

HY-8 User Manual (v7.3)

HY-8 Culvert Analysis Program

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1. Introduction

Introduction

HY-8 Versions 3.1, 4.1, and 6.1 were developed by Philip L. Thompson and were provided to the Federal Highway Administration (FHWA) for distribution. HY-8 Versions 1.1, 2.1, and 3.0 were produced by the Pennsylvania State University in cooperation with FHWA. The HY-8 Versions 3.0 and earlier versions were sponsored by the Rural Technical Assistance Program (RTAP) of the National Highway Institute under Project 18B administered by the Pennsylvania Department of Transportation. Version 6.1 (Energy, HYD and Route) was produced by GKY and Associates under contract with FHWA.

Christopher Smemoe developed HY-8 7.0 at the Environmental Modeling Research Lab at Brigham Young University (BYU) under the direction of Jim Nelson of BYU and with the assistance of Rollin Hotchkiss (BYU) and Philip L. Thompson (Retired from FHWA). The primary purpose of version 7.0 was to provide Windows-based graphical user interface (GUI) for the same hydraulic calculations performed in version 6.1 of HY-8. In the course of the development all program culvert modeling functions were translated from Basic to the C++ programming language. Several minor bugs in version 6.1 were corrected in HY-8 version 7.0. Versions 7.1, 7.2, and 7.3 of HY-8 were incremental updates in which several new features were included and several bugs were fixed. Besides bug fixes, the following new features were added to HY-8 7.1 and 7.2:

1. Energy dissipation calculators
2. A new culvert shape/coefficient database
3. The ability to model buried (embedded) culverts
4. The Utah State University exit loss equation was added as an option when computing outlet losses
5. Modeling of plastic pipes
6. Research was conducted relating to sequent depth computations for hydraulic jump computations
7. Several improvements and fixes were made to the HY-8 report generation tools.
8. Section property matrix of 10 points for interpolation was replaced with direct computation of section properties for each discharge.

Christopher Smemoe and Eric Jones at Aquaveo (LLC) developed HY-8 7.3 with help from Rollin Hotchkiss (BYU) and Philip L. Thompson (Retired from FHWA). The following new features were added to HY-8 7.3:

1. The profile computation code was rewritten to increase program stability and efficiency
2. Capability was added to model hydraulic jumps and their lengths in culverts
3. Capability was added to model broken back culverts and hydraulic jump locations/lengths in broken back culverts
4. Ability to model horizontal and adverse slopes was added
5. Two new culvert types were added to the culvert shape/coefficient database: Concrete open-bottom arch (CON/SPAN) and South Dakota prefabricated reinforced concrete box culverts

Several graduate students contributed to both the theory and programming efforts of HY-8. Brian Rowley assisted in the development of version 7.0 and 7.1 while a graduate student at BYU. Elizabeth Thiele compared several culvert hydraulic computer models in her research and determined several improvements, some of which have just recently been implemented in **HY-8 in Culvert Hydraulics: Comparison of Current Computer Models** ^[1] by Elizabeth Anne Thiele (2007). Nathan Lowe studied hydraulic jumps in various closed conduit configurations to make possible comprehensive hydraulic jump calculations in **Theoretical Determination of Subcritical Sequent Depths for Complete and Incomplete Hydraulic Jumps in Closed Conduits of Any Shape** ^[2] by Nathan John Lowe (2008). Nathan's equations were used to determine locations and lengths of hydraulic jumps in HY-8 7.3.

HY-8 automates the design methods described in HDS No. 5, "Hydraulic Design of Highway Culverts", FHWA-NHI-12-029 and in HEC No.14, FHWA-NHI-06-086. Version 6.1 is the last version of the MS-DOS program that was distributed. Hydrologic calculations are available in the Watershed Modeling System (WMS) and in the FHWA Hydraulic Toolbox.

The software has been structured to be self-contained and this help file functions as the program's user's manual. This facilitates its use by roadway design squads. However, the knowledgeable hydraulic engineer will also find the software package useful because it contains advanced features. This help file provides necessary instructions and clarifications.

References

[1] <http://contentdm.lib.byu.edu/cdm/singleitem/collection/ETD/id/1004/rec/1>

[2] <http://contentdm.lib.byu.edu/cdm/singleitem/collection/ETD/id/1623/rec/2>

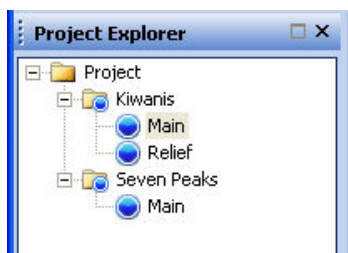
Getting Started

HY-8 automates culvert hydraulic computations. As a result, a number of essential features that make culvert analysis and design easier.

HY-8 enables users to analyze:

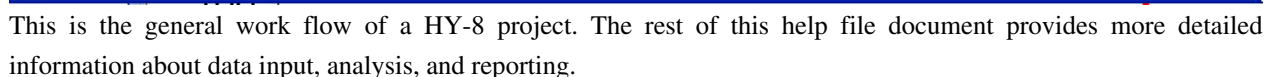
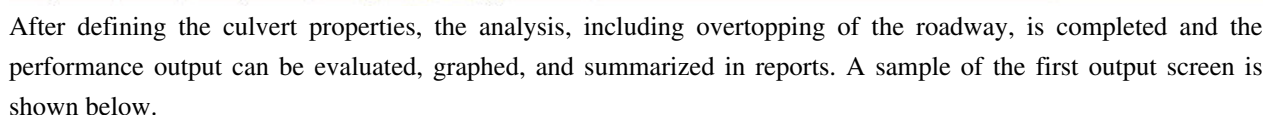
- The performance of culverts
- Multiple culvert barrels at a single crossing as well as multiple crossings
- Roadway overtopping at the crossing and
- Develop report documentation in the form of performance tables, graphs, and key information regarding the input variables

New to HY-8 is the ability to define multiple crossings within a single project. A crossing is defined by 1 to 6 culverts, where each culvert may consist of multiple barrels. In previous versions this defined the entire project. However, with HY-8 any number of projects may be defined within the same project. The diagram below illustrates the hierarchy of a HY-8 project.



Within a project new crossings can be created and then for each crossing up to six culverts can be defined.

The **Microsoft Virtual Map Locator** tool has been included within HY-8 so that a roadway map or aerial photograph can be displayed and culvert crossing locations mapped as shown below.



Differences from DOS HY-8

Differences Between DOS HY-8 and HY-8 7.0

An important objective of the conversion of the HY-8 program to a Windows environment was maintaining the basic philosophy and simplicity model input and operation. While we feel this has been largely achieved, there were obviously some things that we wanted to change and add in order to take advantage of the more modern Windows operating system. This page outlines these changes and new features and will serve as a road map to users who have longed used the DOS version of HY-8.

Crossings

Previous versions of HY-8 allowed for a single crossing to be designed. Multiple culverts and barrels could be defined, but in a given project only the culvert design information for a single roadway crossway could be defined and analyzed. If in the context of a larger design project multiple crossings needed to be analyzed then each one was defined in a separate input file. In HY-8 version 7.0 any number of crossings can be defined within the same project. While it is just as simple to have a single crossing, mimicking older versions of HY-8, you also have the option of performing an analysis on several crossings and grouping them together. The new mapping feature described below helps you to create a map identifying each crossing that can be included in your report. The concept of multiple crossings can also be used to represent separate design alternatives of the same crossing within the same project file. In previous versions of HY-8 you would either have to load them as separate files, or make the incremental changes and reevaluate. In version 7.0 of HY-8 you have the option of “copying” a crossing and then you can make the change you wish to evaluate. The project explorer then makes it easy to toggle back and forth between the alternative crossing designs.

Order of Input

The MS DOS versions of HY-8 presented the input as a series of linear input screens. The order always began with the discharge, followed by the culvert information followed by the tailwater data and ending with the roadway information. In this new Windows compatible version of HY-8 all of the input necessary to analyze a single crossing is presented in the same input screen. However, the grouping of the information has been organized into the “crossing” information and the “culvert” information. The discharge, tailwater, and roadway data are unique to the crossing while the culvert shape, inlet conditions, and site data define a culvert within the crossing. This grouping, and therefore subsequent tabbing through the main input screen, does not follow the same linear progression of input as previous versions of HY-8.

