;">Sheet 2 of 2</p> <p>Hook Dimensions:</p> <p>$h_1 =$ _____ (ft)</p> <p>$h_2 =$ _____ (ft)</p> <p>$h_3 =$ _____ (ft)</p> <p>$r =$ _____ (ft)</p> <p>$\beta = 135^\circ$ in all cases.</p>
Outlet Velocity and Scour Protection				
W_6 / W_o	V_o / V_B	V_B (fps)	Riprap Apron Length (ft)	Cutoff Wall Depth (ft – in)

NOTE:

¹ W_o = culvert span for box culverts, 2 times d_e for all other shapes.

Figure 9A-7
Hook Type Impact Basin Design Worksheet

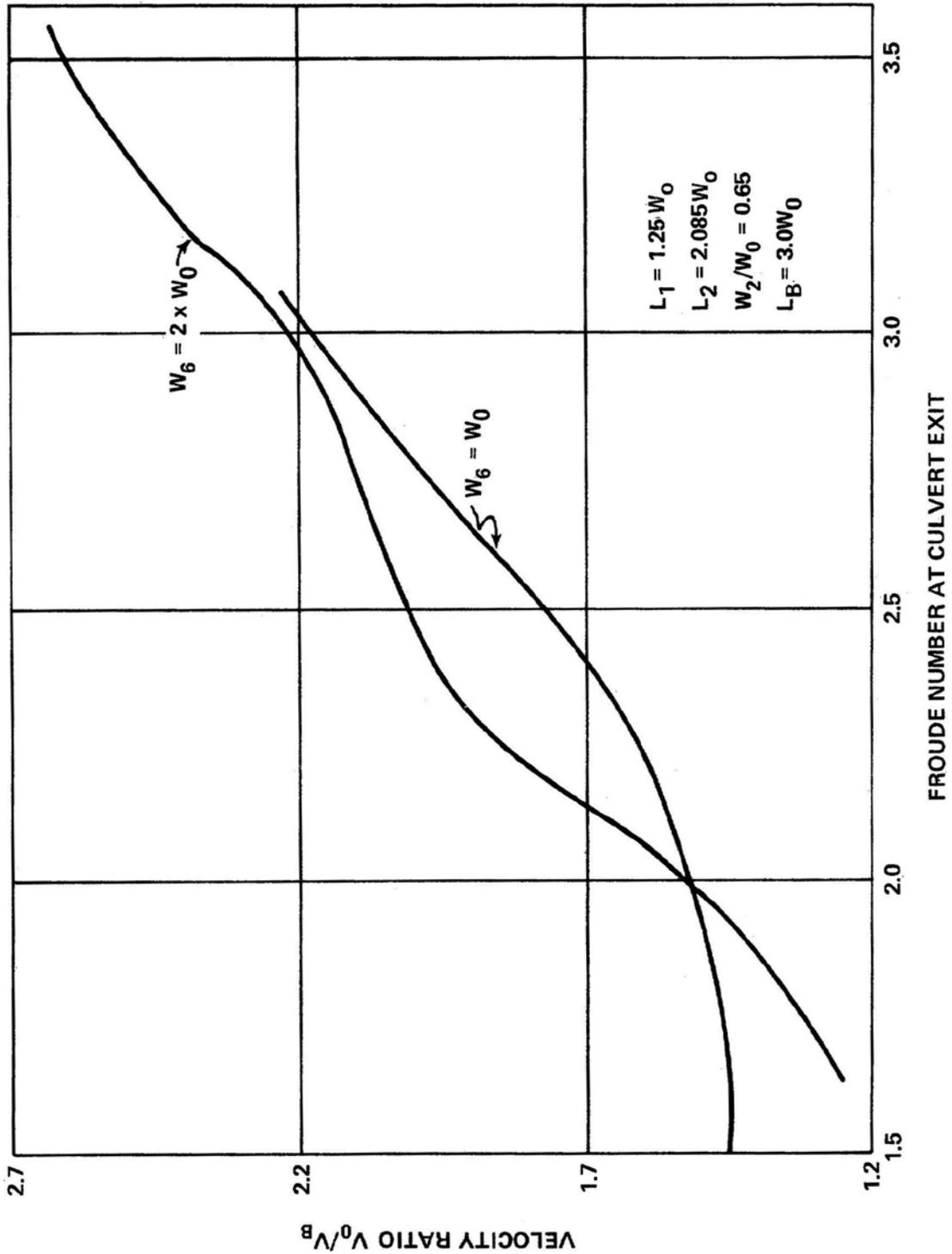


Figure 9A-8
 Ratio of Culvert Outlet Velocity, V_0 , to Basin Exit Velocity, V_B
 Hook Type Impact Basins
 Reference: USDOT, FHWA, HEC-14 (1983)

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Dissipator Type	Culvert V_o (fps)	Outfall Froude Number	Allowable Debris Load			Tailwater Required ?	Special Considerations
			Silt / Sand	Boulders	Floating		
None	< 5						Check for Highly Erodible Soils
Natural Scour Hole	≤ 12	≤ 3	Heavy	Heavy	Heavy	No	No Environmental or Aesthetic Concerns
Riprap Apron	≤ 12		Heavy	Heavy	Heavy	-	$TW \geq 0.75 d_o$
Riprap Stilling Basin		≤ 3	Heavy	Heavy	Heavy	No	$TW < 0.75 d_o$
Tumbling Flow		> 1	Moderate	Low	Low	No	Slope < 15%, Boxes Only, Inlet Control
Increased Resistance		-	Moderate	Low	Low	No	Boxes Only, Inlet Control
Saint Anthony Falls (SAF)	> 15	1.7 to 17	Moderate	Low	Moderate	Yes	
USBR Type VI	< 50	-	Moderate	Low	Low	Desirable	$Q < 400$ cfs
Hook	> 15	1.8 to 3	Moderate	Moderate	Moderate	No	

Table 9A-1
 Energy Dissipator Limitations
 Reference: USDOT, FHWA, HEC-14 (1983)

W	h ₁	L	h ₂	h ₃	L ₁	L ₂	h ₄	W ₁	W ₂	t ₃	t ₂	t ₁	t ₄	t ₅
4' 0"	3' 1"	5' 5"	1' 6"	0' 8"	2' 4"	3' 1"	1' 8"	0' 4"	1' 1"	0' 6"	0' 6"	0' 6"	0' 6"	0' 3"
5' 0"	3' 10"	6' 8"	1' 11"	0' 10"	2' 11"	3' 10"	2' 1"	0' 5"	1' 5"	0' 6"	0' 6"	0' 6"	0' 6"	0' 3"
6' 0"	4' 7"	8' 0"	2' 3"	1' 0"	3' 5"	4' 7"	2' 6"	0' 6"	1' 8"	0' 6"	0' 6"	0' 6"	0' 6"	0' 3"
7' 0"	5' 5"	9' 5"	2' 7"	1' 2"	4' 0"	5' 5"	2' 11"	0' 6"	1' 11"	0' 6"	0' 6"	0' 6"	0' 6"	0' 3"
8' 0"	6' 2"	10' 8"	3' 0"	1' 4"	4' 7"	6' 2"	3' 4"	0' 7"	2' 2"	0' 7"	0' 7"	0' 6"	0' 6"	0' 3"
9' 0"	6' 11"	12' 0"	3' 5"	1' 6"	5' 2"	6' 11"	3' 9"	0' 8"	2' 6"	0' 8"	0' 7"	0' 7"	0' 7"	0' 3"
10' 0"	7' 8"	13' 5"	3' 9"	1' 8"	5' 9"	7' 8"	4' 2"	0' 9"	2' 9"	0' 9"	0' 8"	0' 8"	0' 8"	0' 3"
11' 0"	8' 5"	14' 7"	4' 2"	1' 10"	6' 4"	8' 5"	4' 7"	0' 10"	3' 0"	0' 9"	0' 9"	0' 8"	0' 8"	0' 4"
12' 0"	9' 2"	16' 0"	4' 6"	2' 0"	6' 10"	9' 2"	5' 0"	0' 11"	3' 0"	0' 10"	0' 10"	0' 8"	0' 9"	0' 4"
13' 0"	10' 0"	17' 4"	4' 11"	2' 2"	7' 5"	10' 0"	5' 5"	1' 0"	3' 0"	0' 10"	0' 11"	0' 8"	0' 10"	0' 4"
14' 0"	10' 9"	18' 8"	5' 3"	2' 4"	8' 0"	10' 9"	5' 10"	1' 1"	3' 0"	0' 11"	1' 0"	0' 8"	0' 11"	0' 5"
15' 0"	11' 6"	20' 0"	5' 7"	2' 6"	8' 6"	11' 6"	6' 3"	1' 2"	3' 0"	1' 0"	1' 0"	0' 8"	1' 0"	0' 5"
16' 0"	12' 3"	21' 4"	6' 0"	2' 8"	9' 1"	12' 3"	6' 8"	1' 3"	3' 0"	1' 0"	1' 0"	0' 9"	1' 0"	0' 6"
17' 0"	13' 0"	22' 6"	6' 4"	2' 10"	9' 8"	13' 0"	7' 1"	1' 4"	3' 0"	1' 0"	1' 1"	0' 9"	1' 0"	0' 6"
18' 0"	13' 9"	23' 11"	6' 8"	3' 0"	10' 3"	13' 9"	7' 6"	1' 4"	3' 0"	1' 1"	1' 1"	0' 9"	1' 1"	0' 7"
19' 0"	14' 7"	25' 4"	7' 1"	3' 2"	10' 10"	14' 7"	7' 11"	1' 5"	3' 0"	1' 1"	1' 2"	0' 10"	1' 1"	0' 7"
20' 0"	15' 4"	26' 7"	7' 6"	3' 4"	11' 5"	15' 4"	8' 4"	1' 6"	3' 0"	1' 2"	1' 2"	0' 10"	1' 2"	0' 8"

Table 9A-2
 Recommended Basin Dimensions Based on the Computed Basin Width
 USBR Type VI Impact Basin (See Figure 9A-6)
 (All dimensions expressed in feet and inches)
 Reference: USDOT, FHWA, HEC-14 (1983)

9.06.2 EXAMPLE PROBLEMS

9.06.2.1 EXAMPLE PROBLEM #1: SCOUR HOLE ESTIMATION

GIVEN:

A concrete culvert has been designed as follows:

- Design Discharge (Q_{50}) = 40 ft³/s
- Diameter = 48 inch
- Culvert Length = 100 feet
- Inlet Invert Elevation = 602.5
- Outlet Invert Elevation = 600.0
- Computed TW depth = 1.6 feet

The natural materials in the channel downstream of the culvert outlet consist of gravel and small stones, and the flow line of the channel is at the same elevation as the culvert outfall. The duration of the peak flow may be assumed to be 30 minutes. The downstream receiving channel is trapezoidal in shape, 4 feet wide, and at the same slope as the culvert. The downstream channel n-value is approximately equal to 0.03.

FIND:

Estimate the dimensions of the scour hole for the design discharge. The parameters to be determined will be:

- Depth of the scour hole, d_s
- Width of the scour hole, W_s
- Length of the scour hole, L_s

SOLUTION:

Step 1: Compute and Record Necessary Channel and Culvert Data

The designer should review Chapters 5 and 6 of this Manual to develop a basic understanding of open channel hydraulics and culvert flow. For the given culvert conditions, the designer should complete a standard culvert design form for the proposed structure at this location. A blank culvert design form can be found in the Appendix of Chapter 6. The completed culvert analysis using computer methods is shown in tabular form as Figure 9A-10.

Entered/Given Data:

```

Culvert Shape ..... Circular
Number of Barrels ..... 1
Solving for ..... Headwater
FHWA Chart Number..... 1
Scale Number ..... 1
FHWA Chart Description..... CONCRETE PIPE; NO BEVELED RING ENTRANCE
Scale Description ..... SQUARE EDGE ENTRANCE WITH HEADWALL
Overtopping Analysis..... On
Discharge ..... 40.0000 cfs
Manning's n ..... 0.0130
Roadway Overtopping Elevation... 608.9200 ft
Inlet Elevation ..... 602.5000 ft
Outlet Elevation ..... 600.0000 ft
Diameter ..... 4.0000 ft
Length ..... 100.0000 ft
Entrance Loss ..... 0.5000
Tailwater ..... 1.6000 ft
    
```

Computed Results:

```

Slope ..... 0.0250 ft/ft
Velocity ..... 13.6174 fps
Headwater ..... 605.1675 ft Inlet Control
    
```

Messages and/or Errors:

```

Inlet head > Outlet head.
Computing Inlet Control headwater.
Headwater: 605.1675 ft
    
```

DIS- CHARGE Flow cfs	HEAD- WATER ELEV. ft	INLET CONTROL DEPTH ft	OUTLET CONTROL DEPTH ft	FLOW TYPE	NORMAL DEPTH ft	CRITICAL DEPTH ft	OUTLET VEL. DEPTH fps ft		TAILWATER VEL. DEPTH fps ft	
20.00	604.27	1.77	0.00	NA	0.80	1.32	11.14	0.80	0.00	1.60
25.00	604.51	2.01	0.00	NA	0.90	1.48	11.89	0.90	0.00	1.60
30.00	604.74	2.24	0.40	NA	0.98	1.62	12.54	0.98	0.00	1.60
35.00	604.96	2.46	0.64	NA	1.06	1.76	13.11	1.06	0.00	1.60
40.00	605.17	2.67	0.86	NA	1.14	1.89	13.62	1.14	0.00	1.60

Figure 9A-10
Completed Culvert Analysis

Step 2: Begin Energy Dissipator and Scour Hole Worksheet

The culvert and channel tailwater information obtained in Step 1, along with general project information, will be entered on the top half of the energy dissipator worksheet (see Figure 9A-1). At this time, any known site constraints limiting the geometry of the scour hole may also be entered on the lower portion of the worksheet. The completed energy dissipator worksheet for this culvert site is provided as Figure 9A-11.

The project background and design data should be entered on the natural scour hole computation worksheet (see Figure 9A-2). Additionally, the bed material standard deviation should be determined at this point. Geotechnical analysis may be available for determining this parameter. A default value of 2.10 for the given gravel channel will be used for this example. A

copy of the completed scour hole computational worksheet is provided as Figure 9A-12. To complete the scour hole worksheet, proceed to Steps 3 and 4.

Step 3: Perform Scour Hole Computations to determine depth, d_s

Using the information from the culvert design form, the designer should compute the width, W_s , length L_s , and depth, d_s , of the scour hole by applying Equation 9-4 three times, once for each parameter of the scour hole. C_s and C_h of Equation 9-4 are adjustment factors to account for the effects of culvert slope and drop between the culvert exit and the channel bed. Using the given site information, these factors can be directly obtained or interpolated from Tables 9-2 and 9-3. Enter the values for these coefficients into the depth column at the lower portion of the scour hole computation form.

The terms F_1 , F_2 , and F_3 of Equation 9-4 can be determined by Equations 9-5 through 9-8. A different value of the coefficients termed α , β , and θ will be used to solve these equations for each of the three iterations performed to solve Equation 9-4. The terms α , β , and θ may be obtained from Table 9-1.

The first computation or iteration of Equation 9-4 should be performed to determine the scour hole depth, as follows:

Solve Equation 9-5 for the term F_1 ,

$$F_1 = \frac{\alpha}{\sigma^{1/3}}$$

Where, σ = the given material standard deviation and α is obtained from Table 9-1,

$$F_1 = \frac{2.27}{2.10^{0.333}} \qquad F_1 = 1.77$$

Enter the value for F_1 in the depth column on the lower portion of the natural scour hole computation worksheet as shown in Figure 9A-12.

Solve Equation 9-6 for the term F_2 as follows:

$$F_2 = \left(\frac{Q}{g^{0.5} R_o^{2.5}} \right)^\beta$$

Where, R_c is the hydraulic radius of the culvert flowing full and β is obtained from Table 9-1,

$$F_2 = \left(\frac{40}{32.2^{0.5} 0.654^{2.5}} \right)^{0.39} \qquad F_2 = 3.24$$

Enter the value for F_2 in the depth column of the lower portion of the natural scour hole computation worksheet as shown in Figure 9A-12.

Then, the designer should solve Equation 9-7 for the term F_3 as follows:

$$F_3 = \left(\frac{t}{316} \right)^\theta$$

Where, t is the duration of peak flow (see Section 9.04.1.3 for a discussion of t in terms of a base time of 316 minutes) and θ is obtained from Table 9-1.

$$F_3 = \left(\frac{30}{316} \right)^{0.06} \qquad F_3 = 0.868$$

Enter the value for F_3 in the depth column of the lower portion of the natural scour hole computation worksheet as shown in Figure 9A-12.

With all of the terms of Equation 9-4 computed, the depth of the scour hole can now be determined by solving Equation 9-4 as follows:

$$d_s = C_s C_h F_1 F_2 F_3 R_c$$

$$d_s = (1.037)(1.0)(1.77)(3.24)(0.868)(0.654)$$

$$d_s = 3.35 \text{ feet}$$

Enter the value for d_s at the bottom of the depth column on the scour hole computation worksheet as shown in Figure 9A-12.

Step 4: Perform Scour Hole Computations to Determine Width and Length

At this point in the design procedure, the designer should follow the procedure and equations outlined in Step 3 to solve for the scour hole width and length, W_s and L_s , respectively. The appropriate values for α , β , and θ will be obtained from Table 9-1. Enter the width and length columns of Table 9-2 and Table 9-3 to obtain appropriate values for C_s and C_h .

Solving Equation 9-4 for both width and length, the designer obtains values of 18.59 feet for the width, and 33.25 feet for the scour hole length. These values should be entered at the bottom of the scour hole worksheet. The scour hole worksheet shown in Figure 9A-12 is now complete.

Step 5: Complete Energy Dissipator Worksheet and Verify Results

Using the values obtained in Steps 3 and 4, the designer should now complete the Energy Dissipator Worksheet as shown in Figure 9A-11. The computed depth, width, and length should be compared to any site constraints that may govern maximum allowable values for these parameters. Analysis of the computed values for this example verses the maximum allowable scour dimensions show the computed dimensions will be acceptable.