Execution of SINGLE and BALANCE

The MS DOS versions of HY-8 contained separate analysis functions for computing a culvert performance rating curve (SINGLE), and a roadway overtopping analysis (BALANCE) that included the effects of all culverts within a crossing. When running SINGLE, HY-8 assumed that overtopping was not possible even though roadway data were defined. In HY-8 version 7.0 all culvert analysis is done with all culverts in the crossing and roadway overtopping as considerations (BALANCE). This means that when you view the performance table (or plot) for a given culvert within the crossing you are seeing the performance within the context of any other culverts and overtopping of the roadway for the crossing and not just as an isolated culvert as was the case with SINGLE in older versions of HY-8. If there is only a single culvert and the roadway is high enough that overtopping does not occur, the performance table of HY-8 version 7.0 would match older versions.

Front View

HY-8 version 7.0 contains an option for displaying the front view (elevations) of the culvert and roadway at the crossing. Hydraulic computations in version 7.0, like older versions, are not a function of the lateral placement of culverts within a crossing. Only the elevation relationship to the roadway and other culverts is important. However, if you wish to view this relationship in the front view you will be prompted to enter the lateral stationing of the culverts. While irregular shaped roadway sections in HY-8 have always prompted for lateral stations and elevations, the constant elevation option only prompted for a length. In order to allow for the possibility of defining actual stationing along a roadway HY-8 now includes a beginning station as well as the length for constant roadway profiles. The default is zero and can be left as zero if actual stationing is not known or important. Lateral stations for culverts are defined from the beginning (left) side of the roadway and elevations taken from the upstream invert elevation parameter. Cross section information is generally provided at the downstream end of the culvert, but the front view represents the upstream view and because there is no cross section defined for the upstream end of the culvert, no cross section is plotted for the front view. You can change the station of a culvert once entered in the same way by right-clicking in the front view plot window and choosing the menu option to edit the culvert station.

Background Map

Because multiple crossings can be defined within a single HY-8 project there is an option to create a background map. This map is only a picture and can be defined from any bitmap (*.bmp) file. If you are connected to the internet you may search for a roadway or aerial view map online and save the result as your background map. You may also screen capture any image (i.e. a CAD drawing) and save that image as a bitmap (*.bmp) file to import and use for your map as well. The map is only used for reference purposes and it or locations defined for culverts have no bearing on any calculations. Currently the map is sent to the report document, but you can cut and paste it into the file by capturing it from the screen.

Report Generation

With previous versions of HY-8 a comprehensive table could be generated and sent to a text file, however the ability to include graphs and take advantage of formatting in modern word processing programs was lacking. The **Report Generation** tools in HY-8 7.0 are customizable, include many options for plots and are saved in rich text format (*.rtf). The primary target is an MS-Word document; however the *.rtf format is readable by most Windows-based word processing programs. A few limitations exist with this first version and will likely be improved in future documents. These limitations stem from a problem of placing tables and graphs within document text. In this first version each time a table or graph is saved a new page is started. This is because of a limitation in the library routines being used that do not allow tables and graphs to be “docked” in line with text. After exporting a report you can manually dock tables in MS Word by selecting the table frame and then right-clicking on the frame border and choosing the *Format Frame* option. In this screen select the *Lock Anchor* option. For graphs you will select the graphic and right-click inside choosing the *Format Picture* option. In this screen choose the *Layout* tab and then the *In Line with Text* option. Once these options are set for tables and graphs new page/sections can be deleted and the tables and graphs placed continuously. It is our intention that this limitation within the library functions used for report generation will be corrected soon.

Limitations

Limitations

Inlet and Profile Limitations

Entrance limitations

Since HY-8 is not primarily a water surface profile computation program but is a culvert analysis tool, it assumes a pooled condition at the entrance to the culvert.

Vena contracta assumptions

In some cases, a *vena contracta* drawdown of the water surface profile could occur in a culvert barrel since the culvert has the potential to act as a sluice gate at the entrance. This drawdown at the entrance is sometimes called a *vena contracta*. The vena contracta is not yet computed for S2 curves, but is computed for horizontal if certain conditions exist on horizontal or adversely sloped culverts. A coefficient that is generalized for circular and box culverts is used to compute the location and depth of the vena contracta for all culvert shapes.

Brink depth

For culverts with tailwater elevations below the outlet invert of the culvert, water flowing out of the culvert would theoretically pass through a brink depth instead of through critical depth. In this case, HY-8 uses critical depth to determine the final culvert depth and velocity rather than the brink depth.

Culvert cross section

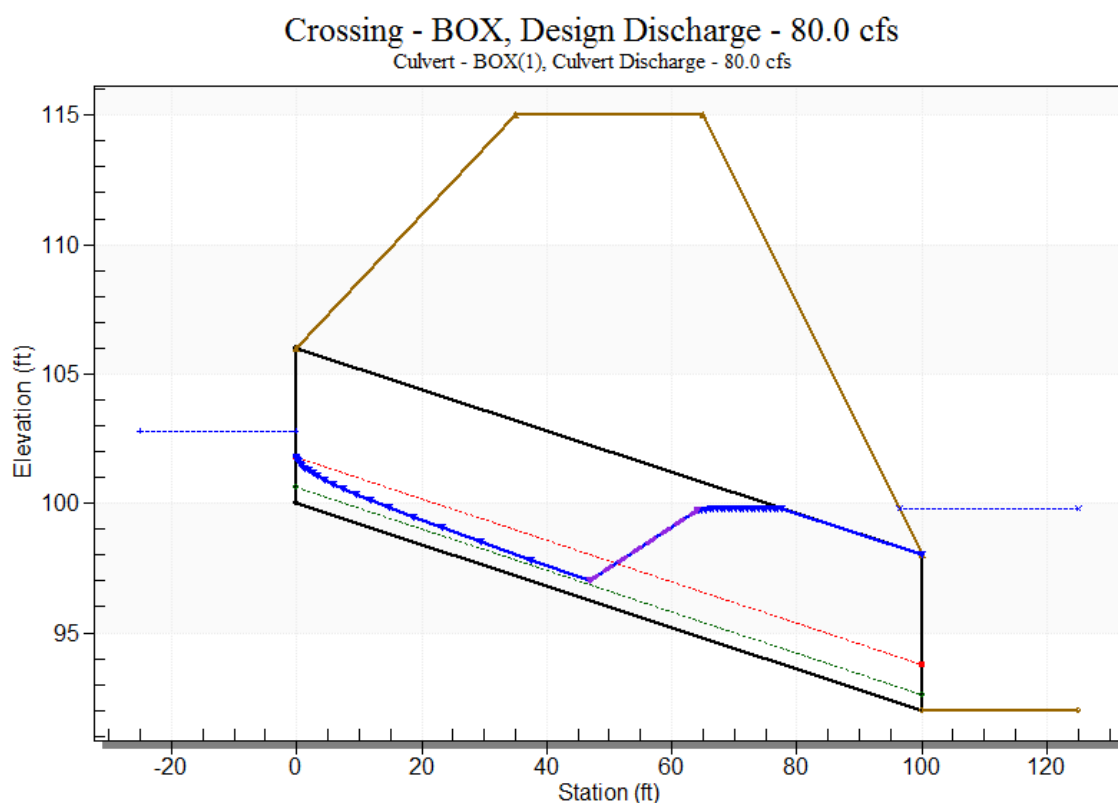
HY-8 assumes the culvert cross section shape, size, and material does not change in the barrel except in the case of broken back runout sections, where you can change the material and Manning's roughness in the runout (lower) culvert section.

Hydraulic Jump Computations

Hydraulic jump computations are supported in HY-8 7.3 and later versions.

Computed outlet velocity and tailwater elevation

The user should be aware that when the tailwater elevation exceeds the elevation of the top of the culvert outlet, the barrel may or may not flow full at the outlet. HY-8 determines a water profile using the direct step method in each direction and the sequent depth associated with each of the steps. If the sequent depth associated with the forward profile matches the depth along the backward profile through the culvert, a hydraulic jump occurs and the length of the jump is calculated from that location. Since the lengths of jumps have not been tested for all culvert sizes and slopes, only a limited set of equations are available for computing the lengths of jumps in HY-8. More information on the jump length computations is available in the section of this manual that describes hydraulic jump computations. A water surface profile for this case is shown below.



In this case, the hydraulic jump length computed by HY-8 may or may not be correct since the equation used to compute hydraulic jump length is for box culverts only, but is applied to all the other possible HY-8 culvert shapes. If a hydraulic jump occurs inside the culvert and the end of the hydraulic jump is located outside the culvert, HY-8 assumes the hydraulic jump occurs outside the culvert and a hydraulic jump is not shown in the profile. If both the beginning and end of the hydraulic jump occur inside the culvert barrel, the hydraulic jump is shown in the profile and is reflected in the profile computations, as shown in the image above.

Culvert Types

Newly supported culvert types

Previous versions of HY-8 did not fully support CON/SPAN culverts, HDPE culverts, or culverts installed with a natural stream bed as the bottom.

CON/SPAN (Concrete Open-bottom Arch) culvert types are supported in HY-8 7.3 and later; HDPE plastic culvert types are supported in HY-8 version 7.1 and later.

Partially buried culverts or culverts with natural stream bottoms are supported in HY-8 version 7.1 and later versions.

Inlet control computation limitations for selected shapes

User Defined, Open Bottom Arch, Low-Profile Arch, High-Profile Arch, and Metal Box do not use, and may not have, original research that describes coefficients that can be used for their inlet control equations. Instead, these shapes use an HW/D interpolation table, defined by a chart in HDS-5, that can be used to determine headwater values at various values of $Q/AD^{0.5}$.

Broken Back Culverts**Broken back culvert support**

Culverts with multiple slopes (broken back) and horizontal/adverse slopes are supported in HY-8 7.3 and later versions.

Side and slope-tapered inlets

Broken back culverts with side and slope-tapered inlets are not currently supported.

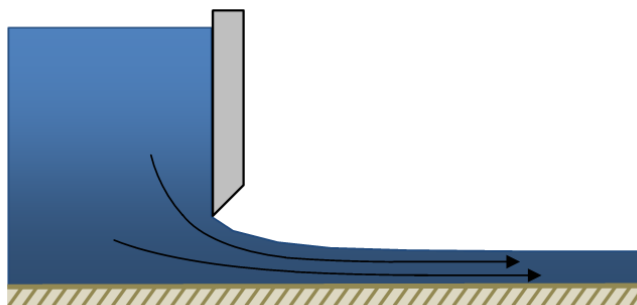
High-slope sections

The equations for broken back culverts used in HY-8 should not be applied to culvert sections with slopes greater than 55 degrees. These equations are not valid for very steep slopes and will give unrealistic results.

Vena Contracta

What is it?

When water is forced through an orifice opening, like a sluice gate, the water continues to decrease in depth as the streamline curves turn to follow the direction of travel. This contraction of depth is called the Vena Contracta.



When and where does it occur in culvert hydraulics?

The Vena Contracta occurs at the inlet of a culvert whenever the inlet control depth is greater than the outlet control depth. These conditions are created when the tailwater is low and the culvert is short.

How does HY-8 handle those computations?

HY-8 neglects the Vena Contracta except when the culvert slope is horizontal or adverse under inlet control.

HY-8 will use the following equation to determine the length of the Vena Contracta:

$$L = 0.5 \times D$$

Where:

- L = Vena Contracta Length
- D = Rise of Culvert

HY-8 uses the following equation to determine the final depth of the Vena Contracta:

$$d_{vc} = c \times y_{inlet}$$

Where:

- d_{vc} = Vena Contracta Final Depth
 - c = Vena Contracta Coefficient
 - y_{inlet} = Headwater Depth or Rise of the Culvert, whichever is smaller
-

2. Building a Project

Building a Project

Building a Project

An HY-8 project involves the design and analysis of single or multiple culverts at one or more crossings. The process of building a culvert project involves the following steps:

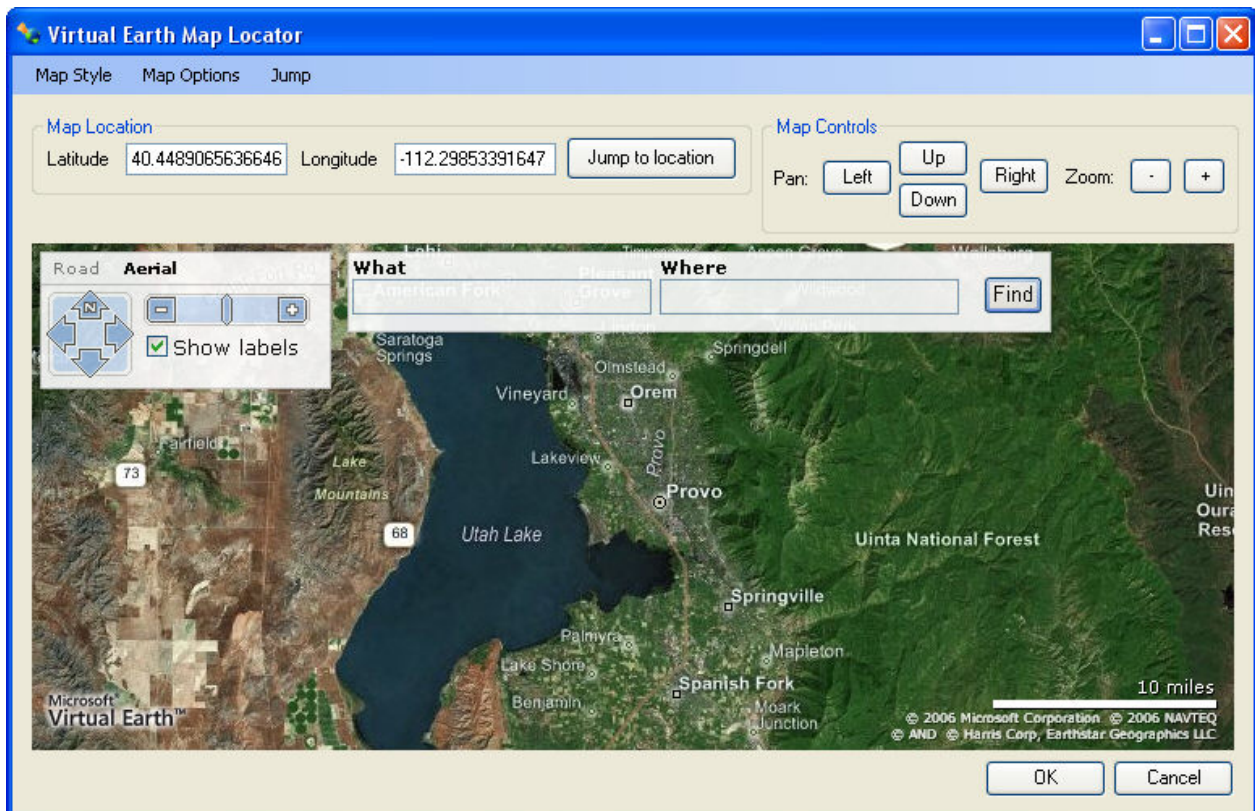
- Locate Project
- Culvert Crossing Data
- Run Analysis
- Report Generation

Crossings may be added to the project as needed.