ENERGY DISSIPATOR WORKSHEET										
Project <u>SR 1234 – Roane County, TN</u>										
Station <u>62+50</u>					Structure Type <u>48" RCP</u>					
Design Frequency <u>50-year</u>					Discharge (cfs) <u>40</u>					
Designer <u>E. Biles</u>					Date <u>April 20, 2004</u>					
CULVERT DATA (See TDOT Drainage Manual, Section 9.04.1.2)										
Type	Size	n-value	Length (feet)	Slope (%)	d _o (feet)	A _o (sf)	V _o (fps)	T (feet)	Fr	End Treatment
RCP	48"	.013	100	2.5	1.14	2.94	13.62	3.61	2.65	Type 'U'
TAILWATER SECTION (See TDOT Drainage Manual, Section 5.03.4.1)										
Bottom Width (feet)	Side Slope (X:1)	n-value	Slope (%)	Depth (feet)	Flow Area (sf)	Velocity (fps)	Type of materials in channel			
4	2:1	0.03	2.5	1.6	11.26	3.65	Gravel & small stone			
SCOUR HOLE COMPUTATIONS (See TDOT Drainage Manual, Section 9.04.1.3)										
Time (min)	d _s (feet)	W _s (feet)	L _s (feet)	(Attach Scour Hole Computation Worksheet, TDOT Drainage Manual, Section 9.06.1)						
30	3.35	18.59	33.25							
SITE CONSTRAINTS										
Allowable Outlet Velocity (fps)		Allowable Scour Dimensions			Other Restrictions					
		Width (feet)	Length (feet)	Depth (feet)						
3.65		25.0	50	4.0						
Comments										
<i>Justification:</i> Velocity at culvert will pose unacceptable risk to roadway and downstream channel.										

Figure 9A-11
Completed Energy Dissipator Worksheet for Example Problem #1

NATURAL SCOUR HOLE COMPUTATION WORKSHEET				
Project <u>SR 1234</u> <u>Roane County</u>				
Station <u>62+50</u> Designer <u>E. Biles</u> Date <u>4/20/04</u>				
BACKGROUND AND DESIGN DATA				
Discharge (cfs)	Culvert Diameter (in)	Culvert Slope (%)	Drop Height (feet)	Peak Flow Duration (min)
40	48	2.50	0.0	30
MATERIAL STANDARD DEVIATION				
Material Type	(Enter if known)		σ	Note: Use $\sigma = 1.87$ for sand or $\sigma = 2.10$ for gravel
	d ₁₆ (mm)	d ₈₄ (mm)		
Gravel	-	-	2.10	
CULVERT HYDRAULIC RADIUS				
Flow Area (square feet)	Wetted Perimeter (feet)	Hydraulic Radius, R _o (feet)		
2.94	4.49	0.654		
SCOUR HOLE DIMENSIONS				
	Depth	Width	Length	
α	2.27	6.94	17.10	
β	0.39	0.53	0.47	
θ	0.06	0.08	0.10	
F ₁	1.77	5.42	13.35	$\alpha/\sigma^{0.333}$
F ₂	3.24	4.98	4.12	$[Q / (g^{0.5} R_o^{2.5})]^\beta$
F ₃	0.868	0.828	0.79	$(t / 316)^\theta$
C _h	1.00	1.00	1.00	
C _s	1.037	1.28	1.17	
	d _s (feet)	W _s (feet)	L _s (feet)	
C _s C _h F ₁ F ₂ F ₃ R _o	3.35	18.59	33.25	
Comments:				
<i>Culvert Hydraulic Radius, R_o, information provided above obtained from computer analysis. Value is for the flow area at 40 cfs</i>				

Figure 9A-12
Completed Scour Hole Worksheet for Example Problem #1

9.06.2.2 EXAMPLE PROBLEM #2: RIPRAP BASIN ENERGY DISSIPATOR DESIGN

GIVEN:

A culvert has been designed as follows:

Design discharge:	100 ft ³ /s
Diameter:	60 inches
Inlet elevation:	601.5 feet
Outlet elevation:	600.0 feet
Length:	100 feet
Endwall:	Type "U"

The channel downstream of the culvert is trapezoidal having a bottom width of 4 feet, a depth of 1.5 feet, and 6H:1V side slopes, and a slope of 0.015 ft/ft. The Manning's n-value of the channel is 0.035. The stream carries a heavy load of sediments, small branches, and corn stalks.

FIND:

Determine whether the site is suitable for a riprap energy dissipator based on the culvert outlet hydraulics, tailwater depth, and debris load.

Design a riprap basin energy dissipator for this site, such as that depicted in Figures 9-9 and 9-10. Select the proper class of riprap and determine the basin dimensions as shown in the definition sketch provided in the TDOT Erosion Control Standard Drawings.

SOLUTION:

This site is a candidate for a riprap stilling basin because of the heavy debris load. Another type of dissipator might become clogged, thus reducing its effectiveness. Furthermore, it is judged that allowing a natural scour hole to form at this site could possibly have undesirable results. Other factors affecting whether a riprap basin would be suitable for this site will be investigated as the design progresses.

As much as possible, the steps below follow the procedure provided in Section 10 of the FHWA publication HEC-14. This sample problem also takes into account the comments provided in Section 9.04.2.2 regarding the HEC-14 procedure.

Step1:

Since the outlet velocity, V_o , is greater than 5 ft/sec, some form of erosion protection should be provided at the culvert outlet. In order to assess the suitability of a riprap stilling basin for the site, the following information is collected from the hydraulic analysis of the culvert:

- brink depth, $d_o = 2.05$ feet
- outlet velocity, $V_o = 13.17$ ft/s
- tailwater depth, $TW = 1.55$ feet
- tailwater velocity $V_n = 4.85$ ft/s

Although the culvert outlet velocity is somewhat higher than 12 ft/s, it is decided to compute the Froude Number, Fr , before deciding whether a riprap stilling basin will be a suitable

energy dissipator for this site. In order to compute the Froude Number, it will be necessary to first compute the equivalent depth.

Using the brink depth of 2.05 feet, the cross sectional area of the outflow is determined using Table 6A-11 as follows:

$$\frac{d_o}{D} = \frac{2.05}{5.0} = 0.410, \text{ and interpolating from Table 6A-11 yields } \frac{A_o}{A_{full}} = 0.391$$

Thus, since the full-flow area of a 60-inch culvert is 19.64 ft²,

$$A_o = 0.391 \times 19.64 = 7.68 \text{ ft}^2$$

The equivalent depth, d_e , at the culvert outfall is computed as:

$$d_e = \left(\frac{A_o}{2} \right)^{0.5} = \left(\frac{7.68}{2} \right)^{0.5} = 1.96 \text{ feet}$$

The Froude Number is then computed as:

$$Fr_o = \frac{V_o}{(g \times d_e)^{0.5}} = \frac{13.17}{(32.2 \times 1.96)^{0.5}} = 1.66$$

The Froude Number for the culvert outflow is considerably less than the maximum allowable value of 3.0. Thus, it is judged that the culvert outflow velocity will not be excessive for the site.

Step2:

Another criteria to be checked is the ratio of the equivalent depth of the culvert outflow, d_e , to the tailwater depth. Based on the information determined above:

$$\frac{TW}{d_e} = \frac{1.55}{1.96} = 0.79$$

The guidance provided in both Chapter 6 and 9 indicates that a riprap apron should be used in place of a basin where the tailwater depth is greater than 75% of the brink depth. However, given the size of the pipe, high outflow velocity and a need to minimize the length of the riprap structure, it is decided to continue with the riprap basin design. If the computed basin depth, H1, is not at least twice the D_{50} of the selected riprap, a riprap apron will be specified for the site.

Step 3:

In order to apply Equation 10.1 from HEC-14, it is first necessary to compute a value for the factor C_o . As discussed in Section 9.04.2.2, The HEC-14 Equation 10.2 will be used for this computation. Since the ratio of TW/d_e determined above is between 0.75 and 1.0, C_o is computed as:

$$C_o = 4.0\left(\frac{TW}{d_e}\right) - 1.6 = 4.0\left(\frac{1.55}{1.96}\right) - 1.6 = 1.56$$

As also mentioned in Section 9.04.2.2, the most common class of riprap used for a riprap stilling basin is Machined Riprap (Class A1), for which the $D_{50} = 0.75$ feet. Since the Froude Number for the culvert outflow was computed above, HEC-14 Equation 10.1 can be written and solved as:

$$\frac{H1}{d_e} = 0.86\left(\frac{D_{50}}{d_e}\right)^{-0.55} \quad Fr - C_o = 0.86\left(\frac{0.75}{1.96}\right)^{-0.55} [1.66] - 1.56 = 0.86$$

From this result, the basin depth, H1, may be computed as $0.86 \times 1.96 = 1.69$ feet.

Step 4:

The suitability of this design is finally checked by computing the ratio of H1 to D_{50} :

$$\frac{H1}{D_{50}} = \frac{1.69}{0.75} = 2.25$$

Since this result is greater than the minimum value of 2.0, it is determined that a riprap stilling basin will be suitable for the site, and that Machined Riprap (Class A1) will provide the most efficient design.

Step 5:

Once the basin depth has been established, the remaining basin dimensions can be determined. The dimensions to be determined are based on the table titled "Rip-Rap Basin Locations, Dimensions, and Quantities" shown in the TDOT Erosion Control Standard Drawings. The dimension of the basin itself will be determined in this step. The design and dimensions of any required transition will be determined in Step 6.

W1 refers to the width of the basin floor at the culvert outfall (this dimension is referred to as W_o in Figure 9-9). This site will be provided with a Type "U" endwall, thus:

$$W1 = 5.0 \text{ feet}$$

L1 refers to the length of the pool portion of the basin. HEC-14 recommends this length be the greater of 10 times H1 or 3 times W1. Thus:

$$10 \times H1 = 10 \times 1.69 = 16.9 \text{ feet} \quad \text{or,} \quad 3 \times W1 = 3 \times 5 = 15.0 \text{ feet. So:}$$

$$L1 = 17.0 \text{ feet (rounded).}$$

L2 refers to the length of the apron portion of the basin. HEC-14 recommends this length be the greater of 5 times H1 or W1. Thus:

$$5 \times H1 = 5 \times 1.69 = 8.5 \text{ feet} \quad \text{or,} \quad W1 = 5 \text{ feet. So:}$$

$$L2 = 9.0 \text{ feet (rounded)}$$

The TDOT standard drawings require the elevation of the basin floor, including both the pool and the apron, be below the natural stream elevation at the end of the apron. The fall in the stream over the length of the basin is computed as:

$$Fall = (L1 + L2)S_n = (17.0 + 9.0)0.015 = 0.39 \text{ feet}$$

Occasionally, the designer may be presented with a situation in which the computed fall is very close to or even greater than H1. In that situation, it would be necessary to redesign the culvert with a lower outlet elevation and begin the riprap basin design again from Step 1. However, in this situation, since the computed fall is sufficiently less than H1, the design may proceed "as-is." Since the slopes at the upstream and downstream ends of the pool are 2:1, the length from the culvert outfall to the basin floor is $2 \times 1.69 = 3.4$ feet, and the length of the transition from the basin floor to the apron is $(1.69 - .39) \times 2 = 2.6$ feet. Thus, the length of the pool bottom is $17.0 - 3.4 - 2.6 = 11.0$ feet.

W2 refers to the width of the pool at the end of the apron. Since the floor expands at a 3:1 ratio on both sides, W2 is computed as:

$$W2 = W1 + (L1 + L2)\left(\frac{2}{3}\right) = 5 + (17.0 + 9.0)\left(\frac{2}{3}\right) = 22.0 \text{ feet}$$

H2 refers to the height at the top of the basin wall above the elevation of the culvert outfall. HEC-14 recommends the top of the basin should provide at least 1 foot of freeboard above the brink depth, d_o . Thus:

$$H2 = d_o + 1.0 = 2.05 + 1.0 = 3.1 \text{ feet (rounded)}$$

W4 refers to the width of the basin side slopes at the culvert outfall. Since the top of the basin is 3.1 feet above the outfall and the side slopes of the basin are 2:1,

$$W4 = 2 \times 3.1 = 6.2 \text{ feet}$$

W5 refers to the width of the basin side slopes above the floor of the pool. The top of the basin is $H1 + H2 = 1.69 + 3.1 = 4.8$ feet the floor of the pool, since the side slopes are also 2H:1V at this point:

$$W5 = 2 \times 4.8 = 9.6 \text{ feet}$$

W6 refers to the width of the basin side slopes above the floor of the apron. The distance to the top of the basin is equal to H2 plus the fall of the stream previously computed. Since the side slopes are still 2:1 at this point:

$$W6 = (H2 + Fall) \times 2 = (3.1 + 0.39) \times 2 = 7.0 \text{ feet}$$

D1 refers to the thickness of the riprap layer beneath the pool portion of the basin. The TDOT standard drawings indicate that the riprap layer beneath the pool should be somewhat thicker than the riprap layer beneath the apron. This varies from the recommendation in HEC-14, which indicates the riprap layer needs to be thicker *only* beneath the transition from the

culvert outfall to the floor of the pool. Thus, the thickness criteria provided by HEC-14 will be applied to the entire pool of the basin. Based on this approach, D1 will be the maximum of 3 times the median stone size, D_{50} , 2 times the maximum stone size, D_{max} , or the minimum thickness of the riprap layer as specified in the Standard Specifications of 18 inches.

$$3 \times D_{50} = 3 \times 0.75 = 2.25 \text{ feet, or } 2 \times D_{max} = 2 \times 1.25 = 2.50 \text{ feet}$$

Thus, $D1 = 2.5$ feet

D2 refers to the thickness of the riprap layer beneath the apron portion of the basin. HEC-14 recommends this layer be equal to the maximum of 2 times the median stone size, D_{50} , 1.5 times the maximum stone size, D_{max} , or the minimum thickness of the riprap layer as specified in the Standard Specifications as 18 inches.

$$2 \times D_{50} = 2 \times 0.75 = 1.50 \text{ feet or } 1.5 \times D_{max} = 1.5 \times 1.25 = 1.9 \text{ feet}$$

This result may be rounded so that $D2 = 2.0$ feet

D3 and **L4** refer respectively to the depth and length of a riprap key which is provided at the downstream end of the apron. The standard cut-off wall depth for a concrete structure is 3 feet. Furthermore, D3 and L4 should be approximately equal. Thus, the values of D3 and L4 will both be 3 feet.

Step 6:

The width of the basin at the downstream end of the apron, $W2$, is 22 feet, which is greater than the natural channel bottom width of 4 feet. Thus, a transition will be provided to allow the basin cross section at the downstream end of the apron to be warped to match the existing channel configuration. Thus, the following dimensions are determined for the transition:

W3 refers to the width of the transition at the downstream end. This should be equal to the existing channel width of 4 feet, therefore,

$$W3 = 4 \text{ feet}$$

L5 refers to the length of the transition from the downstream end of the apron to the basin outlet. The TDOT standard drawings indicate that the transition should be at a rate of 3:1, so L5 is computed as:

$$L5 = (W2 - W3) \left(\frac{3}{2} \right) = (22.0 - 4.0) \left(\frac{3}{2} \right) = 27.0 \text{ feet}$$

W7 refers to the width of the basin side slopes above the floor of the transition just downstream of the end of the apron. At this point, the top of the basin has already been transitioned from H2 computed in Step 5 to the height of the natural channel banks above the channel bed. This transition takes place over a distance, L3, which will be discussed below. At this site, the natural channel is 1.5 feet deep. Since the side slopes of the basin are still 2H:1V at this location,

$$W7 = 2 \times 1.5 = 3.0 \text{ feet}$$

W8 refers to the width of the basin side slopes at the outlet from the transition. The side slopes of the basin are continuously warped from 2H:1V at the beginning of the transition to the natural channel side slopes at the end of the transition. Since the natural channel side slopes are 6:1 and the channel depth is 1.5 feet,

$$W8 = 6 \times 1.5 = 9.0 \text{ feet}$$

L3 refers to the length over which the top of the riprap basin transitions from H2 to the height of the natural stream bank. This transition occurs just upstream from the end of the apron and begins at the point where the top of the slope through the transition intersects the top of the basin above the apron. This length is computed from:

$$L3 = \frac{\left(\frac{W2}{2} + W6\right) - \left(\frac{W2}{2} + W7\right)}{\left[\frac{1}{3} + \frac{(W2/2 + W7) - (W3/2 + W8)}{L5}\right]} = \frac{\left(\frac{22}{2} + 7.0\right) - \left(\frac{22}{2} + 3\right)}{\left[\frac{1}{3} + \frac{(22/2 + 3) - (4/2 + 9)}{27.0}\right]} = 9.0 \text{ feet}$$

As described in step 5 above, the height of the top of the basin above the apron is 3.1 feet and the height of the channel bank is 1.5 feet. Thus, a transition of 1.6 feet will occur over the distance L3. This represents a slope of about 4.5H:1V. This slope will be adequate.

D4 refers to the thickness of the riprap layer beneath the transition. This should be equal to the minimum layer thickness recommended for Class A1 riprap, or 1.5 feet.

The following table summarizes the results for this design example:

Dimension per TDOT Standard Drawings	Dimension per HEC-14	Value
Station		1+90
Distance (ft.)		62
Direction		Lt.
Culvert Size (in.)		60
Culvert Length (ft)		100
W1 (ft)	W _o	5.0
W2 (ft)		22.0
W3 (ft)		4.0
W4 (ft)		6.2
W5 (ft)		9.6
W6 (ft)		7.0
W7 (ft)		3.0
W8 (ft)		9.0
H1 (ft)	H _s	1.69
H2 (ft)		3.1
L1 (ft)		17.0
L2 (ft)		9.0
L3 (ft)		9.0
L4 (ft)		3.0
L5 (ft)		27.0
D1 (ft)		2.5
D2 (ft)		2.0
D3 (ft)		3.0
D4 (ft)		1.5

Table 9A-4
Summary of Results for Riprap Basin Energy Dissipator

9.06.2.3 EXAMPLE PROBLEM #3: SAF ENERGY DISSIPATOR DESIGN

GIVEN:

A box culvert has been designed as follows:

- Design discharge: 120 ft³/s
- Dimensions: 6' wide x 4' high
- Inlet elevation: 574.8 feet
- Outlet elevation: 554.5 feet
- Length: 200 feet

The channel downstream of the culvert is trapezoidal with a bottom width of 10 feet, a bottom slope of 0.007, and 3H:1V side slopes. The Manning's n-value of the channel is 0.045. The stream carries a very small amount of debris.

FIND:

Design a Saint Anthony Falls (SAF) energy dissipator for this site using hand methods. Based on the downstream channel configuration, determine whether a straight or flared basin would be required. Determine the required basin depth and dimensions for this type of structure. The variable names representing the various dimensions of the structure are presented in Figure 9A-13. Once the basin dimensions have been determined, estimate the flow velocity at the basin outfall, V_2 , and design any riprap apron that may be needed downstream.

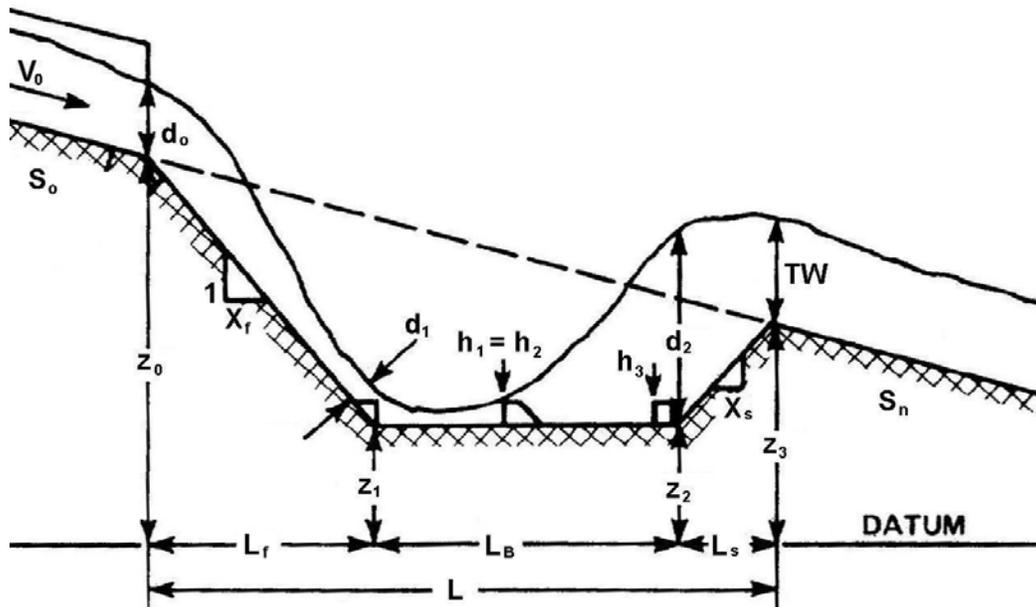


Figure 9A-13
Variable Name Definitions for Various Dimensions of the SAF Stilling Basin

SOLUTION:

This site is a candidate for a SAF energy dissipator because of the high velocity at the culvert outlet and because of the comparatively light debris load. The following steps for designing a SAF stilling basin by hand follow the step-by-step procedure provided in Section 9.04.1.2. A copy of the completed SAF Stilling Basin Design Worksheet is shown in Figure 9A-14.

Step 1:

As described in Section 9.04.1.2, the process should begin by determining the depth, velocity, and Froude Number of the flow at the culvert outfall. Hydraulic analysis of the culvert indicates that the brink depth, d_o , is 0.78 feet. Since the culvert has a width, W , of 6 feet, the outlet flow area, A_o , may be computed as:

$$A_o = Wd_o = 6 \times 0.78 = 4.68 \text{ ft}^2$$

and:

$$V_o = \frac{Q}{A_o} = \frac{120}{4.68} = 25.64 \text{ ft/sec}$$

The outlet Froude Number, Fr_o , is then computed as:

$$Fr_o = \frac{V_o}{(g d_o)^{0.5}} = \frac{25.64}{(32.2 \times 0.78)^{0.5}} = 5.12$$

Step 2:

Using Manning's Equation as described in Section 5.06.1.3.4, the normal depth, TW , and flow velocity, V_n , in the downstream channel may be determined as:

$$TW = 2.08 \text{ ft, and } V_n = 3.55 \text{ ft/sec}$$

Step 3:

Because the culvert is a box, the basic width of the basin, WB_1 , is equal to the width of the culvert, or 6 feet. The variables X_f and X_s , which express the slopes of the basin chute and the back slope respectively, may be given values of either 2 or 3. For this problem, these variables are assigned a value of 2, which yields slopes of 2H:1V.

Step 4:

The sequent depth of the culvert outflow, d_{jo} , may be computed as:

$$= d_o \frac{[1 + 8Fr_o^2]^{0.5} - 1}{2} = 0.78 \frac{[1 + 8(5.12)^2]^{0.5} - 1}{2} = 5.27 \text{ feet}$$

Step 5:

Because the Froude Number of the culvert outflow, Fr_o , is between 1.7 and 5.5, the jump height, d_2 , may be computed from:

$$d_2 = \left(1.1 - \frac{Fr_o^2}{120}\right) d_{jo} = \left(1.1 - \frac{(5.12)^2}{120}\right) 5.27 = 4.65 \text{ feet}$$

Step 6:

The jump height, d_2 , computed in Step 5 is compared to the flow depth in the natural channel, TW. If d_2 is less than the tailwater depth, the SAF stilling basin might not be an effective energy dissipator and another dissipator type should be selected. However, for this problem, the computed jump height of 4.65 feet is greater than the tailwater depth of 2.08 feet. Thus, the SAF basin is feasible and the floor of the basin should be lowered such that the water surface elevation after the hydraulic jump in the basin is lower than the elevation of the tailwater. As described in Section 9.04.2.2.3, the determination of the basin floor elevation, z_1 or z_2 , may require some trial and error calculations. As a first estimate, the floor elevation may be computed as:

$$z_1 = z_o - 1.5(d_2 - TW)$$

Where: z_1 = basin floor elevation,
 z_o = elevation of the culvert outfall,
 d_2 = jump height, and
 TW = tailwater depth.

Thus:

$$z_1 = 554.50 - 1.5(4.65 - 2.08) = 550.65 \text{ feet}$$

Step 7:

Based on the floor elevation assumed in Step 6, the depth of flow on the chute just upstream of the chute blocks, d_1 , may be computed from the expression:

$$Q = d_1 W B_1 \left[2g(z_o - z_1 + d_o - d_1) + V_o^2 \right]^{0.5}$$

Thus:

$$120 = d_1 (6) \left[2(32.2)(554.5 - 550.65 + 0.78 - d_1) + 25.64^2 \right]^{0.5}$$

Solving by trial and error yields a value for d_1 of 0.66 feet.

Step 8:

Once the flow depth has been computed, the velocity just upstream of the chute blocks, V_1 , may be computed as:

$$V_1 = \frac{Q}{WB_1 \times d_1} = \frac{120}{6 \times 0.66} = 30.21 \text{ ft/sec}$$

The Froude Number just upstream of the blocks, Fr_1 , may then be computed as:

$$Fr_1 = \frac{V_1}{(g \times d_1)^{0.5}} = \frac{30.21}{(32.2 \times 0.66)^{0.5}} = 6.54$$

Step 9:

The sequent depth for a hydraulic jump, d_j , just in front of the chute blocks, is computed next, along with the jump height, d_2 . The sequent depth is computed as:

$$d_j = d_1 \frac{[1 + 8Fr_1^2]^{0.5} - 1}{2} = 0.66 \frac{[1 + 8(6.54)^2]^{0.5} - 1}{2} = 5.8 \text{ feet}$$

Since the Froude Number is between 5.5 and 11, the jump height is computed from:

$$d_2 = 0.85d_j = 0.85 \times 5.8 = 4.93 \text{ feet}$$

Step 10:

The lengths of each of the sections of the basin are computed as follows. The length of the chute, L_f , is computed from:

$$L_f = X_f(z_o - z_1) = 2(554.5 - 550.65) = 7.70 \text{ feet}$$

The length of the basin floor, L_B , is computed from:

$$L_B = \frac{4.5d_j}{Fr_1^{0.76}} = \frac{4.5 \times 5.80}{6.54^{0.76}} = 6.26 \text{ feet}$$

The length of the backslope, L_s , is affected by the slope of the stream. That is, as the length of the basin increases, the elevation where it rejoins the natural stream grade becomes lower. Thus, L_s is computed from:

$$L_s = \frac{z_o - z_1 - (L_f + L_B)S_n}{\frac{1}{X_s} + S_n} = \frac{554.50 - 550.65 - (7.70 + 6.26) \times 0.007}{\frac{1}{2} + 0.007} = 7.40 \text{ feet}$$

The total basin length is then computed as:

$$L = L_f + L_B + L_s = 7.70 + 6.26 + 7.40 = 21.36 \text{ feet}$$

The elevation at which the basin outfall intersects with the natural stream bed, z_3 , is:

$$z_3 = z_1 + \frac{L_s}{X_s} = 550.65 + \frac{7.40}{2} = 554.35 \text{ feet}$$

Once the jump height at the chute blocks, d_2 , the length of the basin, L , and the elevation of the basin outlet, z_3 , have been computed, it is possible to check whether the tailwater depth will be adequate to insure that the basin will function properly using the expression:

$$z_1 + d_2 \leq z_3 + TW \text{ or } 550.65 + 4.93 \leq 554.35 + 2.08$$

This expression evaluates to: $555.58 \leq 556.43$

Although this expression is true indicating the tailwater depth will be adequate, it also indicates the water surface just downstream of the hydraulic jump will be about 0.85 feet lower than the height of the water in the natural stream channel. Thus, the proposed design could be optimized by raising the basin floor elevation and returning to Step 7. This would match the jump height to the tailwater depth and result in a somewhat shorter basin, which should provide some construction and right-of-way cost savings. Thus, for this example, the elevation of the basin floor is raised to an elevation of 551.60 feet. After repeating Steps 7 through 10, the final basin dimensions are as follows:

	Parameter	Final Value
Step 7	d_1	0.69 feet
Step 8	V_1	29.10 ft/sec
	Fr_1	6.186
Step 9	d_j	5.68 feet
	d_2	4.83 feet
Step 10	L_f	5.80 feet
	L_B	6.40 feet
	L_s	5.55 feet
	L	17.75 feet
	z_3	554.38 feet

Table 9A-5
Final Basin Dimensions

Checking the tailwater depth for the adjusted design yields:

$$z_1 + d_2 \leq z_3 + TW \text{ or } 551.60 + 4.83 \leq 554.38 + 2.08$$

This expression evaluates to: $556.43 \leq 556.46$

With the adjustment to the basin floor elevation, the difference between the two sides of this expression is 0.03 feet. Matching the jump height to the tailwater has resulted in reducing the total length of the basin by 3.6 feet.

Step 11:

Once the total basin length has been computed, it is possible to determine whether the basin should be straight or flared. Adding a flare to the basin will not affect the overall basin length computed in Step 10. In this situation, the proposed culvert has a width of 6 feet, while the channel has a width of 10 feet. Since the channel bottom is wider than the culvert, a flared basin will provide the best fit. The width of the basin at the outfall will be 10 feet to match the existing channel bottom, and the 3:1 side slopes of the natural channel will be accommodated by providing wingwalls. The degree of flare is described by the parameter z , as shown in Figure 9-11. Since the chute portion of the basin is always straight, the degree of flare may be computed as:

$$z = \frac{2(L_B + L_s)}{WB_4 - WB_1} = \frac{2(6.40 + 5.55)}{10 - 6} = 6.0$$

Step 12:

The height of the chute blocks, h_1 , should be approximately equal to the approach depth of 0.69 feet. Thus, h_1 would be rounded to 8 inches. An initial value for the width and spacing of the blocks, W_1 and W_2 respectively, may be computed from:

$$W_1 = W_2 = 0.75d_1 = 0.75(0.69) = 0.52 \text{ feet}$$

which may be rounded to 0.5 feet, or 6 inches. The number of blocks may then be computed from:

$$N_b = \frac{WB_1}{2W_1} = \frac{6}{2 \times 0.5} = 6$$

Since $N_b(W_1 + W_2) = 6 = WB_1$; it will not be necessary to adjust the width or spacing of the blocks. As described in Section 9.04.2.2.3, half-blocks with a width of 3 inches would be attached to each side wall, and 5 full-width blocks would be evenly spaced across the toe of the chute.

Step 13:

The leading edge of the floor blocks should be at a distance equal to $\frac{1}{3} L_B$ from the toe of the chute, or $\frac{1}{3} \times 6.40 = 2.1$ feet or 26 inches. The basin width at the leading edge of the floor blocks, WB_2 , may be computed as:

$$WB_2 = WB_1 + \frac{2L_B}{3z} = 6 + \frac{2 \times 6.40}{3 \times 6.0} = 6.71 \text{ feet}$$

It is necessary to maintain a minimum space of $\frac{3}{8} d_1$ between the basin side wall and the outside edge of the nearest floor block. Thus, the greatest possible value for the floor block width, W_3 (which is equal to the spacing, W_4), may be computed from:

$$W_3 = \frac{WB_2 - 3/4 d_1}{2N_b - 1} = \frac{6.71 - 3/4(0.69)}{(2 \times 6) - 1} = 0.563 \text{ feet}$$

which equals about 6.8 inches. Rounding the block width up to the next inch would result in a spacing at the side wall which is too narrow. Thus, the width and spacing of the floor blocks will be 6 inches. The selected width is checked by computing the ratio:

$$\frac{N_b W_3}{WB_2} = \frac{6 \times 0.50}{6.71} = 0.45$$

Since this ratio is between 0.40 and 0.55, the block sizing will be adequate.

Step 14:

The basin is to be provided with a sill at the downstream end of the floor. The width of this sill, WB_3 , is computed as:

$$WB_3 = WB_1 + \frac{2L_B}{z} = 6 + \frac{2 \times 6.40}{6.0} = 8.13 \text{ feet}$$

The height of the sill, h_3 , is computed as:

$$h_3 = 0.07d_j = 0.07 \times 5.68 = 0.398 \text{ feet, which may be rounded to 5 inches.}$$

Step 15:

The height of the basin side walls above the basin floor is computed as:

$$d_2 + \frac{d_j}{3} = 4.83 + \frac{5.68}{3} = 6.72 \text{ feet}$$

These walls should extend the full length of the basin, L , and should terminate with wingwalls placed at an angle of 45° to the stream.

Step 16:

The flow velocity at the basin outlet, V_2 , is computed as:

$$V_2 = \frac{Q}{(z_1 + d_2 - z_3)WB_4} = \frac{120}{(551.60 + 4.83 - 554.38)(10.0)} = 5.85 \text{ ft/sec}$$

Section 6.04.3.3 of this Manual recommends that riprap scour protection be provided at any site where the exit velocity exceeds 5 ft/s. Because the basin outlet velocity is only somewhat greater than the minimum, it is not entirely clear whether riprap scour protection would be required. However, because of the general turbulence generated by a hydraulic jump, it is judged that providing a riprap apron would be a prudent measure for this site.

Based on the procedure provided in Section 6.05.5 of this Manual, it is first necessary to compute the flow depth and velocity at the basin outlet. The outlet velocity, V_2 , has been computed above, and the outlet depth, d_B , may be computed as:

$$d_B = z_1 + d_2 - z_3 = 551.60 + 4.83 - 554.38 = 2.05 \text{ feet}$$

To apply the equations presented in Section 6.05.5, it is necessary to convert the flow area at the basin outlet to an equivalent circular area. The outflow area is:

$$A_B = WB_4 \times d_B = 10.0 \times 2.05 = 20.5 \text{ feet}^2$$

Converting this area into an effective round diameter may be accomplished by:

$$D_{eff} = \left[\frac{4A_B}{\pi} \right]^{0.5} = \left[\frac{4(20.5)}{\pi} \right]^{0.5} = 5.11 \text{ feet}$$

The natural stream flow velocity, V_n , for this site is 3.55 ft/s. However, for the purpose of computing a riprap apron length, the lowest value that should be used for V_n is 5.0 ft/sec. Thus, the ratio of the natural stream velocity to the basin outlet velocity should be computed as:

$$\frac{V_n}{V_B} = \frac{5.0}{5.85} = 0.85$$

Because this ratio is greater than 0.6, Equation 6-14 would be used to compute the apron length, L_a , as:

$$\frac{L_a}{D_{eff}} = 19.612 \left\{ \left[1.053 - \left(\frac{V_n}{V_B} \right) \right]^{0.5} - 0.171 \right\} = 19.612 \left\{ [1.053 - 0.85]^{0.5} - 0.174 \right\} = 5.39$$

Since the effective diameter, D_{eff} , is 5.11 feet, the required riprap apron length will be 5.11 feet times 5.39, or 28 feet. The apron would be constructed of Class A-1 riprap.

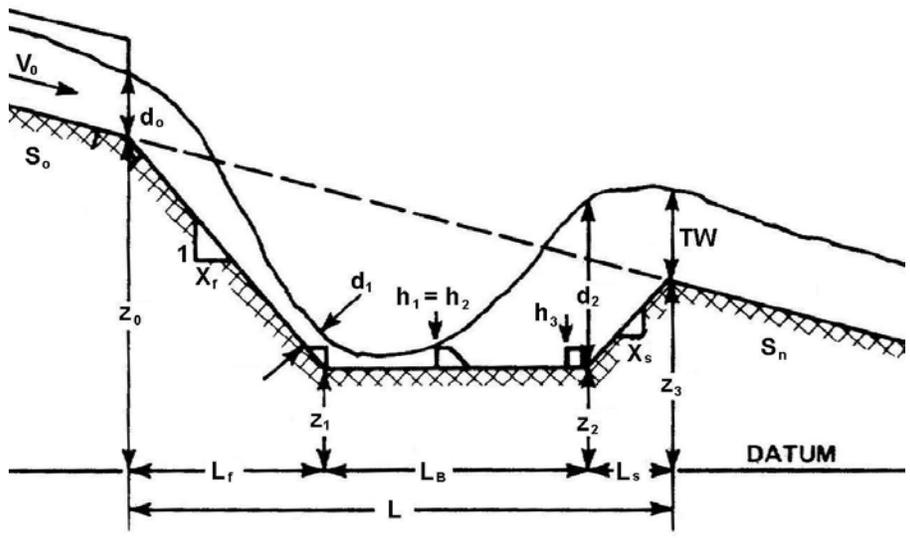
Finally, the structure should be provided with a 3 foot deep cutoff wall.