Locate Project

Locate Crossing

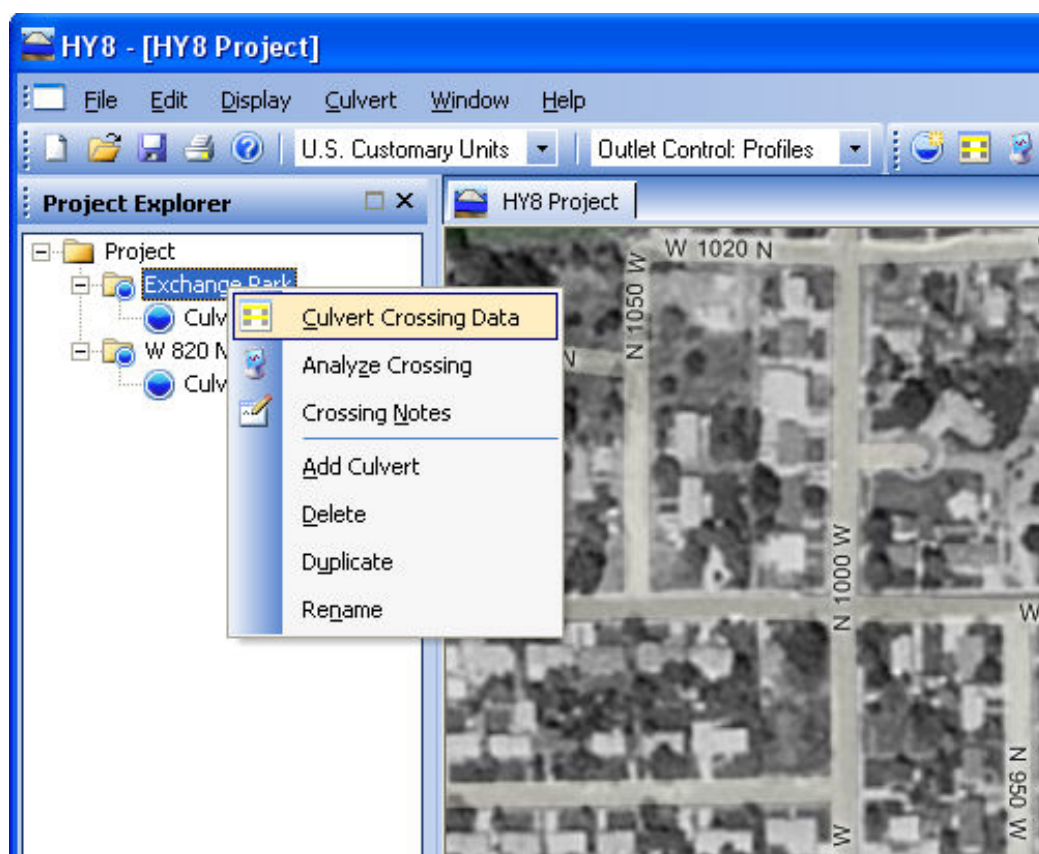
The first step in building a project is to identify the location of the crossing. The project contains all of the crossings while the crossings are the locations at which the culverts are placed. If desired (not required), the map viewer tool may be used to locate the crossing by entering (latitude,longitude) coordinates or the address of the crossing as shown in the figure below.



Culvert Crossing Data

Input Crossing and Culvert data

The user may choose up to 99 barrels for each culvert that is defined by the same site conditions, shape configuration, culvert type, and "n", and/or up to 6 independent culverts. In both cases the culverts share the same headwater pool, tailwater pool or channel, and roadway characteristics. The input properties define the crossing and culvert. The data defining each culvert are entered in the input parameters window. This window is accessed from the File menu, or from Project Explorer window by right-clicking on the culvert or crossing and selecting **Culvert Crossing Data** from the list. The user may also select the culvert properties icon from the tool bar. From the *Culvert Crossing Data* window, the site, culvert, tailwater, discharge, and roadway data are all entered.



Culvert Crossing Data Window

All of the parameters necessary to define crossing and culvert information can be defined from the *Culvert Crossing Data Window* as shown below.

Crossing Data - IRRTEST

Crossing Properties

Name: IRRTEST

Parameter	Value	Units
DISCHARGE DATA		
Minimum Flow	0.00	cfs
Design Flow	100.00	cfs
Maximum Flow	500.00	cfs
TAILWATER DATA		
Channel Type	Irregular Channel	
Irregular Channel	Define...	
Rating Curve	View...	
ROADWAY DATA		
Roadway Profile Shape	Constant Roadway Elevation	
First Roadway Station	0.00	ft
Crest Length	100.00	ft
Crest Elevation	115.00	ft
Roadway Surface	Paved	
Top Width	50.00	ft

Help Click on any icon for help on a specific topic

Culvert Properties

IRRTEST(1) Add Culvert Duplicate Culvert Delete Culvert

Parameter	Value	Units
CULVERT DATA		
Name	IRRTEST(1)	
Shape	Concrete Box	
Material	Concrete	
Span	5.00	ft
Rise	5.00	ft
Manning's n	0.0120	
Inlet Type	Conventional	
Inlet Edge Condition	Square Edge (90°) Headwall	
Inlet Depression?	No	
SITE DATA		
Site Data Input Option	Culvert Invert Data	
Inlet Station	0.00	ft
Inlet Elevation	100.00	ft
Outlet Station	100.00	ft
Outlet Elevation	98.00	ft

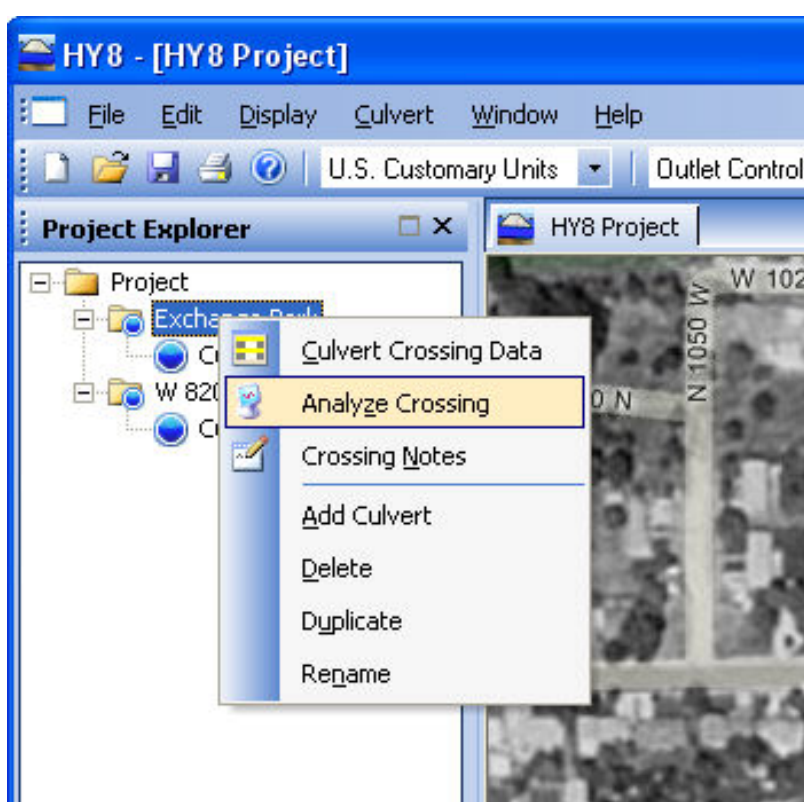
Analyze Crossing OK Cancel

Run Analysis

Run Analysis

After defining the culvert and crossing data the culvert hydraulics are analyzed, including balancing flow through multiple culverts and over the roadway. Viewing the analysis of a crossing can be done by right clicking on the desired crossing in the *Project Explorer* window and selecting **Analyze Crossing** as seen in the figure below. The *Analyze Crossing* feature can also be accessed for the currently selected crossing from the *Culvert Crossing Data Window*, the *Culvert* menu, or from the culvert toolbar .

During the analysis the program completes the necessary hydraulic computations after which the overtopping performance table will be displayed. A summary of flows at the crossing will be displayed, including any overtopping flows if they occur. While viewing the analysis the user will also be able to view individual culvert summary tables, water surface profiles, the tapered inlet table, as well as a customized table made up of any of the parameters computed during the analysis.