SAINT ANTHONY FALLS STILLING BASIN DESIGN WORKSHEET

Page 1 of 2

Project Sample Problem 9-3

Station _____ Designer U. R. Smart Date 03/17/04



Profile View

Background Information:

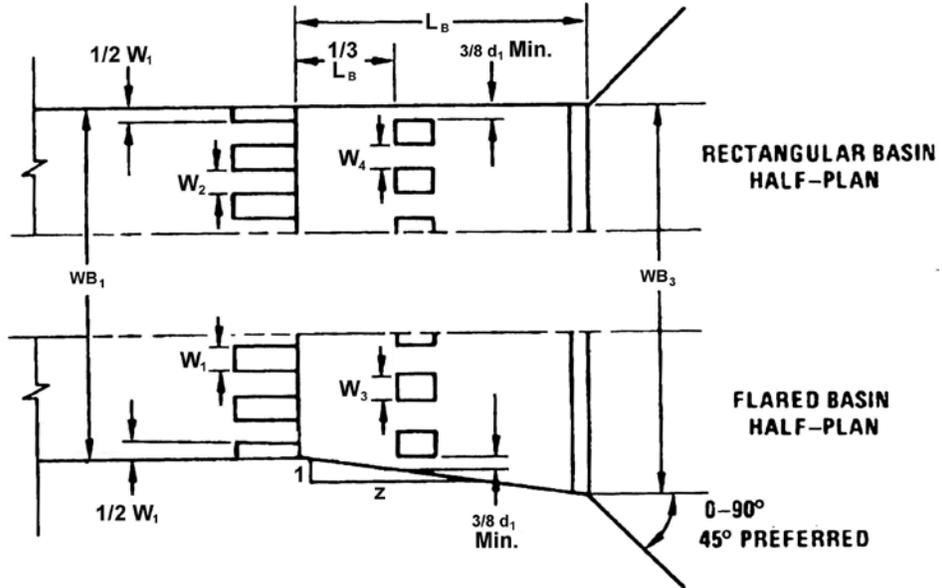
Q = 120
(cfs)

S₀ = 0.102
(%)

d₀ = 0.78
(ft)

V₀ = 25.64
(fps)

Fr = 5.12



Plan View

Z₀ = 554.50
(ft)

S_n = 0.007
(%)

TW = 2.08
(ft)

d_{jo} = 5.27
(ft)

d₂ (initial) = 4.65 (ft)

Initial Basin Parameters

BASIN TYPE (check)	Rect- angular	Flared X	z (flare)	D _o (ft) ¹	WB ₁ (ft)	X _r	X _s
			X	6.0	6.0	6.0	2

(Continued next page)

SAINT ANTHONY FALLS STILLING BASIN DESIGN WORKSHEET					
					Page 2 of 2
Basin Dimensions					
z_1 (trial) (ft)	d_1 (ft)	V_1 (fps)	Fr_1	d_j (ft)	d_2 (ft)
551.60	0.69	29.10	6.186	5.68	4.83
L_f (ft)	L_B (ft)	L_s (ft)	L (ft)	z_3 (ft)	
5.80	6.40	5.55	17.75	554.38	
$z_1 + d_2$ (ft)	$z_3 + TW$ (ft)	$[z_1 + d_2]$ must be $\leq [z_3 + TW]$ (ok)			
556.43	556.46				
Chute Blocks					
h_1 (ft)	$0.75 d_1$ (ft)	N_b	$W_1 (= W_2)$ (ft)		
0.69 (8")	0.52	6	0.5 (6")		
Floor (Baffle) Blocks					
h_2 (ft)	WB_2 (ft)	$W_3 (= W_4)$	$(N_b W_3)$	$(N_b W_3) / WB_2^*$	
(8")	6.71	0.5 (6")	3.0	0.45 (ok)	
Other Basin Details					
End Sill, h_3 (ft)	Sidewall Height $d_2 + (d_j / 3)$	Cutoff Wall Depth (ft)	V_2 (fps)	Riprap Apron Length (ft)	
0.398 (5")	6.72	3.0	5.85	28	

NOTES:

¹ Enter diameter for a pipe culvert, span for a box culvert.

* This value should be between 0.40 and 0.55

Figure 9A-14
Completed Saint Anthony Falls Stilling Basin Computation
Worksheet for Example Problem #3

9.06.2.3.1 EXAMPLE PROBLEM #3: SAF DISSIPATOR DESIGN USING HY-8ENERGY**GIVEN:**

A box culvert has been designed as follows:

Design discharge:	120 ft ³ /s
Dimensions:	6' wide x 4' high
Inlet elevation:	574.8 feet
Outlet elevation:	554.5 feet
Length:	200 feet

The channel downstream of the culvert is trapezoidal with a bottom width of 10 feet, a bottom slope of 0.70 percent, and 3H:1V side slopes. The Manning's n-value of the channel is 0.045. The stream carries a very small amount of debris.

FIND:

Design a Saint Anthony Falls (SAF) energy dissipator for this site using computer acceptable methods. This problem is a repeat of the design problem presented in the previous section and is provided to show how the problem may be solved using readily available software.

SOLUTION:

This site is a candidate for a SAF energy dissipator because of the high velocity at the culvert outlet and because of the comparatively light debris load. The following steps discuss the computerized methods utilized for the design as well as a few of the hand-computations needed to complement the computerized results.

Step 1:

The hydraulic performance of the box culvert is analyzed using the computer program HY-8. The performance curve computed by HY-8 is shown in Figure 9A-15. As shown, the brink depth, d_o , and outlet velocity, V_o , are 0.78 feet and 25.6 ft/s, respectively. Detailed information on determining the hydraulic performance of a culvert using HY-8 is provided in Chapter 6.

HY-8 includes a module which may be used to design a number of energy dissipation devices. However, as implemented in version 6.1 of HY-8, the program will not allow the design of a SAF energy dissipator below grade. That is, it does not provide for lowering the floor of the basin with respect to the flow line of the stream, and therefore does not fully reflect the methods prescribed in HEC-14. In fact, because of the relatively shallow tailwater depth, HY-8 will indicate that a SAF basin is not feasible for this site.

The Windows-based computer program HY-8Energy provides a more complete implementation of the methods provided in HEC-14 and will thus be used for the energy dissipator design.

C:\HY8\Hy8.exe

PERFORMANCE CURVE FOR CULVERT NO. 1 - 1< 6.00 ft by 4.00 ft> RCB

DIS-CHARGE FLOW (cfs)	HEAD-WATER ELEU. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	FLOW TYPE <F4>	NORMAL DEPTH (ft)	CRIT. DEPTH (ft)	OUTLET DEPTH (ft)	TW DEPTH (ft)	OUTLET UEL. (ft)	TW UEL. (ft)
0	574.80	0.00	0.00	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
12	575.50	0.70	0.70	1-S2n	0.11	0.50	0.10	0.59	19.99	1.74
24	575.91	1.11	1.11	1-S2n	0.22	0.79	0.19	0.87	20.65	2.19
36	576.25	1.45	1.45	1-S2n	0.33	1.04	0.24	1.09	24.99	2.49
48	576.56	1.76	1.76	1-S2n	0.42	1.26	0.36	1.28	22.22	2.72
60	576.85	2.05	2.05	1-S2n	0.48	1.46	0.36	1.44	27.62	2.91
72	577.14	2.34	2.34	1-S2n	0.53	1.65	0.45	1.59	26.60	3.07
84	577.42	2.62	2.62	1-S2n	0.59	1.83	0.53	1.72	26.43	3.21
96	577.68	2.88	2.88	1-S2n	0.65	2.00	0.60	1.85	26.66	3.34
108	577.94	3.14	3.14	1-S2n	0.70	2.16	0.72	1.97	24.88	3.45
120	578.19	3.39	3.39	1-S2n	0.76	2.32	0.78	2.08	25.61	3.55

INVERT ELEVATIONS--> In let - 574.80 ft Crest - 0.00 ft
 FILE: SAFBOX Out let - 554.50 ft Throat - 0.00 ft

PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE
 <P> TO PLOT <I> FOR IMPROVED INLET TABLE

1-Help 2 3 4-Type 5-End 6 7 8 9-DOS 10

Figure 9A-15
Box Culvert Hydraulic Analysis by HY-8

Step 2:

Upon starting the program HY-8Energy, the user is presented with the window shown in Figure 9A-16. The program may be used to compute the dimensions of a scour hole and design internal or external energy dissipators. Thus, to begin the design, the user would click on the tab marked "External."

Design of Energy Dissipators -

File View Options Help

Scour Internal External

Culvert Details

Title: [] Culvert slope (So): 0.0000

Shape: Circular Peak duration: 30.0 min

Flow (Q): 0.000 m³/s Drop height: 0.000 m

Velocity (Vo): 0.000 m/s Reference depth: 0.000 m

Diameter (D): 0.000 m Hydraulic radius: 0.000 m

Bed material

Cohesive Non-cohesive

Non-cohesive bed material

Estimate Sigma using D16 and D84

D16: 0.000 mm D84: 0.000 mm

Sigma: 0.000

Scour hole geometry

Length: 0.000 m

Width: 0.000 m

Volume: 0.0 m³

Maximum depth: 0.000 m

Max. depth location: 0.000 m

Figure 9A-16
HY-8Energy Opening Screen

Step 3:

Before designing the energy dissipator, it is necessary to import the results from HY-8 into the program and check whether a SAF basin would be feasible for the site. This is done by selecting “File” on the program menu bar and then clicking the “Import inp data” option. This opens a window which allows the designer to browse for the HY-8 input file created in Step 1.

Selecting an HY-8 input file causes the window shown in Figure 9A-17 to appear. This window allows the designer to select the culvert in the HY-8 file that will be used for the dissipator design. Usually, there will be only one culvert in the HY-8 file, so the designer should verify the proper units are selected for the design and click “OK” to continue.

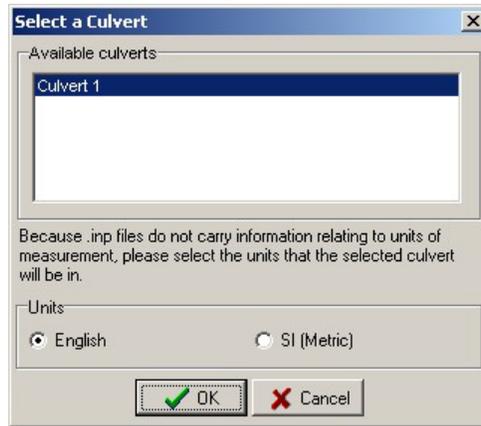


Figure 9A-17
Selecting a Culvert for Dissipator Design

Once the basic culvert data has been loaded into the program, the designer should fill in the “Title” box with a name for the design, as shown in Figure 9A-18. It is also necessary to compute the Froude Number at the culvert outlet, Fr_o , which is accomplished by clicking the calculator button next to the “Froude (Fr):” box. Any of the other items in the boxes within the “Input” portion of the window may also be filled in or edited as necessary.

The designer may then check the feasibility of the various external energy dissipator options for this site by clicking the calculator button near the upper right corner of the window. This causes the program to fill in the site-specific feasibility data for each dissipator type in the bottom half of the window, as shown in Figure 9A-19. Since the Saint Anthony Falls basin is one of the feasible options, the design may proceed.

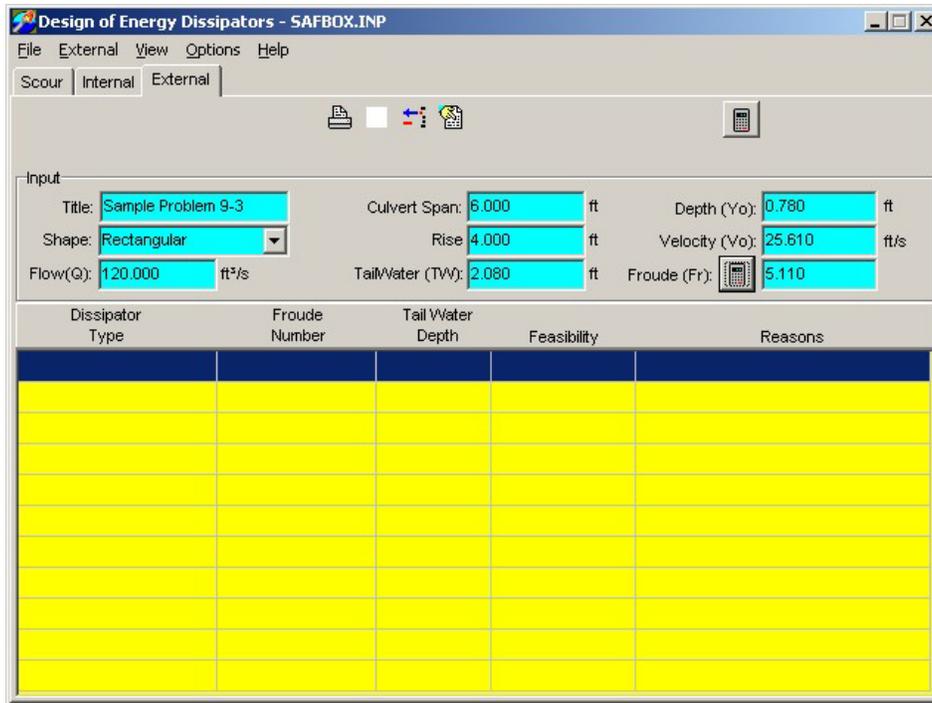


Figure 9A-18
Computing the Culvert Outlet Froude Number

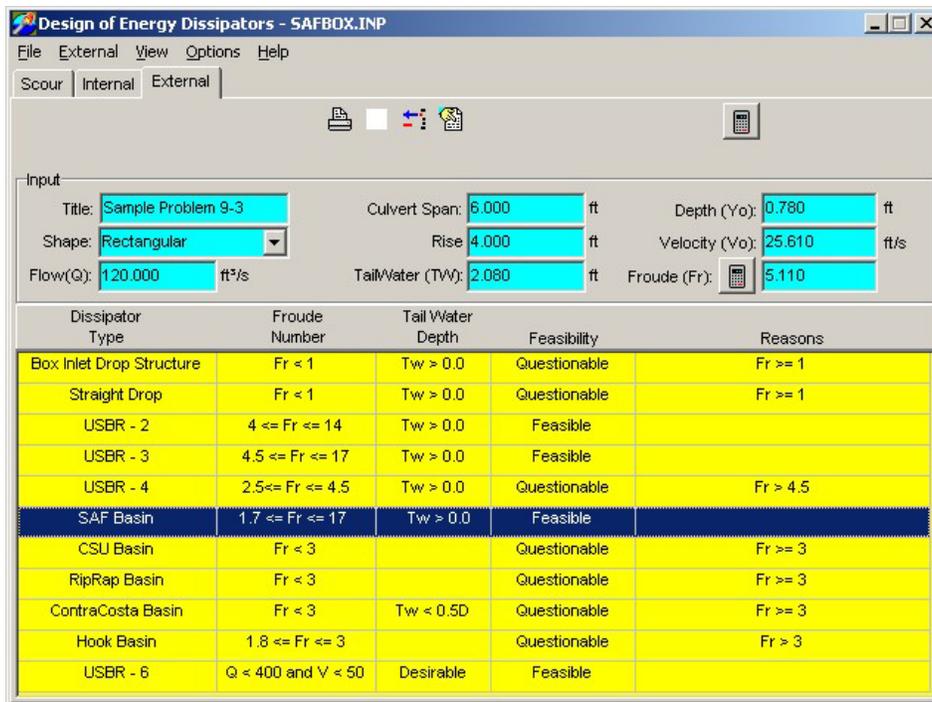


Figure 9A-19
Feasibility of Various Energy Dissipator Options

Step 4:

Double-clicking the “SAF Basin” line within the lower portion of the external energy dissipator window will bring up a blank SAF basin design form, as shown in Figure 9A-20. To determine the basin dimensions, the designer would click the calculator in the upper right corner of the SAF Basin design form. This causes the program to compute the basin dimensions and fill in the output boxes located at various places on the form, including the “Output” section as shown in Figure 9A-21.

Figure 9A-20
Blank SAF Basin Design Form

The designer should next determine whether a straight or flared basin will best fit the project site. If a straight basin is selected, the process would proceed to Step 5. However, in this case, the proposed culvert has a width of 6 feet while the channel has a width of 10 feet. Since the channel bottom is wider than the culvert, a flared basin will provide the best fit for the site. The width of the basin at the outfall will be 10 feet to match the existing channel bottom, and the 3:1 side slopes of the natural channel will be accommodated by providing wingwalls. Since the chute portion of the basin is always straight, the degree of flare may be computed as:

$$z = \frac{2(L_B + L_s)}{WB_4 - WB_1}$$

- Where:
- z = the degree of flare
 - L_B = the length of the basin floor
 - L_s = the length of the basin backslope
 - WB₄ = the desired width of the basin at the outfall
 - WB₁ = the basin width at the bottom of the chute.

This yields:

$$z = \frac{2(6.40 + 5.76)}{10.0 - 6.0} = 6.08$$

Since the recommended minimum value of “z” is 2.0, this result is acceptable. It is now necessary to return to HY-8Energy and select the “Flared” radio button in the “SAF Basin Shape” portion of the design window. The value for “z” is rounded to 6.1 and entered into the box marked “Flare.” Clicking the calculator button in the upper right corner of the design form causes the program to re-compute the basin dimensions for the flared configuration. The length of the flared basin is exactly the same as the length of the straight basin. Thus, it is not necessary to make any further adjustments to the basin dimensions.

The screenshot shows the 'Roughness Basins' software window with the following data:

Input			
Basin Type: <input checked="" type="radio"/> SAF Basin	SAF Basin Shape: <input checked="" type="radio"/> Flared	Basin width: 6.000 ft	Elev. (Z1, Z2): 551.620 ft
Flare: 6.1 z: 1	In slope (ST): 0.50 H:1V		Basin L: 17.669 ft
	Out slope (SS): 0.50 H:1V		Chute R: 13.19 ft
			Sill H4: 0.398 ft

Output			
LB: 6.396 ft	Fr1: 6.189	NCB: 6	wB2: 6.699 ft
LS: 5.513 ft	Y2: 4.828 ft	Yj: 5.680 ft	wB3: 8.097 ft
LT: 5.760 ft	H1: 0.687 ft	H3: 0.687 ft	Len: 2.132 ft
Y1: 0.687 ft	w1: 0.500 ft	w3, w4: 0.479 ft	SWH: 6.721 ft
V1: 29.110 ft/s	w2: 0.500 ft	NBB: 7	% Blocks: 50

Figure 9A-21
Results of SAF Basin Design

Step 5:

Output can be obtained from the SAF design form by selecting “File” from the menu bar, then “Print current item.” The designer will have the option of choosing to send the output either to the printer or to a file on a disk. Choosing to direct the output to a printer will open a print preview screen where the designer will be allowed to modify the size of the text output. If output to a file is selected, the designer will have an opportunity to browse for a suitable location for the output file.

Figure 9A-22 provides a copy of the output file. Because a few of the variable names and other notation used in HY-8Energy differ from those used in this Manual, notes have been added in italics to the output report as an aid in understanding the output.

Step 6:

A few hand computations are useful in verifying the parameters specified by the computer program and in completing the design.

First, the elevation of the basin at the outlet, z_3 , was computed by the program as 554.38 feet. This may be checked by multiplying the basin length, L , times the slope of the natural channel, S_n , and subtracting the result from the elevation of the culvert outfall, z_0 :

$$z_3 = z_0 - L \times S_n = 554.5 - 17.7 \times 0.007 = 554.38 \text{ ft}$$

Next, the solution should be checked for an adequate tailwater depth, as described in Section 9.04.2.2.3, Step 11. This specifies that the height of the jump on the basin floor should be less than the height of the tailwater at the downstream end of the basin. This is checked by the equation:

$$z_1 + d_2 \leq z_3 + TW$$

For this site, the floor elevation of the basin, z_1 , is 551.62 feet, the jump height, d_2 , (called Y2 by the program) is 4.83 feet, the elevation of the basin at the outlet, z_3 , is 554.38 feet, and the tailwater depth is 2.08 feet. Thus, the above expression becomes:

$$551.62 + 4.83 \leq 554.38 + 2.08 \quad \text{or} \quad 556.45 \leq 556.46$$

Since this expression is true, the tailwater depth will be adequate.

As described in Section 9.04.2.2.3, Step 16, the velocity at the outlet of the structure should be evaluated to determine whether any additional erosion protection will be needed. Because details of these computations are presented in Section 9.06.2.3, only a general discussion is provided here.

The flow velocity at the basin outlet, V_B , is computed as 5.80 ft/sec. Section 6.04.3 of this Manual recommends riprap scour protection be provided at any site where the exit velocity exceeds 5 ft/sec. Because the exit velocity computed for the SAF basin is only somewhat greater than the minimum, it is not entirely clear whether riprap scour protection would be required. However, because of the general turbulence generated by a hydraulic jump, it is judged that providing a riprap apron would be a prudent measure for this site.

Based on the procedure provided in Section 6.05.5 of this Manual, it is found that:

- the outlet velocity, V_2 , is 5.80 ft/sec;
- the outlet depth, d_B , is 2.07 feet;
- the flow area at the basin outfall, A_B , is 20.7 ft²;
- the round diameter related to this flow area, D_{eff} , is 5.13 feet;
- the ratio of the natural stream flow velocity to the basin outflow velocity, V_n/V_B , is 0.86;
- the ratio of the apron length to the effective diameter, L_a/D_{eff} , is 5.20; and
- the required riprap apron length is 27 feet.

The apron would be constructed of Class A-1 riprap, and the structure should be provided with a cutoff wall 3 feet deep.

Type: St. Anthony Fall's Basin
 Title: Sample Problem 9-3
 Date: 2/23/2004
 Units: English

Shape: Rectangular
 Flow (Q) 120.000 ft³/s
 Velocity (V_o) 25.610 ft/s
 Channel slope 0.00700
 Channel width 10 ft
 Depth (Y_o) 0.780 ft
 Diameter 6.000 ft
 Outlet elev. (Z_o) 554.500 ft
 Channel tail water 2.080 ft
 ST: Slope of inlet 0.50
 SS: Slope of outlet 0.50
 Flare 6.1

Results:

[COMMENTS]

Fro: Froude number of Culvert	5.110	
WB: Basin Width	6.000 ft	[Width at upstream end of basin]
Z1,Z2: Elevation of basin bottom	551.620 ft	
LB: Length of basin bottom	6.396 ft	
LS: Horiz. length of chute	5.513 ft	
LT: Horiz. length of basin exit slope	5.760 ft	[Basin backslope, L _s]
Basin L: Total basin length: Lt + Ls + Lb	17.669 ft	[Total basin length]
Y1: Depth before jump	0.687 ft	[Variable is d ₁ in manual]
Y2: Depth after jump	4.828 ft	[Jump height, d ₂]
V1: Velocity before jump	29.110 ft/s	[Velocity on the chute]
Fr1: Froude number = V1/Sqrt(g*Y1)	6.189	
Z3: Elevation of channel at basin exit	554.376 ft	[Length*stream slope=0.12 feet]
H1: Height of chute blocks	0.687 ft	
W1: Width of chute blocks	0.500 ft	
W2: Spacing of chute blocks	0.500 ft	
Y _j	5.680 ft	[Hydraulic jump sequent depth, d _j]
NCB: Number of chute blocks	6	
H3	0.687 ft	[Height of baffle blocks]
W3,W4: Width & spacing of baffle blocks	0.479 ft	[Usually rounded to the nearest inch]
Chute R: Transition radius at chute crest	13.19 ft	
NBB	7	[Number of floor blocks]
SWSB: Sidewall spacing	0.000 ft	
H4: Sill height	0.398 ft	
WB2: Basin width at baffles	6.699 ft	
WB3: Basin width at sill	8.097 ft	[Width at the end of basin = 10 ft]
Len:	2.132 ft	[Length between chute and baffle blocks]
SWH: Side wall height	6.721 ft	
Percent of WB2 occupied by baffle blocks.	50	[WB ₂ = width of basin at blocks]

Figure 9A-22
 Computer Program HY-8Energy Output for an SAF Basin

9.06.2.4 EXAMPLE PROBLEM #4: USBR TYPE VI IMPACT BASIN DESIGN

GIVEN:

A culvert has been designed as follows:

Design discharge:	120 ft ³ /s
Diameter:	72 inches
Inlet elevation:	574.8 feet
Outlet elevation:	554.5 feet
Length:	200 feet

The channel downstream of the culvert is trapezoidal with a bottom width of 4 feet, 3H:1V side slopes, and a slope of 0.005 ft/ft. The Manning's n-value of the channel is 0.065. The stream carries a very small amount of debris. Hydraulic analysis of the culvert indicates a brink depth, d_o , of 1.25 feet and a velocity of 27.91 ft/s at the design flow.

FIND:

Design a USBR Type VI impact basin for this site. Determine the required basin dimensions as shown on the design form for this type of structure. Determine the depth of cutoff wall required at the basin outfall. Estimate the flow velocity, V_E , at the basin outfall and design any riprap apron that may be needed downstream.

SOLUTION:

This site is a candidate for a USBR Type VI impact basin because the discharge is less than 400 cfs, and the debris load is light. The step-by-step procedure for designing a USBR Type VI impact basin provided in Section 9.04.2.2.4 of the chapter text is provided below. The equations used can be found in the chapter text as well. A copy of the completed USBR Type VI Impact Basin Worksheet for this problem is shown in Figure 9A-23.

Step1:

The flow depth at the culvert outfall is divided by the culvert diameter to compute the ratio $d_o/D = 0.208$. Interpolating from Table 6A-11 yields $A_o/A = 0.151$, where A_o is the flow area at the outlet and A is the full-flow area. Since the culvert has a full flow area of 28.27 ft², A_o is 4.27 ft². The equivalent depth, d_e , for this flow area may be computed as:

$$d_e = \left(\frac{A_o}{A} \right)^{0.5} = \left(\frac{4.27}{28.27} \right)^{0.5} = 1.46 \text{ feet}$$

The Froude Number of the outflow, Fr_o , is then computed as:

$$Fr_o = \frac{V_o}{(g \times d_e)^{0.5}} = \frac{27.91}{(32.2 \times 1.46)^{0.5}} = 4.07$$

Using Manning's Equation as described in Chapter 5, the normal depth, tailwater, and flow velocity, V_n , in the downstream channel may be determined as:

$$TW = 3.41 \text{ ft, and } V_n = 2.48 \text{ ft/sec}$$

Step 2:

The specific energy of the flow at the culvert outlet, H_o , is computed from:

$$H_o = d_o + \frac{V_o^2}{2g} = 1.25 + \frac{27.91^2}{64.4} = 13.35 \text{ feet}$$

Step 3:

The ratio of the outflow specific energy to the basin width, H_o/W , is computed from:

$$\frac{H_o}{W} = 0.0348Fr_o^2 + 0.1343Fr_o + 0.1128 = 0.0348(4.07^2) + 0.1343(4.07) + 0.1128 = 1.236$$

The width of the basin, W , is thus computed as:

$$\frac{H_o}{H_o/W} = \frac{13.35}{1.236} = 10.8 \text{ feet}$$

which is rounded to 11 feet for this example.

Step 4:

Referring to Table 9A-2 with a basin width of 11 feet, h_2 is 4 feet, 2 inches (4.17 feet), and h_3 is 1 foot, 10 inches (1.83 feet). Thus, the tailwater depth is checked using the expression:

$$TW \leq h_3 + \frac{h_2}{2} \text{ which evaluates to } 3.41 \leq 1.83 + \frac{4.17}{2} = 3.92$$

Since this expression is true, the tailwater depth is adequate. Per Step 4 of Section 9.04.2.2.4, it will not be necessary to raise the culvert outlet.

Step 5:

Using Table 9A-2, the dimensions of the USBR Type VI basin for this site will be as follows:

Dimension	ft-in	feet
W	11'-0"	11.0
h ₁	8'-5"	8.42
L	14'-7"	14.58
h ₂	4'-2"	4.17
h ₃	1'-10"	1.83
L ₁	6'-4"	6.33
L ₂	8'-5"	8.42
h ₄	4'-7"	4.58
W ₁	0'-10"	0.83
W ₂	3'-0"	3.0
t ₃	0'-9"	0.75
t ₂	0'-9"	0.75
t ₁	0'-8"	0.67
t ₄	0'-8"	0.67
t ₅	0'-4"	0.33

Table 9A-2
Recommended Basin Dimensions Based on the Computed Basin Width

Step 6:

The head loss created by the basin, H_L , is determined by first computing a value for the ratio of the head loss to the specific energy at the culvert outlet, H_L/H_o :

$$\frac{H_L}{H_o} = 0.2718 \ln(Fr_o) + 0.2328 = 0.2718 \ln(4.07) + 0.2328 = 0.614$$

Thus, the head loss in the basin is:

$$H_L = H_o \times \frac{H_L}{H_o} = 13.35 \times 0.614 = 8.20 \text{ feet}$$

Step 7:

The specific energy at the impact basin outlet, H_E , is computed from:

$$H_E = H_o - H_L = 13.35 - 8.20 = 5.15 \text{ feet}$$

Step 8:

The flow depth at the basin outlet, d_E , should be determined by comparing the flow depth computed for the specific energy at the outlet, the critical depth at the outlet, and the tailwater depth.

Based on the specific energy at the basin outlet, the flow depth may be computed from:

$$H_E = d_E + \frac{\left[\frac{Q}{W \times d_E} \right]^2}{2g} \quad \text{or} \quad 5.15 = d_E + \frac{\left[\frac{120}{11.0 \times d_E} \right]^2}{64.4}$$

Solving by trial and error yields a value for d_E of 5.08 feet, which is in the subcritical regime. However, this depth is greater than the computed tailwater depth of 3.41 feet. Therefore, this depth should not be used as the actual basin outfall flow depth.

Because the depth computed above is greater than the tailwater depth, the critical depth on the basin outlet should be computed from:

$$d_{Ec} = \left[\frac{Q}{W \sqrt{g}} \right]^{0.667} = \left[\frac{120}{11 \sqrt{32.2}} \right]^{0.667} = 1.55 \text{ feet}$$

Since this is less than the tailwater depth, it may be assumed that d_E will be equal to the tailwater depth of 3.41 feet.

Step 9:

The flow velocity at the basin outlet, V_E , can be determined from:

$$V_E = \frac{Q}{W \times d_E} = \frac{120}{11.0 \times 3.41} = 3.20 \text{ ft/sec}$$

Since this is less than 5 ft/sec, it will not be necessary to provide a riprap apron at the outlet of the basin.

Step 10:

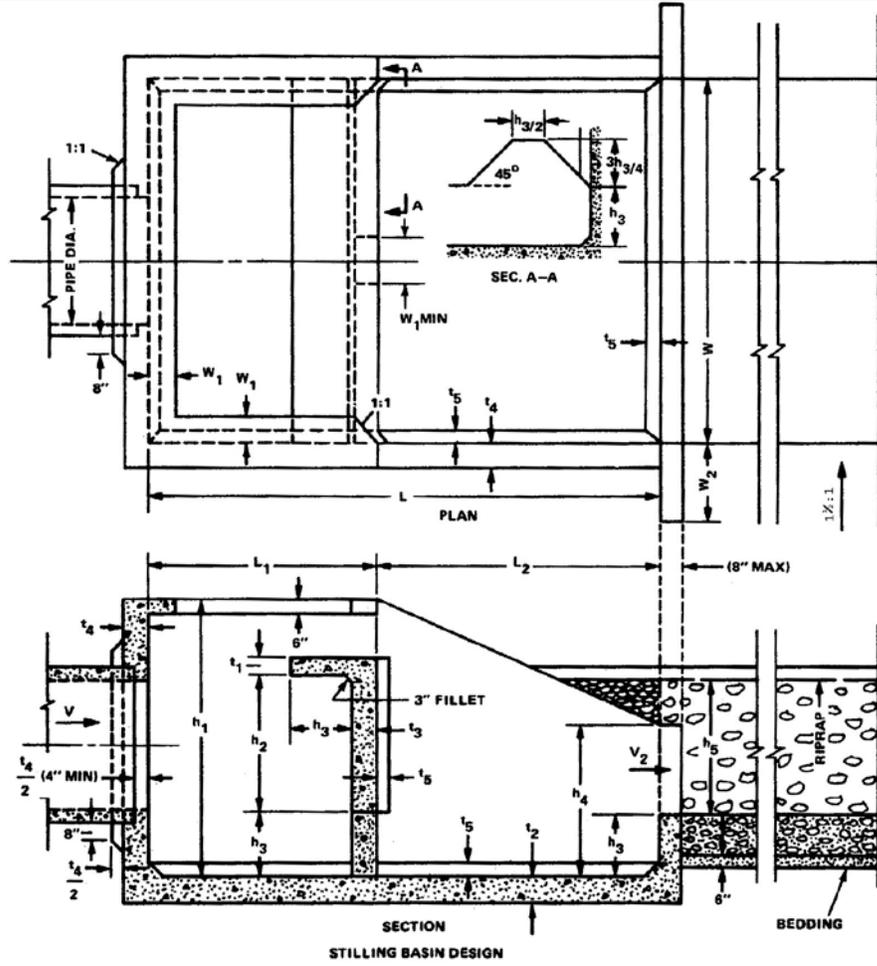
The basin should be provided with a cut-off wall with the standard 3-foot depth. This is especially important since a riprap apron is not planned for the outlet.

USBR TYPE VI IMPACT BASIN DESIGN WORKSHEET

Sheet 1 of 2

Project Sample Problem 9-4

Station _____ Designer U. R. Smart Date 3/17/04



Design Information:

Q = 120
(cfs)

TW = 3.41
(ft)

d_o = 1.25
(ft)

A_o = 4.27
(sf)

V_o = 27.91
(fps)

d_e = 1.46
(ft)

Fr_o = 4.07

H_o = 13.35
(ft)

Basin Width and Baffle Height

H _o / W	W (ft)	h ₂ (ft)	h ₃ (ft)	h ₂ + (h ₃ /2)	If TW is not ≤ h ₂ +(h ₃ /2) raise basin
1.24	11.0	4.17	1.83	3.92 (ok)	

Other Basin Parameters

h ₁ (ft-in)	L (ft-in)	L ₁ (ft-in)	L ₂ (ft-in)	h ₄ (ft-in)	W ₁ (ft-in)
8'-5"	14'-7"	6'-4"	8'-5"	4'-7"	0'-10"
W ₂ (ft-in)	t ₃ (ft-in)	t ₂ (ft-in)	t ₁ (ft-in)	t ₄ (ft-in)	t ₅ (ft-in)
3'-0"	0'-9"	0'-9"	0'-8"	0'-8"	0'-4"

USBR TYPE VI IMPACT BASIN DESIGN WORKSHEET			
			Sheet 2 of 2
Estimate Energy Loss			
H_L / H_o	H_L (ft)	H_E (ft)	
0.614	8.20	5.15	
Outlet Depth			
d_E (by energy)	d_{Ec} (ft)	d_E (actual) (ft)	d_E (actual) = max of d_E (by energy) and TW if $TW > d_{Ec}$. If $TW < d_{Ec}$, d_E (actual) = d_{Ec}
5.08	1.55	3.41	
Other Basin Design Elements			
V_E (fps)	Riprap Apron Length (ft)	Cutoff Wall Depth (ft)	
3.20	N/A	3.0	

Figure 9A-23
Design Worksheet for Hand Computations of
USBR Type VI Impact Basin Design Problem

9.06.2.4.1 EXAMPLE PROBLEM #4: USBR TYPE VI IMPACT BASIN DESIGN USING HY-8

GIVEN:

A culvert has been designed as follows:

Design discharge:	120 ft ³ /s
Diameter:	72 inches
Inlet elevation:	574.8 feet
Outlet elevation:	554.5 feet
Length:	200 feet

The channel downstream of the culvert is trapezoidal with a bottom width of 4 feet, a bottom slope of 0.005 ft/ft, and 3H:1V side slopes. The Manning's n-value of the channel is 0.065. The stream carries a very small amount of debris.

FIND:

Design a USBR Type VI impact basin for this site using computerized methods. Determine whether a horizontal section of pipe will be required upstream of the basin and check that the tailwater depth will be adequate. Estimate the flow velocity at the basin outfall, V_E , and design any riprap apron that may be needed downstream.

SOLUTION:

A USBR Type VI impact basin is being considered for this site possibly due to limited right of way. The site is a candidate for this type of structure because the discharge is less than 400 cfs and only a small amount of debris expected in the flow.

The following steps discuss the computer method utilized for the design as well as hand-computations needed to complement the computer results.

Step 1:

The hydraulic performance of the culvert is analyzed first. The resulting performance curve computed by HY-8 is shown in Figure 9A-24. As can be seen, the brink depth, d_o , and outlet velocity, V_o , are 1.25 feet and 27.9 ft/s, respectively. Detailed information on determining the hydraulic performance of a culvert using HY-8 is provided in Chapter 6.

Step 2:

With the hydraulic analysis of the structure completed, the designer should return to the main HY-8 screen shown in Figure 9A-25. Press the letter "J" to initiate the energy dissipator design.

After passing an introductory screen the designer is prompted to enter the name of the culvert design data file, as shown in Figure 9A-26.