Report Generation

Report Generation

Once a culvert project is completed and analyzed you have the option of creating a report. A report can be created for just one or multiple crossings. The user can also select from the available fields which data to include and reporting what order. The report file type is a rich text file (*.rtf) which can be opened in Microsoft Word for editing. The report generation window is divided into the following sections:

Choose Crossing(s) to Include:

All crossings in the project appear here. The user may select a single, multiple, or all of the crossings to include in the report.

Format:

Three report types are available. The user may select the default standard report, which includes the results in the figure below. The second report type is Summary, which includes the crossing and culvert summary tables along with the site, tailwater, roadway, and culvert data. Custom is the final report type in which the user designates which topics to include in the report.

Report Content:

This section is divided into available fields and included fields. The available fields section comprises a list of all possible report topics the user can include in the report. Topics found in the included fields section are what will be displayed in the final report. These fields will appear in the report in the same order they appear here, but they may be moved up or down in the list by selecting the desired topic and clicking on the button describing the direction the user wants the topic to move. To add or remove topics, the user selects the appropriate topic and clicks the right or left arrow button, depending on the desired result.

Report Generator

Choose crossing(s) to include:

- BOX
- CIRCLE

Format:

Report Type: Standard Report

File Format: RTF

File name: HY8Report ...

Formatting Options...

Report Content:

Choose fields to include.

Available Fields:

- Project Notes
- Project Plan View Image
- Project Units
- Project Outlet Control Option
- Crossing Summary Table
- Crossing Rating Curve Plot
- Culvert Summary Tables
- Culvert Performance Curve
- Water Surface Profile Table
- Water Surface Profile Plot
- Improved Inlet Table
- Site Data
- Culvert Data
- Culvert Shape Plot
- Tailwater Data
- Tailwater Rating Curve Plot
- Roadway Data
- USGS Flow Types Table

>

<

Include All >>

<< Remove All

Move fields up or down.

Included Fields:

- Crossing Summary Table
- Crossing Rating Curve Plot
- Culvert Summary Tables
- Culvert Performance Curve
- Water Surface Profile Plot
- Site Data
- Culvert Data
- Tailwater Data
- Roadway Data
- Project Plan View Image
- Water Surface Profile Table
- Tailwater Rating Curve Plot
- USGS Flow Types Table

Up

Down

Save Custom Report Type

OK Cancel

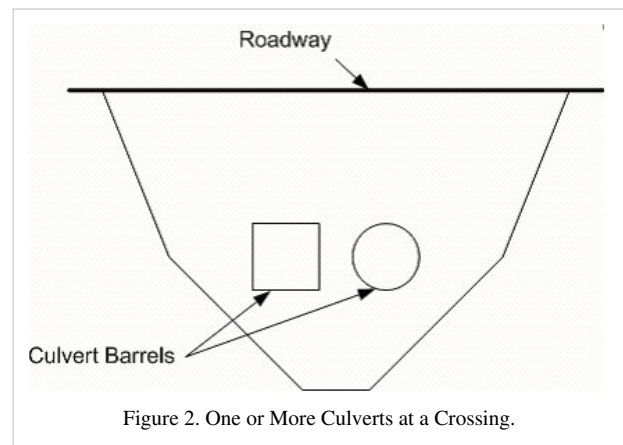
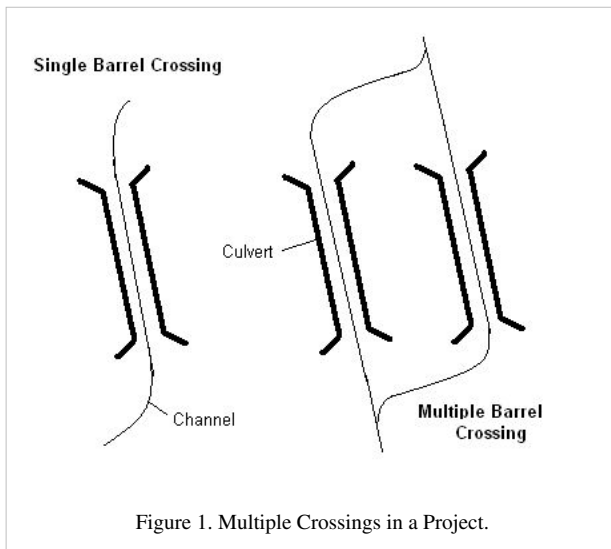
3. Crossing Data

3.1. General Data

Crossings

Crossings

The culvert crossing is where a collection of culverts can be placed. A crossing may consist of single or multiple culverts, and each culvert can be defined with multiple barrels. A project may contain multiple crossings, as seen in Figure 1, and each crossing may contain one or multiple culverts (Figure 2).



Discharge Data

Discharge Data

There are options to enter discharge data into HY-8: "Minimum, Design, and Maximum", "User-Defined", and "Recurrence". The "Minimum, Design, and Maximum" is the default option and historically was the only option available.

Minimum, Design, and Maximum

HY-8 will perform culvert hydraulic calculations based on the input minimum, design, and maximum discharge values. Calculations comprising the performance curve are made for ten equal discharge intervals between the minimum and maximum values. A user may input a narrower range of discharges in order to examine culvert performance for a discharge interval of special interest.

MINIMUM DISCHARGE

Lower limit used for the culvert performance curve. Can be edited to a number greater than '0'.

DESIGN DISCHARGE

Discharge for which the culvert will be designed. Always included as one of the points on the performance curve.

MAXIMUM DISCHARGE

Upper limit used for the culvert performance curve.

User-Defined

The user first specifies the number of flows they wish to enter. The user then enters the flows in ascending order (smallest flows at the top, highest at the bottom). The user can assign a name to a flow if desired. If no name is given the name column will not be shown in the results or report.

Recurrence

The user simply specifies the flow next to the recurrence year. The user does not need to enter all the years in the table and any flows that are left at zero will not show up in the results or report.

3.2. Roadway Data

Roadway Data

When defining the roadway data for the culvert, the following parameters are required:

- Roadway Profile
- Roadway Station
- Crest Length
- Crest Elevation
- Roadway Surface
- Top Width

The roadway elevation can be either a constant or vary with station. An initial roadway station may be defined by the user or left at the default of 0.0. The stationing is used to position culverts along the length of the roadway profile when choosing the *Front View* option.

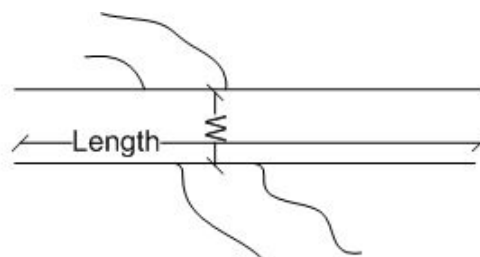
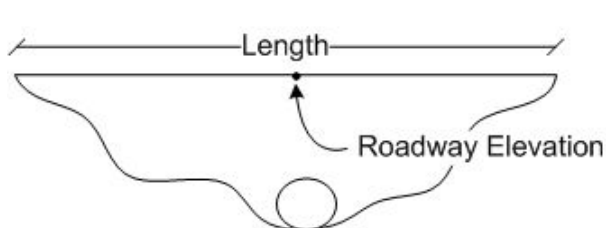
The roadway surface may be paved or gravel, or an overtopping discharge coefficient in the weir equation may be entered. The user may select a paved roadway surface or a gravel roadway surface from which the program uses a default weir coefficient value. If input discharge coefficient is selected, the user will enter a discharge coefficient between 2.5 and 3.095.

The values entered for the crest length and top width of the roadway have no effect on the hydraulic computations unless overtopping occurs.

Roadway Profile

Roadway Profile

There are two options available when defining the roadway profile: constant elevation and irregular. With the constant roadway elevation option selected, the user is prompted to enter values for the crest length and elevation of the roadway, shown in the figure below. While not necessary for culvert hydraulic calculations, the beginning station of the roadway is also entered (the default is 0.0 and does not need to be changed if you do not know the station or do not wish to enter it). By defining the beginning station, culverts can be located laterally and displayed in proper relationship to the roadway in the front view. When the irregular profile shape is selected, the user is prompted to enter between 3 and 15 points defining the station and elevation of each point along the roadway profile. The user is prompted to enter a beginning station for the roadway when viewing the culvert from the front using the *Views* toolbar.