C:\HY8\Hy8.exe

PERFORMANCE CURVE FOR CULVERT NO. 1 - 1< 6.00 ft by 6.00 ft> RCP

DIS-CHARGE FLOW (cfs)	HEAD-WATER ELEU. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	FLOW TYPE <F4>	NORMAL DEPTH (ft)	CRIT. DEPTH (ft)	OUTLET DEPTH (ft)	TW DEPTH (ft)	OUTLET UEL. (ft)	TW UEL. (ft)
0	574.80	0.00	0.00	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
12	575.69	0.89	0.89	1-S2n	0.26	0.86	0.16	1.17	17.98	1.36
24	576.15	1.35	1.35	1-S2n	0.51	1.27	0.37	1.64	19.02	1.64
36	576.57	1.77	1.77	1-S2n	0.65	1.56	0.56	1.99	24.58	1.82
48	576.95	2.15	2.15	1-S2n	0.73	1.83	0.77	2.27	21.94	1.96
60	577.30	2.50	2.50	1-S2n	0.81	2.04	0.74	2.51	28.81	2.08
72	577.63	2.83	2.83	1-S2n	0.89	2.25	0.85	2.72	28.21	2.17
84	577.92	3.12	3.12	1-S2n	0.97	2.45	0.95	2.91	28.30	2.26
96	578.20	3.40	3.40	1-S2n	1.05	2.62	1.02	3.09	29.47	2.34
108	578.46	3.66	3.66	1-S2n	1.13	2.79	1.09	3.26	30.44	2.41
120	578.70	3.90	3.90	1-S2n	1.21	2.96	1.25	3.41	27.91	2.48

INVERT ELEVATIONS--> In let - 574.80 ft Crest - 0.00 ft
 FILE: SAMP4 Out let - 554.50 ft Throat - 0.00 ft

PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE
 <P> TO PLOT <I> FOR IMPROVED INLET TABLE

1-Help 2 3 4-Type 5-End 6 7 8 9-DOS 10

Figure 9A-24
72-Inch Culvert Hydraulic Analysis by HY-8

C:\HY8\Hy8.exe

FHWA CULVERT ANALYSIS DATE: 02-24-2004
 HY8, VERSION 6.1 TIME: 13:20:49

OPTION MENU: PRESS <LETTER>

CULVERT FILE	SINGLE CULVERT <NO OVERTOPPING>
<C> Create	<S> Calculate
<E> Edit	<M> Minimize Width
<N> Name	<R> Report - Display or Print
<D> Directory	<F> File - Save PC and LST files
AVAILABLE FILES	MULTIPLE CULVERTS & OVERTOPPING
Culvert: SAMP4.IMP	<O> Overtopping
Output: SAMP4.PC	<R> Report - Display or Print
Report: SAMP4.LST	<L> List - Save PC and LST files
DESIGN OPTIONS	DEFAULT OPTIONS
<H> Hydrograph	<U> Units Used - English
<I> Routing	<W> Outlet Control - Profiles
<J> Dissipator	<P> Paths for files & Defaults
<Enter> for Documentation Menu	
<Q> Quit	

1-Help 2-Progr 3 4 5-End 6 7-Edit 8 9-DOS 10

Figure 9A-25
HY-8 Main Screen

Once the name of the data file has been entered, the designer will be prompted to select which culvert in the file is to be used for the energy dissipator design (since most files will contain only one culvert, this screen is not shown). The next screen provides an opportunity for the designer to select the type of analysis. Since the dissipator desired for this site is a USBR Type VI, which is an external dissipation structure, the designer would enter the number "4" as shown in Figure 9A-27.

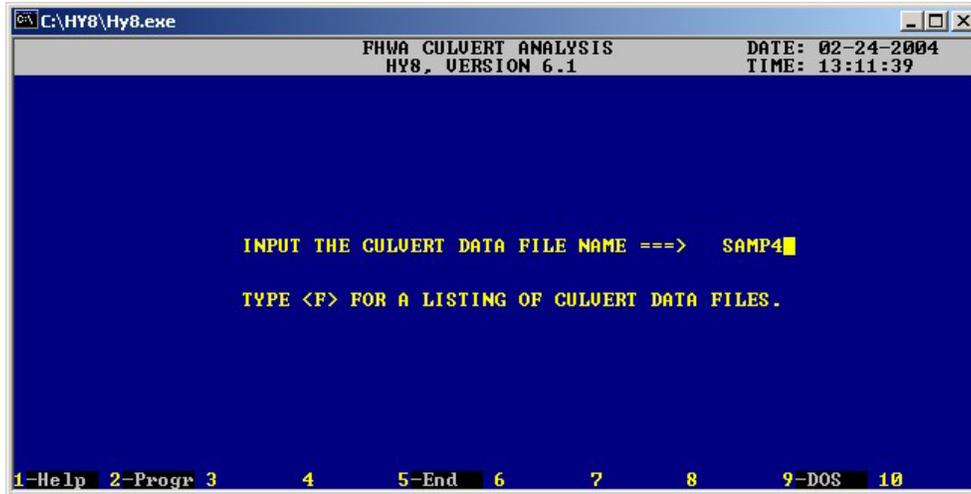


Figure 9A-26
Entering the Culvert Data File Name

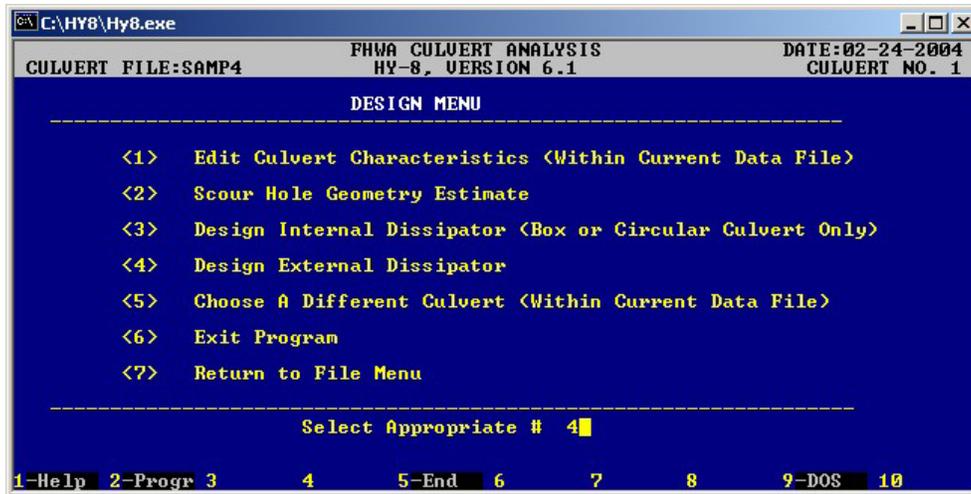


Figure 9A-27
Choosing the Desired Type of Analysis

Because HY-8 divides external dissipators into three different categories, the designer is prompted next to enter the general type of structure desired, as shown in Figure 9A-28. Because the USBR Type VI is considered an “At-Streambed-Level Structure,” the designer would enter the letter “C.”

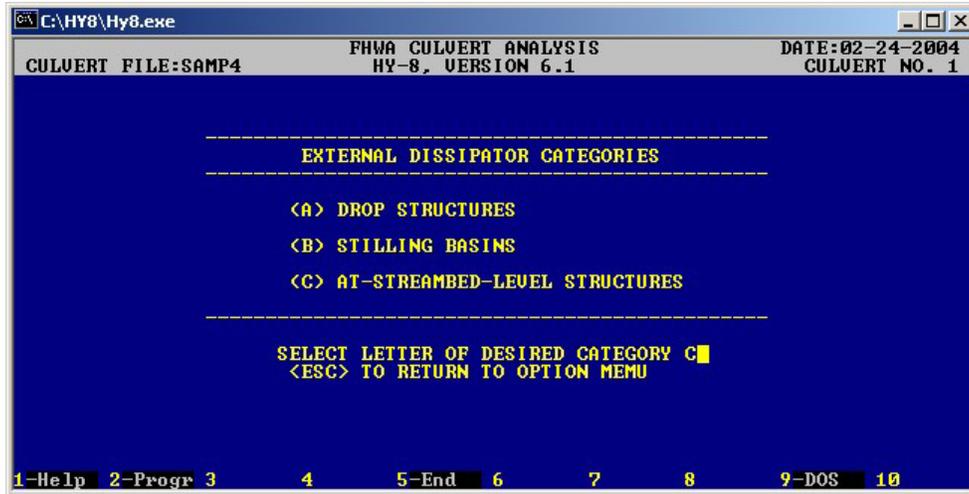


Figure 9A-28
Selecting the External Dissipator Category

Once a category of dissipator has been selected, HY-8 automatically provides a report of the feasibility of each of the different dissipators in that category for the project site. This report is shown in Figure 9A-29. As seen in the figure, the USBR Type VI impact basin is the only dissipator which may be considered feasible at this project site.

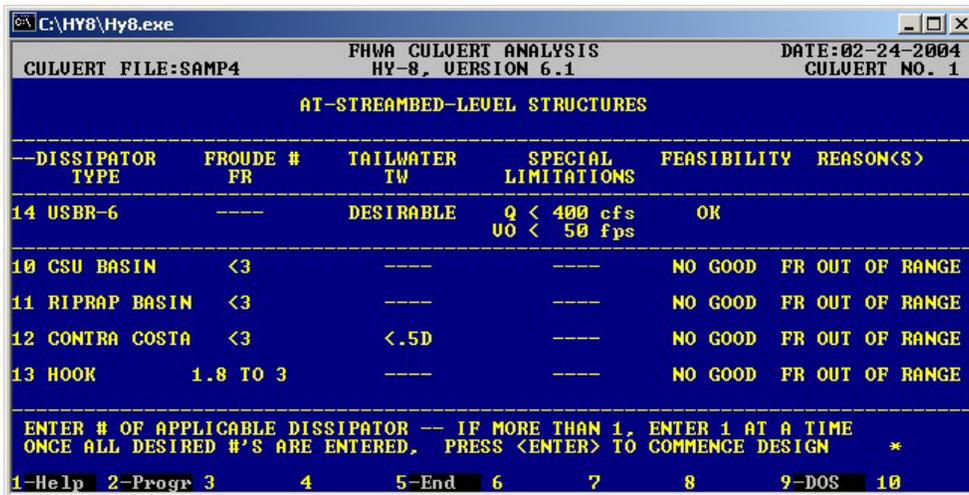


Figure 9A-29
Feasibility Report for At-Streambed-Level Structures

Since the USBR Type VI basin is the only type of “at-streambed-level” structure feasible for this site, the designer would enter the number “14” and press “enter” twice. In a situation where more than one type of dissipator is feasible, the designer may select more than one structure for analysis by entering the number for each structure followed by the “enter” key.

After typing the number for the last desired structure type, the designer would then press “enter” twice.

When the number corresponding to the desired structure type has been entered, the program will compute the dimensions of each type of structure and display a design report on the screen. The HY-8 design report screen for the USBR Type VI dissipator is shown in Figure 9A-30. As recommended in HEC-14, the computed basin width is rounded to the nearest foot (11 feet for this run). The other basin dimensions shown in the output report correspond to the dimensions recommended for an 11-foot wide basin in Table 9A-2.

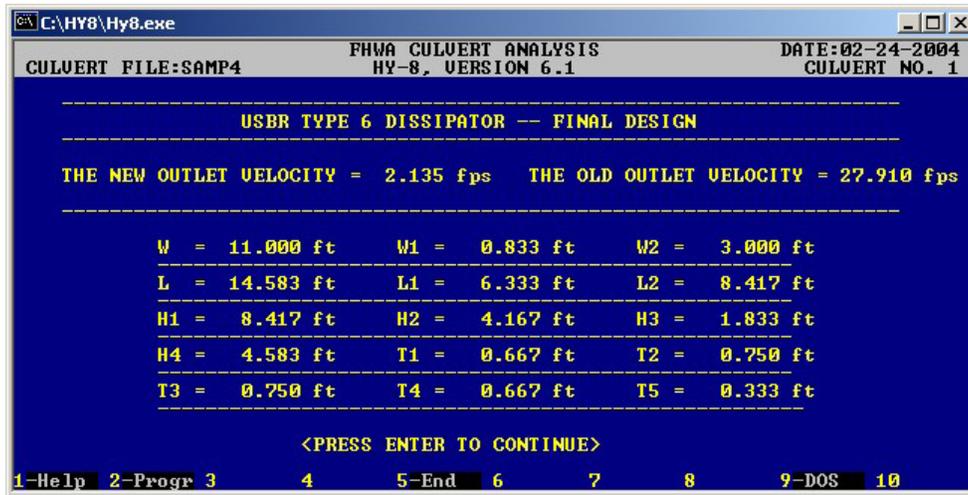


Figure 9A-30
HY-8 On-Screen Design Report for the USBR Type VI Impact Basin

Step 3:

Once an output report has been generated, the designer would press enter to continue. This action brings up the screen shown in Figure 9A-31. The designer is provided an opportunity to output a copy of the design report. Pressing “escape” at this screen will direct the program back to the menu for choosing the desired type of design analysis (see Figure 9A-27). Pressing “enter” would direct the program to the report output screen, shown in Figure 9A-31.

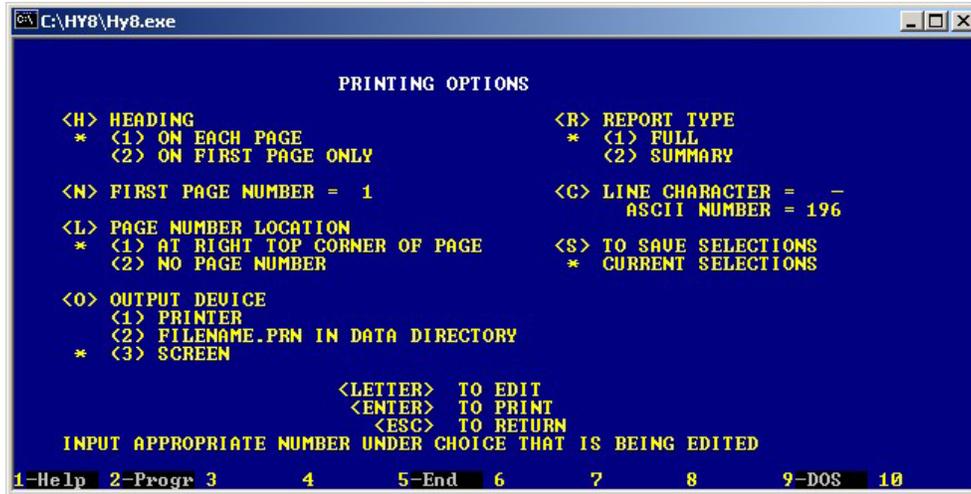


Figure 9A-31
HY-8 Report Output Screen

The report output screen provides the designer the opportunity to send the design report to either the screen, the default printer, or to a data file. To access this option, the designer would enter “O” then enter a number from 1 to 3, depending on the desired output destination. Pressing “enter” will cause the design report to be printed. Option “2” will direct the output to a data file. This file is automatically named with the base name of the culvert input file name (for this example, SAMP4) with a “.prn” extension. The file is stored in the directory where the culvert input file is located. A hard copy of the design report for this site is presented in Figure 9A-32.

Once the file has been selected, the designer may press “escape” to exit the report output page, and “escape” a second time to return to the menu for selecting the desired type of design. Pressing “6” at this menu will cause the program to exit the energy dissipator module and return to the main screen of HY-8.

Step 4:

A good check of the HY-8 results is to verify the tailwater depth will meet the condition specified in Section 9.04.2.2.4, Step 4, which recommends that the tailwater depth be below the midpoint of the baffle wall, or:

$$TW \leq h_3 + \frac{h_2}{2}$$

Based on the HY-8 results for this site, the above expression becomes:

$$3.41 \leq 1.833 + \frac{4.167}{2} \quad \text{or} \quad 3.41 \leq 3.92$$

Since this expression is true, the design is adequate with respect to the tailwater depth.

Step 5:

The HY-8 output report for this site shows a basin exit velocity, V_E , of 2.14 ft/s, but does not provide an estimate of the depth at the exit, d_E . However, it is important to know d_E since it must be compared to the depth in the natural channel to compute the actual exit velocity. As a check of the HY-8 results, this depth will be computed based on the head loss in the basin.

Using the equations presented in Section 9.04.2.2.4, the specific energy of the flow at the culvert outlet can be computed. Based on the culvert analysis, the brink depth, d_o , is 1.25 feet and the outlet velocity, V_o , is 27.91 ft/s. Therefore:

$$H_o = d_o + \frac{V_o^2}{2g} = 1.25 + \frac{27.91^2}{2 \times 32.2} = 13.35 \text{ ft}$$

The head loss in the basin is computed using the Froude Number of the culvert outflow, Fr_o . To determine this parameter, it is first necessary to compute the equivalent depth, d_e , of the flow as follows:

The ratio of d_o to the culvert diameter, D , is 1.25/6 or 0.208. Interpolating from Table 6A-11 yields a value of 0.151 for the ratio A_o / A_{full} , where A_o is the flow area at the brink, and A_{full} is the area of the culvert flowing full. Thus, A_o is computed as:

$$A_o = 0.151 \times \pi \times 3^2 = 4.276 \text{ ft}^2$$

The equivalent depth, d_e , would be:

$$d_e = \left(\frac{A_o}{2} \right)^{0.5} = \left(\frac{4.276}{2} \right)^{0.5} = 1.462 \text{ ft}$$

The outlet Froude Number, Fr_o , would then be computed as:

$$Fr_o = \frac{V_o}{(g \times d_e)^{0.5}} = \frac{27.91}{(32.2 \times 1.462)^{0.5}} = 4.068$$

Once the Froude Number has been computed, it is then possible to compute the ratio of the head loss in the basin, H_L , to the specific energy at the culvert brink, H_o .

$$\frac{H_L}{H_o} = 0.2718 \ln(Fr) + 0.2328 = 0.2718 \ln(4.068) + 0.2328 = 0.614$$

Since the specific energy at the outlet has already been computed, the head loss in the basin may be computed as:

$$H_L = 0.614 H_o = 8.20 \text{ ft}$$

The energy at the basin exit can be computed as:

$$H_E = H_o - H_L = 13.35 - 8.20 = 5.15 \text{ ft}$$

Given a value for H_E , it is then possible to compute a value for the depth at the basin exit, d_E , from:

$$H_E = d_E + \frac{\left[\frac{Q}{W \times d_E} \right]^2}{2g} = d_E + \frac{\left[\frac{120}{11 \times d_E} \right]^2}{2 \times 32.2}$$

This equation is solved by trial and error and results in a value for d_E of 5.08 feet in the subcritical flow regime. Using the Continuity Equation, the flow velocity at the exit, V_E , is computed as:

$$V_E = \frac{Q}{W \times d_E} = \frac{120}{11 \times 5.08} = 2.15 \text{ ft/s}$$

The computed velocity matches very well with the velocity returned by HY-8. However, a depth of 5.08 feet is considerably greater than the tailwater depth of 3.41 feet. Therefore, it is necessary to check whether the tailwater depth is above or below the critical depth at the basin exit, d_{Ec} . This is computed as:

$$d_{Ec} = \left[\frac{Q}{W \sqrt{g}} \right]^{0.667} = \left[\frac{120}{11 \times \sqrt{32.2}} \right]^{0.667} = 1.546 \text{ ft}$$

Because the tailwater depth is in between the critical depth at the exit and the depth computed based on energy, the actual exit depth is assumed to be equal to the tailwater depth of 3.41 feet and the exit velocity is computed from the Continuity Equation as:

$$V_E = \frac{Q}{W \times d_E} = \frac{120}{11 \times 3.41} = 3.20 \text{ ft/s}$$

Since the exit velocity is less than 5 ft/sec, it will not be necessary to provide a riprap apron. Rather, adequate erosion protection should be provided by the standard 3-foot deep cut-off wall.