The length for a horizontal roadway is somewhat arbitrary but should reflect the top width of the water surface in the channel upstream from the culvert at the roadway elevation. Roadway width includes the shoulders, traffic lanes, and median.

3.3. Tailwater Data

Tailwater Data

Tailwater Data

HY-8 provides the following options for calculating the tailwater rating curve downstream from a culvert crossing:

- Channel Shape
- Irregular Channel
- Rating Curve
- Constant Tailwater Elevation

Uniform depth is used to represent tailwater elevations for both a defined channel shape and an irregular channel. The cross section representing these two options should be located downstream from the culvert where normal flow is assumed to occur (downstream from channel transitions, for example). The calculated water surface elevations are assumed to apply at the culvert outlet.

Channel Shape

There are three available channel shapes to define the downstream tailwater channel: rectangular, trapezoidal, and triangular. When selecting a channel shape the input window adjusts to display only those parameters required for the defined shape. When defining a channel shape, the following channel properties are required for analysis:

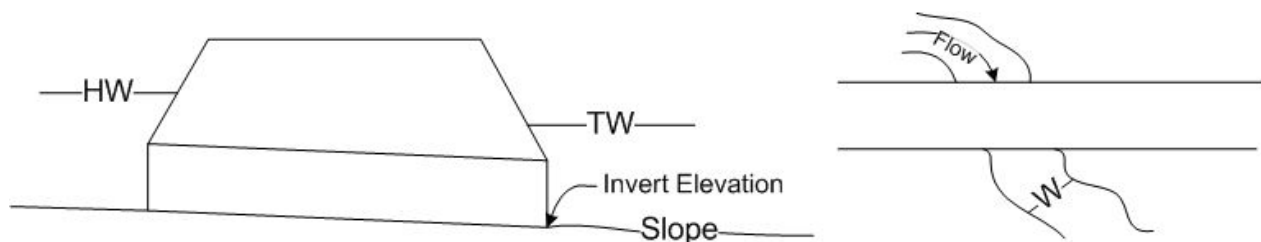
Bottom Width — Width of channel at downstream section, shown in drawing below.

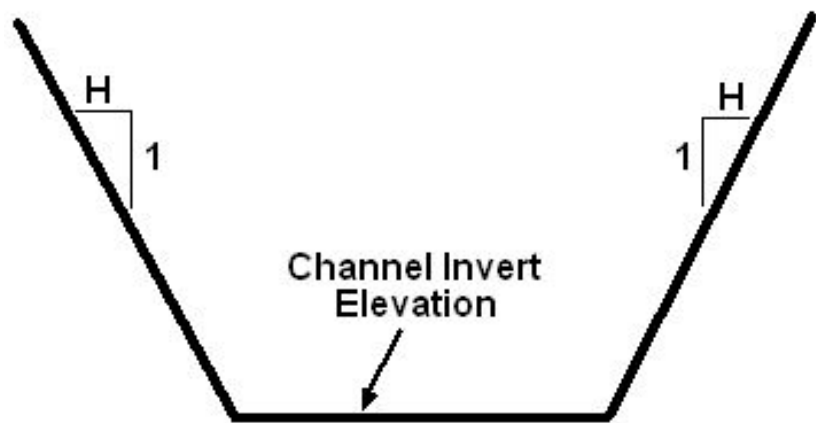
Side Slope (H:V) (_:1) — This item applies only for trapezoidal and triangular channels. The user defines the ratio of Horizontal/Vertical by entering the number of horizontal units for one unit of vertical change.

Channel Slope — Slope of channel in m/m or ft/ft. If a zero slope is entered, an error message appears upon exiting the input data window. The user must enter a slope greater than zero before the crossing may be analyzed.

Manning's n — User defined MANNING'S roughness coefficient for the channel.

Channel Invert Elevation — User must enter elevation. Program will show actual barrel #1 outlet invert elevation





Rating Curve

The rating curve option represents flow rate versus tailwater elevation for the downstream channel. When the *Enter Rating Curve* option is selected, the user is prompted to define 11 increasing flow and elevation values, as shown below. When using this option a channel invert elevation (generally the same as the downstream invert of the culvert) is required so that a tailwater depth can be computed from the rating curve.

Rating Curve	
Flow (cfs)	Elevation (ft)
0.000	100.000
10.000	100.614
20.000	100.973
30.000	101.284
40.000	101.572
50.000	101.845
60.000	102.105
70.000	102.360
80.000	102.608
90.000	102.852
100.000	103.091

Plot

OK

Cancel

Constant Tailwater Elevation

A constant tailwater elevation means that the tailwater elevation entered remains constant for all flows. When using this option a channel invert elevation (generally the same as the downstream invert of the culvert) is required so that a tailwater depth can be computed. A constant tailwater elevation may represent, for example, the design elevation of a lake, bay, or estuary into which the culvert(s) discharge.

3.3.1. Irregular Channel

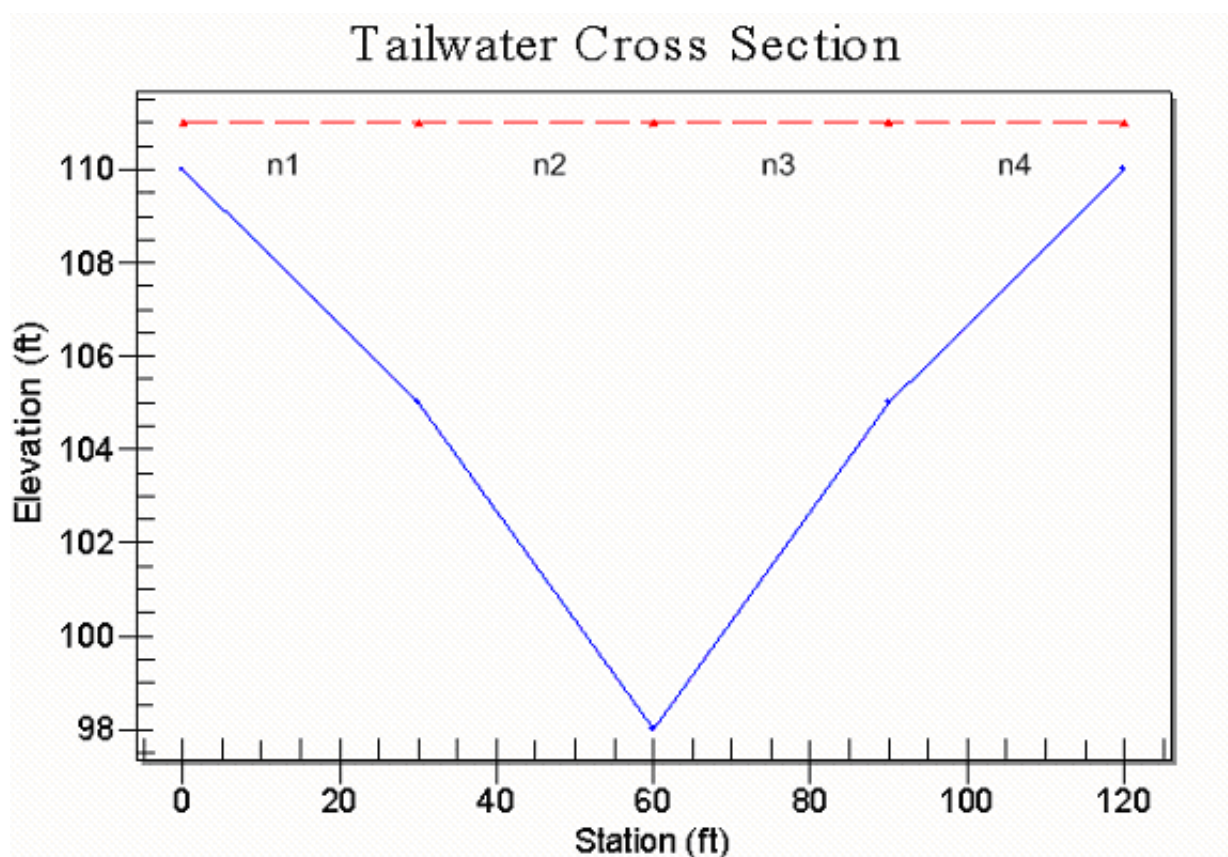
Irregular Channel

An irregular channel cross section option defines a channel using the channel slope and the station, elevation, and Manning's n at each input coordinate point. The number of coordinates allowed is unlimited, but using more coordinates will take longer to compute the results. All coordinates and n values may be copied from Microsoft Excel and pasted into the table. After all data have been entered, the user can plot and view the channel cross section looking downstream.