Step 6:

From the criteria provided in Section 9.03.3.4.2, the culvert should be provided with a horizontal segment just upstream of the basin where the culvert slope exceeds 27 percent. The slope of the proposed culvert is:

$$\frac{574.80 - 554.50}{200} = 10.1\% \quad \text{Thus, the horizontal culvert segment will not be necessary.}$$

FHWA CULVERT ANALYSIS, HY-8, VERSION 6.1

CURRENT DATE	CURRENT TIME	FILE NAME	FILE DATE
02-24-2004	13:16:50	SAMP4	02-24-2004

AA
 CULVERT AND CHANNEL DATA
 AA

CULVERT NO. 1	DOWNSTREAM CHANNEL
CULVERT TYPE: 6.000 ft CIRCULAR	CHANNEL TYPE : TRAPEZOIDAL
CULVERT LENGTH = 201.028 ft	BOTTOM WIDTH = 6.000 ft
NO. OF BARRELS = 1.0	TAILWATER DEPTH = %-554.500 ft
FLOW PER BARREL = 120.000 cfs	TOTAL DESIGN FLOW = 120.000 cfs
INVERT ELEVATION = 554.500 ft	BOTTOM ELEVATION = 554.500 ft
OUTLET VELOCITY = 27.910 fps	NORMAL VELOCITY = 2.476 fps
OUTLET DEPTH = 1.250 ft	

AA
 USBR TYPE 6 DISSIPATOR -- FINAL DESIGN
 AA

BASIN OUTLET VELOCITY = 2.135 fps

AA
 W = 11.000 ft W1 = 0.833 ft W2 = 3.000 ft
 AA
 L = 14.583 ft L1 = 6.333 ft L2 = 8.417 ft
 AA
 H1 = 8.417 ft H2 = 4.167 ft H3 = 1.833 ft
 AA
 H4 = 4.583 ft T1 = 0.667 ft T2 = 0.750 ft
 AA
 T3 = 0.750 ft T4 = 0.667 ft T5 = 0.333 ft
 AA

Figure 9A-32
 HY-8 Output Report for the USBR Type VI Energy Dissipator Design
 Of Example Problem #4

9.06.2.5 EXAMPLE PROBLEM #5: HOOK TYPE IMPACT BASIN DESIGN USING HY-8

GIVEN:

A culvert has been designed as follows:

Design discharge: 125 ft³/s
 Diameter: 60 inches
 Inlet elevation: 726.7 feet
 Outlet elevation: 724.2 feet
 Length: 100 feet

The channel geometry downstream of the culvert is irregular, as shown in the Figure 9A-33. The Manning's n-value of the channel is 0.045 while the n-value of the overbanks is 0.10. The natural stream slope of 0.006 ft/ft carries a moderate amount of floating debris.

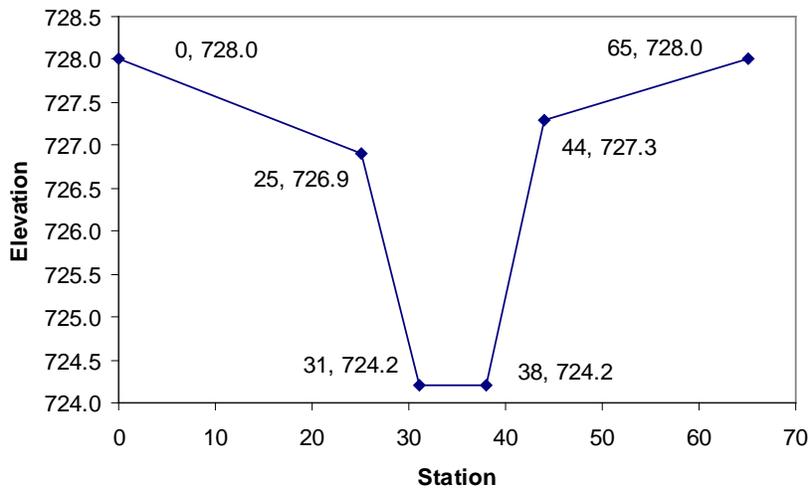


Figure 9A-33
 Plot of Downstream Cross Section for Example Problem #5

FIND:

Design a Hook type impact basin for this site, beginning by determining the width and side slopes of the trapezoidal basin. Using computerized methods, determine the required dimensions and locations of the hooks. Estimate the flow velocity at the basin outfall, V_B , and design any riprap apron that may be needed downstream.

SOLUTION:

A hook energy dissipator is the preferred option at this site due to the relatively moderate conditions at the culvert outlet and the presence of floating debris, which could clog another type of structure.

The following steps discuss the computer methods utilized for the basin design as well as the hand computations needed to complement the computer solution.

Step 1:

The hydraulic performance of the culvert is analyzed first. The resulting performance curve computed by HY-8 is shown in Figure 9A-34. As seen, the brink depth, d_o , and outlet velocity, V_o , are 2.14 feet and 15.6 ft/s, respectively. Detailed information on determining the hydraulic performance of a culvert using HY-8 is provided in Chapter 6.

DIS-CHARGE FLOW (cfs)	HEAD-WATER ELEU. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	FLOW TYPE (F4)	NORMAL DEPTH (ft)	CRIT. DEPTH (ft)	OUTLET DEPTH (ft)	TW DEPTH (ft)	OUTLET UEL. (fps)	TW UEL. (fps)
0	726.70	0.00	0.00	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
13	727.81	1.11	1.11	1-S2n	0.57	0.96	0.60	0.81	9.19	1.93
25	728.43	1.73	1.73	1-S2n	0.80	1.37	0.77	1.17	12.68	2.36
38	728.97	2.27	2.27	1-S2n	1.02	1.69	1.07	1.45	12.13	2.66
50	729.44	2.74	2.74	1-S2n	1.16	1.98	1.25	1.69	12.92	2.89
63	729.86	3.16	3.16	1-S2n	1.30	2.21	1.41	1.89	13.65	3.07
75	730.24	3.54	3.54	1-S2n	1.44	2.44	1.58	2.08	14.01	3.23
88	730.59	3.89	3.89	1-S2n	1.56	2.65	1.73	2.25	14.52	3.37
100	730.94	4.24	4.24	1-S2n	1.66	2.84	1.87	2.41	14.92	3.50
113	731.27	4.57	4.57	1-S2n	1.77	3.02	2.01	2.56	15.19	3.61
125	731.61	4.91	4.91	1-S2n	1.88	3.19	2.14	2.70	15.60	3.71

INVERT ELEVATIONS--> Inlet - 726.70 ft Crest - 0.00 ft
 FILE: SAMP5 Outlet - 724.20 ft Throat - 0.00 ft

PRESS: <KEY> TO CONTINUE <W> FOR PROFILE TABLE
 <P> TO PLOT <I> FOR IMPROVED INLET TABLE

1-Help 2 3 4-Type 5-End 6 7 8 9-DOS 10

Figure 9A-34
60-Inch Culvert Hydraulic Analysis by HY-8

Step 2:

The trapezoidal dimensions of the hook basin should be selected before the other dimensions of the basin can be determined by the computer program. Examination of the stream cross section presented in the "Given" section of this problem will show the channel has a bottom width of 7 feet and side slopes of approximately 2H:1V. As discussed in HEC-14, the bottom width of the basin, W_6 , may be any value between the diameter of the culvert, D (W_0 in HEC-14) and 2 times the diameter of the culvert. The natural stream cross section has a bottom width of 7 feet, which is less than twice the culvert diameter of 5 feet. Therefore, the bottom width of the basin will be 7 feet to match the natural cross section. HEC-14 also states that the side slopes of the basin may be either 2:1 or 1.5:1. Thus, 2:1 side slopes will be selected for the basin as this most closely matches the existing conditions.

Step 3:

Once the trapezoidal dimensions of the basin have been determined, and the hydraulic analysis of the structure has been completed, the designer should return to the main screen of HY-8 as shown in Figure 9A-35 and press the letter "J" to initiate the energy dissipator design.

After passing an introductory screen, the designer is prompted to enter the name of the culvert design data file as shown in Figure 9A-36.

Once the name of the data file has been entered, the designer will be prompted to select the culvert which will be used for the energy dissipator design. (Since most files will contain only one culvert, this screen is not shown). The next screen will provide an opportunity to select the type of analysis to be conducted. Since the type of dissipator desired for this site is a hook basin, which is an external dissipation structure, the designer would type the number "4," as shown in Figure 9A-37.

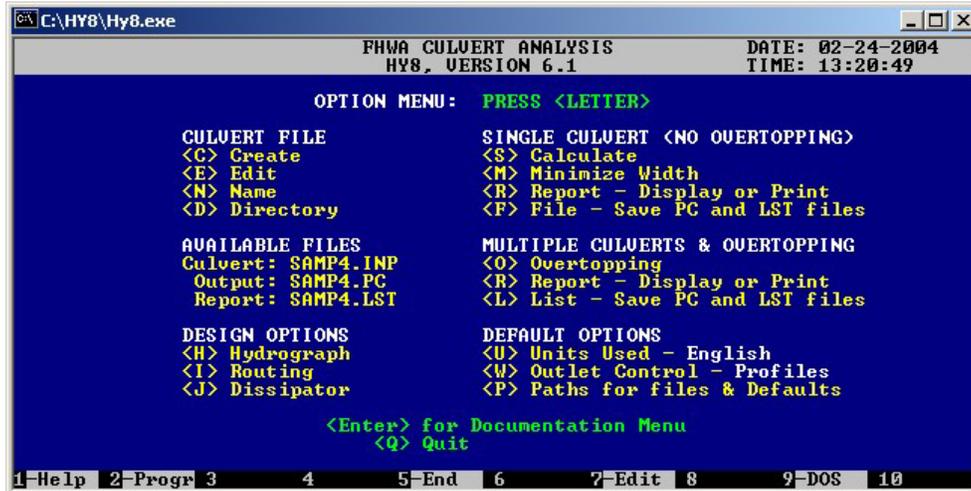


Figure 9A-35
HY-8 Main Screen

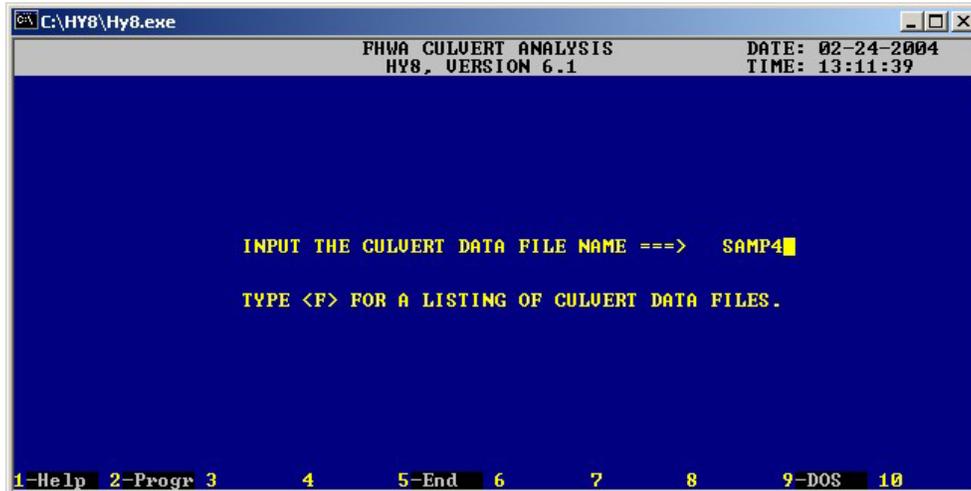


Figure 9A-36
Entering the Culvert Data File Name

Because HY-8 divides external dissipators into three different categories, the designer is prompted next to enter the general type of structure desired, as shown in Figure 9A-38.

Because the hook basin is considered an “At-Streambed-Level Structure,” the designer would type the letter “C.”

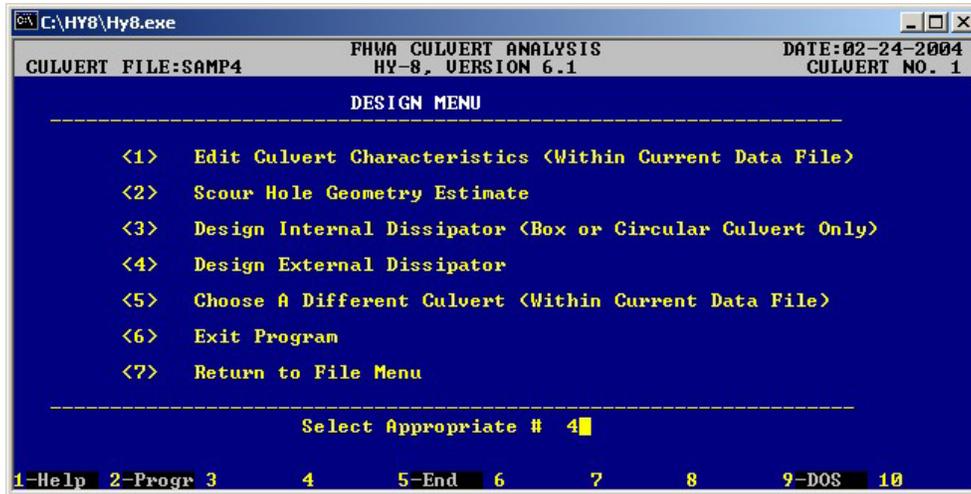


Figure 9A-37
Choosing the Desired Type of Analysis

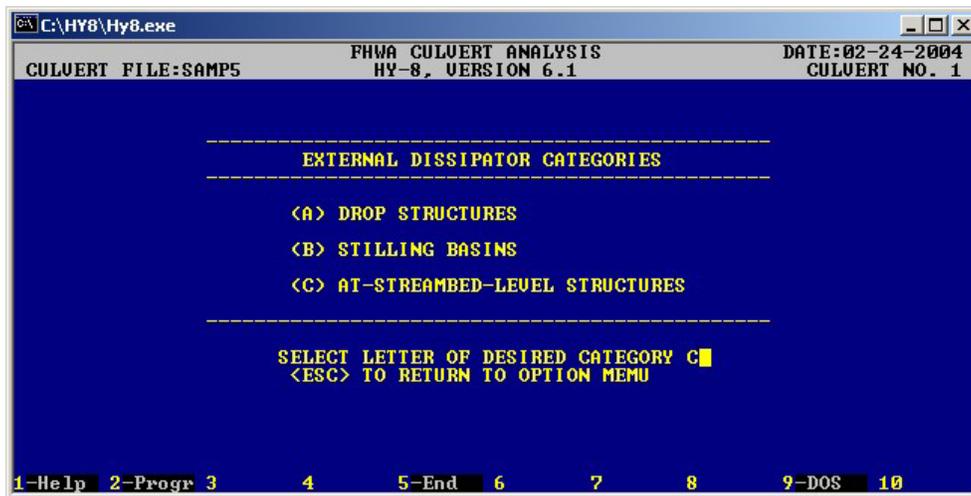


Figure 9A-38
Selecting the External Dissipator Category

Once a category of dissipator has been selected, HY-8 automatically provides a report of the feasibility of each of the different dissipators in that category for the project site, as shown in Figure 9A-39. As can be seen, many different basins may be considered feasible at this site. Because the hook basin is the desired type of dissipator, the designer would type the number “13” and press “enter” twice. Since more than one type of dissipator is feasible at this site, the designer could select more than one structure for analysis by entering the number for each

structure followed by the “enter” key. After typing the number for the last desired structure type, the designer would press “enter” twice. However, in this example only the hook basin will be selected for design.

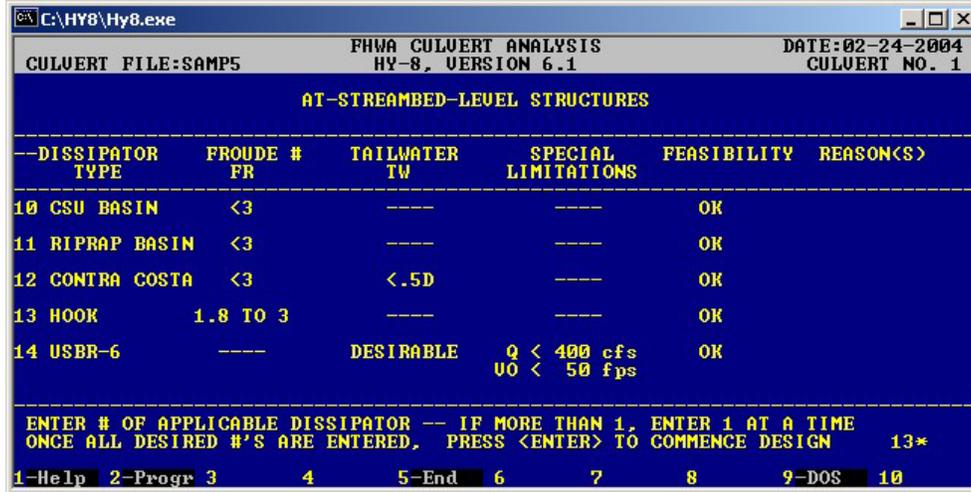


Figure 9A-39
Feasibility Report for At-Streambed-Level Structures

Selecting the hook basin for design directs the program to a screen that is used to enter the trapezoidal dimensions of the basin. As shown in Figure 9A-40, a value of 2 is entered for 2:1 basin side slopes and a value of 7 is entered for the basin bottom width.

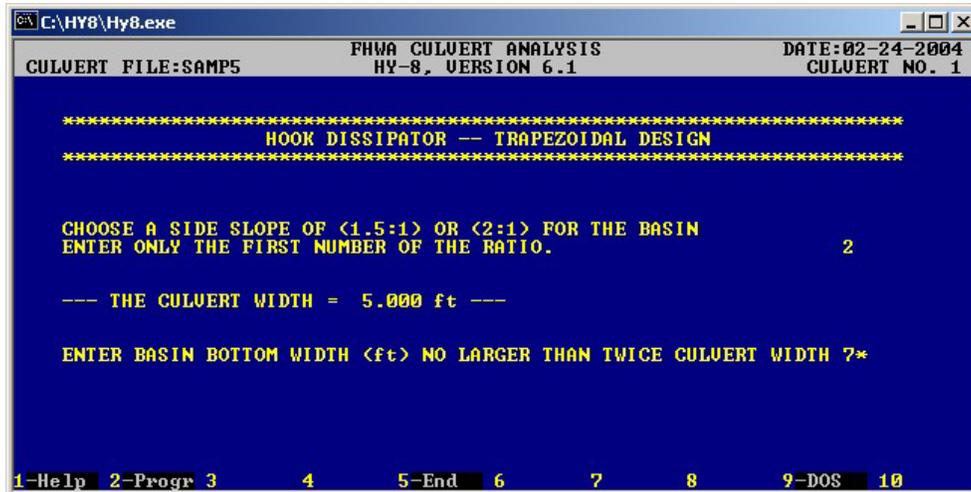


Figure 9A-40
Entering the Hook Basin Trapezoidal Dimensions

Once the trapezoidal basin dimensions have been entered, the program will return a design report to the screen, as shown in Figure 9A-41.

If the design returned by the program appears to be adequate, the designer would type the letter "Y" to accept the design. Otherwise, the designer would type "N" to enter different trapezoidal dimensions for the basin.

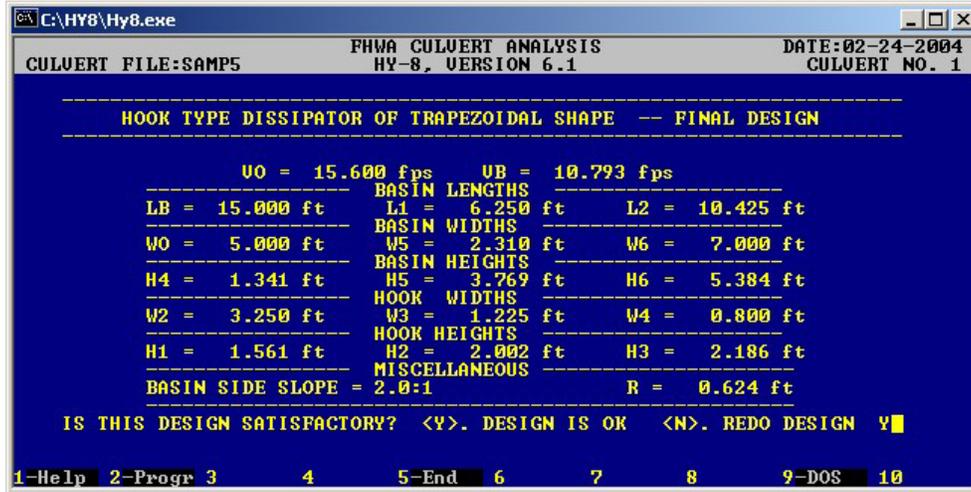


Figure 9A-41
HY-8 Hook Basin Design Report

Step 3:

After a design has been accepted, the program brings up a screen, whereby the designer is provided an opportunity to output a copy of the design report. Pressing "escape" at this screen would direct the program back to the menu for choosing the desired type of design analysis (see Figure 9A-37). Pressing "enter" would direct the program to the report output screen, as shown in Figure 9A-42.

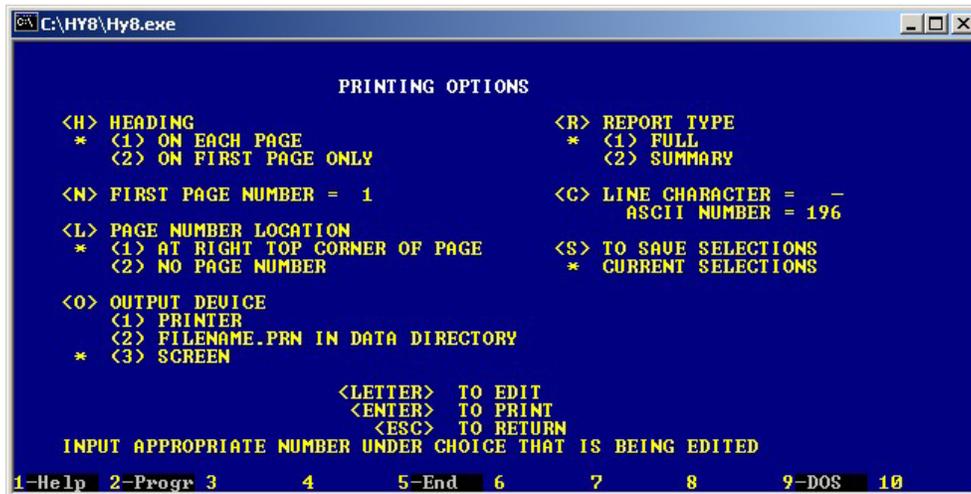


Figure 9A-42
HY-8 Report Output Screen

Step 4:

The basin outlet velocity, V_B , computed by HY-8 is about 10.8 ft/s, which indicates that there is a need for a riprap apron downstream of the hook basin. However, prior to determining the length of this apron, the basin outlet velocity computed by HY-8 is checked.

Since the basin outlet velocity is determined from the Froude Number of the culvert outflow, Fr_o , the equivalent depth at the culvert brink, d_e , should be determined. Using the Continuity Equation, the flow area at the culvert outlet, A_o , may be determined as:

$$A_o = \frac{Q}{V_o} = \frac{125}{15.60} = 8.01 \text{ ft}^2$$

The equivalent depth, d_e , may then be computed from Equation 9-2 as:

$$d_e = \left(\frac{A_o}{2} \right)^{0.5} = \left(\frac{8.01}{2} \right)^{0.5} = 2.00 \text{ ft}$$

The culvert outlet Froude Number, Fr_o , is computed from Equation 9-3 as:

$$Fr_o = \frac{V_o}{(g \times d_e)^{0.5}} = \frac{15.60}{(32.2 \times 2.00)^{0.5}} = 1.94$$

Table 9-5 in the chapter text provides values of the ratio of the culvert outlet velocity to the basin outlet velocity, V_o / V_B , for differing values of Fr_o , and for basin bottom widths, W_6 , equal to the culvert diameter, D (W_6 in HEC-14), and twice the culvert diameter. Interpolating from Table 9-5 for $Fr_o = 1.94$ yields:

	$W_6 = D$	$W_6 = 2 \times D$
$V_o / V_B =$	1.502	1.489

Since $D = 5$ feet and 2 times $D = 10$ feet, interpolating these results for a basin width of 7 feet yields a value for $V_o / V_B = 1.489$, with the result that:

$$V_B = \frac{V_o}{(V_o / V_B)} = \frac{15.60}{1.489} = 10.48 \text{ ft/s}$$

Although this value is somewhat different than the result returned by HY-8, the result should be considered more correct than what HY-8 produced.

Step 5:

Since the basin outlet velocity, V_B , is greater than 5 ft/s, a riprap apron should be provided for additional erosion protection. To determine the length of this apron, it will first be necessary to determine the cross sectional flow area at the basin outlet, A_B , and apply the procedure provided in Section 6.05.5.

The flow area at the basin outlet, A_B , may be computed from the Continuity Equation as:

$$A_B = \frac{Q}{V_B} = \frac{125}{10.48} = 11.927 \text{ ft}$$

Assuming a trapezoidal cross section with a 7-foot bottom width and 2:1 side slopes, this area corresponds to a depth at the basin outlet, d_B , of 1.25 feet, a top width of 12.02 feet, and a Froude Number of 1.853.

Because the flow at the basin outlet is in the supercritical regime at a depth less than the tailwater depth (TW) of 2.70 feet, it is apparent that a hydraulic jump will occur on the apron downstream of the hook basin. Because the jump will be weak in nature, the length of the apron may be computed using the procedure provided in Section 6.05.5.

The effective diameter of the flow area at the basin outlet may be computed as:

$$D_{eff} = \left[\frac{4A_B}{\pi} \right]^{0.5} = \left[\frac{4 \times 11.927}{\pi} \right]^{0.5} = 3.90 \text{ ft} \quad (\text{see Section 6.05.5})$$

The natural channel velocity computed by HY-8 is 3.71 ft/s. Thus, the value to be used for the natural channel velocity, V_n , will be the minimum value of 5 ft/s. Thus, the ratio V_n / V_B is:

$$\frac{V_n}{V_B} = \frac{5.0}{10.48} = 0.48$$

Since this ratio is less than 0.6, the length of the riprap apron (see Section 6.05.5) would be computed as:

$$\frac{L_a}{D_{eff}} = 5.933 \left(\frac{V_n}{V_B} \right)^{-1.005} = 5.933(0.48)^{-1.005} = 12.41 \text{ ft}$$

Since $D_{eff} = 3.90$ feet, L_a would be 49 feet. This should be combined with the hook basin length of 15 feet for a total length for erosion protection of 64 feet. The apron should be constructed from Class B riprap, and the basin should be provided with the standard 3-foot deep cut-off wall.

Step 6:

The drainage easement that would be needed for the length of erosion protection described above is comparatively large. Thus, it may be prudent to investigate whether another type of energy dissipator could be built in a smaller space. Because the tailwater depth is less than 75% of the culvert diameter and the Froude Number at the culvert outfall, Fr_o , is less than 3, this site would be a good candidate for a riprap stilling basin, which would also be able to tolerate the debris load in the flow.

Analysis of the riprap basin option by HY-8 (this is left to the reader as an exercise) indicates the required basin length would be 36 feet. Because this basin would have an exit velocity of about 9.4 ft/s, the additional riprap apron required downstream might be as long as

50 to 60 feet. In any case, the combined length would be significantly greater than the distance required for the hook basin. Thus, it appears that the hook basin would remain the best option for the site.

Step 7:

It should be noted that the overall basin depth, h_6 , computed by HY-8 is 5.38 feet, which reflects the recommendations given in HEC-14. However, as shown in the "Given" section of this problem, the existing channel cross section is only about 3 feet deep. Thus, judgment should be made for fitting the basin to the natural site constraints.

The outlet depth computed in Step 5 was 1.25 feet. This depth was computed assuming a trapezoidal cross section with a base 7 feet wide and 2:1 side slopes. A conservative estimate of the flow depth in this basin may be computed by applying this depth to the height of the sill at the downstream end of the basin. Since the HY-8 results yielded a value for h_4 of 1.34 feet, this estimate becomes $1.25 + 1.34$, or 2.59 feet, which is less than the existing channel depth. Thus, it may be assumed that the main force of the flow in the basin would be contained within a depth of 3 feet and the basin height above that depth is needed to account for the splashing which will occur.

Given these assumptions, it should be adequate to provide the basin with 3-foot high concrete walls at a slope of 2H:1V. Above the concrete, the basin walls would consist of Class B riprap placed at the natural grade, on geotextile fabric, up to the required basin height. This design should ensure adequate performance by the hook basin while minimizing the earth work required for the basin construction.

9.06.3 GLOSSARY

The following list of terms is representative of those used in the design of energy dissipators. All of the terms may not necessarily be used in the chapter text; but rather, are commonly used by engineers, scientists, and planners.

BAFFLE – A plate or other structure that redirects flow by imposing an obstruction.

BED MATERIAL – The natural soils, rocks, or other materials in which the channel of a given stream has formed.

BUOYANCY – An uplifting force created on an object as the result of the displacement of water. When the buoyant force on an object exceeds the weight of the object, the object will float.

CAVITATION – A phenomenon that creates small cavities of very low pressure along the edges of a structure within a high-velocity flow. These cavities usually collapse suddenly causing damage to the structure.

CHANNEL FLOW – The flow of water in a defined conveyance such as a stream, ditch, or pipe.

COHESIONLESS SOILS – Soils in which electrostatic or other forces tend to bind the particles together, are insignificant.

COHESIVE SOILS – Soils, usually very fine-grained, in which electrostatic or other forces, that tend to bind the particles together, are sufficient to affect the properties of the soil.

CONVEYANCE – A measure of the capacity of an open channel or pipe to pass water based on its geometric and flow resistance properties.

CRITICAL DEPTH – The depth at which the gravitational and inertial forces acting on the flow are exactly balanced and where the specific energy is at a minimum. For a given discharge and cross-section geometry there is only one critical depth.

CRITICAL FLOW – An open channel flow condition where the depth is exactly at critical depth and velocity is at critical velocity.

CUT-OFF WALL – A vertical wall that extends downward into the sediments beneath the outlet of a drainage structure and that serves to prevent the undermining of the outlet.

D₅₀ (or d₅₀) – The effective particle size at which half of the particles in a given sample of soil or rock are smaller and half of the particles are larger than the average particle or stone size.

DEBRIS – Material such as sediments, stones, tree limbs, etc., carried by flow in a waterway, either by the force of the flow or by buoyancy.

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 be accommodated by the proposed drainage facility.

DISCHARGE INTENSITY – A parameter representing the ratio between the flow rate through a structure and some dimension of the structure such as diameter, hydraulic radius or width.

DRAINAGE EASEMENT – The right, obtained from the owner of property adjoining a roadway or other development site, to use a portion of that property to place and maintain part of a proposed drainage facility.

ENERGY DISSIPATOR – Some means, usually structural, employed at a drainage structure outfall to reduce the force or velocity of the flows leaving the structure to reduce or prevent damage by erosion.

EQUIVALENT DEPTH – A parameter used to apply hydraulic equations based on a rectangular cross section to non-rectangular structures. It represents a rectangular cross section having a width equal to twice its depth and has an area equal to the area of the flow in the non-rectangular structure.

EROSION – The removal of sediments or other soil from a site by natural processes, particularly by the force of moving water.

EXTERNAL ENERGY DISSIPATOR – A basin or other type of structure placed at a drainage outfall to reduce the force of the flow leaving the structure.

FROUDE NUMBER – A parameter that represents the ratio of the inertial forces to the gravitational forces acting on a flow of water and thus indicating whether the flow is in the subcritical or the supercritical flow regime.

GRAIN SIZE DISTRIBUTION – A measure of the proportions of a given soil sample falling within a defined range of particle sizes.

GRAVITATIONAL FORCES (acting on a flow of water) – The forces acting on a body of water due to its weight, causing it to move in a downward direction.

HEADWATER – The depth or elevation of the water surface upstream of a drainage structure, usually determined by the behavior of the flow through the structure.

HYDRAULIC RADIUS – A parameter used in the analysis of uniform flow. Computed as the flow area divided by the wetted perimeter.

HYDRAULIC JUMP – A often quite turbulent flow phenomenon where a high-energy supercritical flow shifts suddenly to the subcritical flow regime.

HYDRAULIC ROUGHNESS – The frictional resistance of a given surface to the flow of water.

HYDRODYNAMIC FORCE – The force imposed against or along a structure by moving water as a result of altering the momentum or direction of the flow.

IMPACT BASIN – A type of energy dissipator that operates by providing some form of obstruction, often blocks or a vertical baffle, in direct line with high-energy flows from a drainage structure outfall.

INERTIAL FORCES (acting on a flow of water) – The forces exerted on or by a body of water due to the tendency of a moving mass to continue moving in the same direction.

INITIAL DEPTH – The supercritical flow depth occurring just upstream of a hydraulic jump.

INLET CONTROL – A culvert flow condition where the capacity of the culvert entrance determines the behavior of the flow through the culvert.

INTERNAL ENERGY DISSIPATORS – Blocks or other means provided inside the barrel upstream of a drainage structure outfall to reduce the force of the flow before it leaves the structure.

JUMP HEIGHT – The difference between the initial and sequent depths of a hydraulic jump.

MANNING'S N-VALUE: - An empirical number assigned to a given material as a gauge of its frictional resistance to the flow of water.

MORPHOLOGY – The science dealing 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 SCOUR HOLE – An eroded area that will often form due to the force of flow from the outfall of a drainage structure having no other form of erosion protection.

NORMAL DEPTH – The depth of flow occurring in an open channel of a given cross section, for a given flow rate, when the slope of the water surface is exactly equal to the slope of the channel

OUTFALL (or OUTLET) – The point at which flows in a closed drainage system, such as a storm sewer, pass into another drainage system, usually an open conveyance such as a ditch.

OUTLET CONTROL – A culvert flow condition in which the behavior flow through the culvert is determined by either the capacity of the culvert barrel to pass flows or by conditions at the outlet.

RIPRAP – Crushed rock, usually manufactured to a specific gradation and used to prevent erosion on slopes or in stream channels.

RIPRAP APRON – A lining composed of crushed rock to prevent erosion due to high-velocity flows from a drainage structure outfall, typically placed within a waterway or other open conveyance.

RIPRAP STILLING BASIN – An energy dissipation structure constructed from crushed rock that provides a pool at the drainage structure outlet for a hydraulic jump to occur.

ROUGHNESS COEFFICIENT – A numerical measure of the frictional resistance to flow in a channel, such as the Manning's coefficient.

ROUGHNESS ELEMENTS – Usually block structures placed on the bottom of culvert or other type of conveyance to increase its frictional resistance to flow.

SEQUENT DEPTH – The subcritical flow depth occurring just downstream from a hydraulic jump.

SILL – A short, vertical structure, placed at the downstream end of an energy dissipator to create an abrupt transition between the floor of the structure and the downstream channel. Often improves the overall performance of the dissipator.

SPECIFIC ENERGY – The energy available in a flow of water, without consideration of its elevation; that is, the sum of the depth and velocity head.

STILLING BASIN – A structure that dissipates the energy of a high-velocity flow by means of a pool into which the flow will fall, resulting in a hydraulic jump.

STORM SEWER – A system of catch basins, manholes and pipes designed to remove stormwater runoff from the ground surface and convey it to a suitable outlet point.

SUBCRITICAL FLOW – A flow condition in which the behavior of the flow is determined more by gravitational forces than by inertial forces. The Froude Number of subcritical flows are <1 .

SUPERCritical FLOW – A flow condition in which the behavior of the flow is determined more by inertial forces than by gravitational forces. The Froude Number of supercritical flows are >1 .

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.

TOP WIDTH – The distance across the water surface in open channel flow, measured perpendicular to the channel in plan view.

TUMBLING FLOW – A flow condition which consists of a series of hydraulic jumps and overfalls created by properly spaced roughness elements in a culvert or other drainage structure.

UNDERMINING – Erosion extending beneath a structure by removing material which is necessary to the integrity of the structure foundation.

WEIR – A ridge or raised sill over which flow may freely fall. Gravity is the dominant influence over the flow rate.

9.06.4 REFERENCES

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9.06.5 ABBREVIATIONS

- EPA - Environment Protection Agency
- FEMA - Federal Emergency Management Agency
- FHWA - Federal Highway Administration
- Fr – Froude Number
- HDS-4 - Hydraulic Design Series Number 4
- HDS-5 - Hydraulic Design Series Number 5
- HEC-5 - Hydrologic Engineering Circular Number 5
- HEC-14 - Hydrologic Engineering Circular Number 14
- HYDRAIN – Integrated Drainage Design Computer System
- IP – Instructional Paper
- RD – Reference Document
- SAF - Saint Anthony Falls
- SCS – Soil Conservation Service
- TDOT - Tennessee Department of Transportation
- TDEC - Tennessee Department of Environment and Conservation
- TR – Technical Release
- USBR - United States Bureau of Reclamation
- USDA - United States Department of Agriculture
- USDOT - United States Department of Transportation
- USGS - United States Geological Survey