No.	Station (ft)	Elevation (ft)	Manning n
1	0.000	110.000	0.1500
2	30.000	105.000	0.0300
3	60.000	98.000	0.0300
4	90.000	105.000	0.1500
5	120.000	110.000	

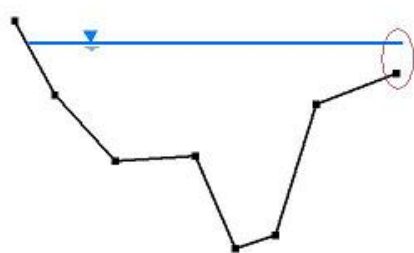
Figure 1. Irregular Channel Tailwater Editor.

Manning's n is defined as shown in the figure below. An n value is assigned for each segment of the cross section beginning at the left (looking downstream) coordinate (below). If the n value is the same throughout the cross section, the user may copy the n value by dragging the value from the first cell.



Irregular Channel Error

When the capacity of an irregular channel is not sufficient to convey the range of discharges, version 6.1 of HY-8 “spilled” excess water into an infinitely wide floodplain (see drawing below). The rating curve shows a constant tailwater elevation, cross-section velocity and computed shear stress for all discharges exceeding the channel capacity.



In HY-8, the “spill” concept is not used. If the irregular cross section cannot convey the range of discharges entered by the user, the following error message is displayed: “Irregular tailwater channel is not big enough to convey flow.”

The user has two options to correct this error. The first option is to enter additional data points for the purpose of extending the cross section horizontally and vertically based on field surveys or best judgment. This option could be used to simulate the “spill” concept of HY-8 by simulating a very wide floodplain with extended channel points. A second option is to create vertical walls to trap the flow so the depth of flow increases. Previous versions of HY-8 simply “spilled” excess flow onto an infinitely wide floodplain, resulting in a constant rating curve above the lowest cross section endpoint.

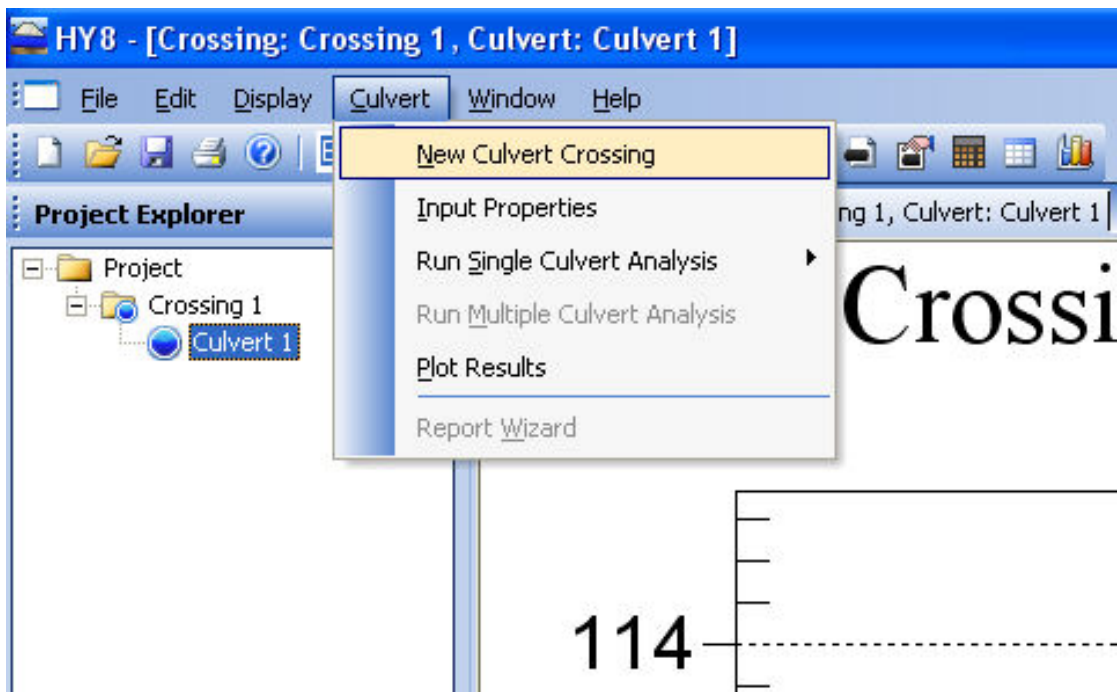
4. Culvert Data

4.1. Culvert Data

Culvert Data

Culvert data are entered by selecting the **Input Properties** option from the *Culvert* menu, or by right-clicking on the culvert in the *Project Explorer* window and selecting **Input Properties**. The following culvert data are required:

- Shape
- Material (Manning's n)
- Size
- Culvert Type
- Inlet Configurations
- Inlet Depression

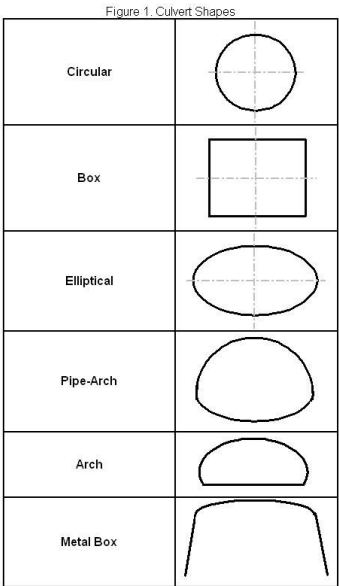


The site data for each culvert are also entered in the culvert data portion of the *culvert properties* window. The user has the option of entering culvert invert data or embankment toe data.

Shapes

HY-8 will perform hydraulic computations for the following culvert shapes (see Figure 1):

- Circular Pipe
- Box
- Elliptical long axis horizontal
- Pipe-Arch
- Arch
- Low-Profile Arch
- High-Profile Arch
- Metal Box
- Concrete Open-Bottom Arch
- South Dakota Concrete Box
- User Defined



Material

The following culvert materials are available:

- Corrugated Steel
- Steel Structural Plate
- Corrugated Aluminum
- Aluminum Structural Plate
- Reinforced Concrete
- PVC
- Smooth HDPE
- Corrugated PE

Only certain culvert materials are available for each culvert type. HY-8 assigns a default Manning's 'n' value for the selected material, but this value can be changed if desired. For more information on the plastic pipes (PVC, HDPE, and PE) please see Plastic Pipe Materials.

Plastic Pipe Materials

HY-8 7.1 has been updated to incorporate different types of plastic pipes. The following types of plastic pipes and their associated inlet configurations have been added to HY-8 7.1:

1. PVC

a. Manning's n (From HDS-5): 0.009-0.011 (use 0.011)

b. Inlet Configurations:

i. Square Edge with Headwall

1. Notes:

a. Use HY8 Equation Number 9

b. HDS5 Chart Number 1-1

c. Equation for Concrete Pipe Square Edge with Headwall

ii. Beveled Edge (1:1)

1. Notes:

a. Use HY8 Equation Number 6

b. HDS5 Chart Number 3-A

c. Equation for Circular pipe culvert with beveled edge (1:1)

iii. Beveled Edge (1.5:1)

1. Notes:

a. Use HY8 Equation Number 7

b. HDS5 Chart Number 3-B

c. Equation for Circular pipe culvert with beveled edge (1.5:1)

iv. Mitered to Conform to Slope

1. Notes:

a. Use HY8 Equation Number 2

b. HDS5 Chart Number 2-2

c. Equation for Corrugated Metal pipe culvert, Mitered to conform to slope

2. Smooth HDPE

a. Manning's n (From HDS-5): 0.009-0.015 (use 0.012)

b. Inlet Configurations:

i. Square Edge with Headwall

1. Notes:

a. Use HY8 Equation Number 9

b. HDS5 Chart Number 1-1

c. Equation for Concrete Pipe Square Edge with Headwall

ii. Beveled Edge (1:1)

1. Notes:

a. Use HY8 Equation Number 6

b. HDS5 Chart Number 3-A

c. Equation for Circular pipe culvert with beveled edge (1:1)

iii. Beveled Edge (1.5:1)

1. Notes:

a. Use HY8 Equation Number 7

b. HDS5 Chart Number 3-B

c. Equation for Circular pipe culvert with beveled edge (1.5:1)

iv. Thin Edge Projecting

1. Notes:

a. Use HY8 Equation Number 1

b. HDS5 Chart Number 2-3

c. Equation for Corrugated Metal pipe culvert, Thin edge projecting

v. Mitered to Conform to Slope

1. Notes:

a. Use HY8 Equation Number 2

b. HDS5 Chart Number 2-2

c. Equation for Corrugated Metal pipe culvert, Mitered to conform to slope

3. Corrugated PE

a. Manning's n (From HDS-5): 0.009-0.015 (use 0.024)

b. Inlet Configurations:

i. Square Edge with Headwall

1. Notes:

a. Use HY8 Equation Number 3

b. HDS5 Chart Number 2-1

c. Equation for Corrugated Metal pipe culvert with Headwall

ii. Beveled Edge (1:1)

1. Notes:

- a. Use HY8 Equation Number 6
 - b. HDS5 Chart Number 3-A
 - c. Equation for Circular pipe culvert with beveled edge (1:1)
- iii. Beveled Edge (1.5:1)
 - 1. Notes:
 - a. Use HY8 Equation Number 7
 - b. HDS5 Chart Number 3-B
 - c. Equation for Circular pipe culvert with beveled edge (1.5:1)
- iv. Thin Edge Projecting
 - 1. Notes:
 - a. Use HY8 Equation Number 1
 - b. HDS5 Chart Number 2-3
 - c. Equation for Corrugated Metal pipe culvert, Thin edge projecting
- v. Mitered to Conform to Slope
 - 1. Notes:
 - a. Use HY8 Equation Number 2
 - b. HDS5 Chart Number 2-2
 - c. Equation for Corrugated Metal pipe culvert, Mitered to conform to slope

Concrete Open Bottom Arch

HY-8 Version 7.3 and later has coefficients for computing inlet control depths for concrete open-bottom arch (commonly called Con/Span) culverts.

Geometric Characteristics

Con/Span culverts have unique geometric configurations, and several sizes and shapes are available. The exact coordinates used in HY-8 to compute areas and other geometric cross section parameters are available in this document ^[1]. Since the culverts can be made to accommodate any required rise for a given span, HY-8 contains culvert geometry in 3-inch increments of rise.

Inlet Control Polynomial Coefficients

The polynomial coefficients used by HY-8 were derived from a study and document prepared by Don Chase at the University of Dayton, Ohio (1999). Dr. Chase determined a different set of coefficients for culverts with different span-to-rise ratios. Con/Span culverts with a 4:1 span-to-rise ratio performed better (resulted in a lower headwater) than culverts with a 2:1 span-to-rise ratio. Because of this, separate polynomial coefficients were determined for culverts with each of these span-to-rise ratios.

Dr. Chase's study determined the K, c, M, and Y NBS coefficients described in HDS-5, and these coefficients were fitted to a 5th degree polynomial equation so they can be used in HY-8.

In HY-8, the 2:1 coefficients are used if the span:rise ratio is less than or equal to 3:1 and the 4:1 coefficients are used if the span:rise ratio is greater than 3:1. If the culvert you are modeling has less than a 2:1 or greater than a 4:1 span-to-rise ratio, you will see a note in HY-8 saying that your culvert is outside of the tested span-to-rise ratios.

Further testing may be required to account for these large or smaller span-to-rise ratios, but it is likely that your computed headwater will be higher than the observed headwater if your span:rise ratio is greater than 4:1 and your computed headwater will be less than that observed if the span:rise ratio is less than 2:1.

For information on the exact coefficients used and to view diagrams showing the different culvert wingwall configurations, see the help describing the HY-8 polynomial coefficients.

References

[1] <http://hy8.aquaveo.com/ConspanCoordinates.pdf>

South Dakota Concrete Box

HY-8 Version 7.3 and later has coefficients for computing inlet control depths using research contained in FHWA Publication No. FHWA-HRT-06-138, October 2006: **Effects of Inlet Geometry on Hydraulic Performance of Box Culverts** ^[1].

Overview and implementation

The document "Effects of Inlet Geometry on Hydraulic Performance of Box Culverts" (FHWA Publication No. FHWA-HRT-06-138, October 2006) describes a series of tests that were performed to obtain design coefficients for various inlet configurations on reinforced concrete box culverts. The following variations in inlet configurations were tested: wingwall and top edge bevels and corner fillets, multiple barrels, different culvert span-to-rise ratios, and skewed headwalls. The results of the tests were K, M, c, and Y inlet control design coefficients and 5th degree polynomial coefficients (required by HY-8) that were given in the FHWA document. The 5th degree polynomial coefficients given in the FHWA document cannot be used directly in HY-8 because the coefficients were only developed for a HW/D range between 0.5 and 2.0. HY-8 requires the polynomial coefficients to be valid between HW/D values of 0.5 and 3.0. Therefore, the polynomial coefficients had to be re-computed using the K, M, c, and Y coefficients from the FHWA report.

Several recommendations were made at the end of the FHWA document. Since the recommendations were a consolidation of the FHWA research, these recommendations were used in HY-8. The recommendations consolidated the results of the South Dakota box culvert testing into 13 different sets of coefficients, called "Sketches", which represent different inlet conditions. The HY-8 developers further consolidated the results into 10 sets of inlet configurations that were added as a "South Dakota Concrete Box Culvert" type in HY-8.

For information on the exact coefficients used and to view diagrams showing the different culvert configurations that were implemented in HY-8, see the help describing the HY-8 South Dakota Concrete Box polynomial coefficients.

References

[1] <http://www.fhwa.dot.gov/publications/research/infrastructure/hydraulics/06138/>

Culvert Type

Five culvert types are supported in HY-8:

- **Straight**
- **Side Tapered**
- **Slope Tapered**
- **Single Broken-back**
- **Double Broken-back**

Straight

Straight inlets are those for which no special or additional modification is made by the manufacturer or when constructed in the field. Straight inlets for corrugated metal pipes (CMP) include thin edge projecting, pipes mitered to conform to the fill slope, or pipes with a headwall. Straight inlets for concrete pipes and boxes include the standard groove-end section (pipe only), and inlets with a headwall and/or wingwall. Flared end sections fit to either CMP or concrete are also considered straight inlets. Since beveling the entrance is so common, a beveled entrance appears on the straight inlet menu for HY-8, but a beveled inlet is technically called a tapered inlet.

Side Tapered

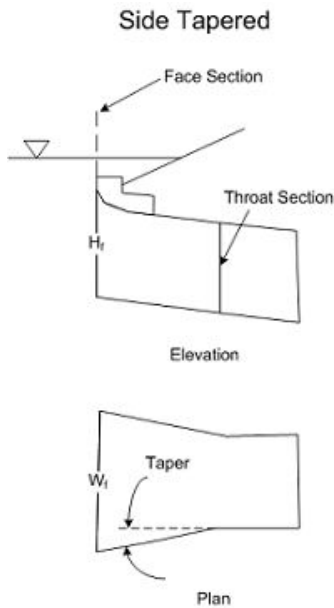
The side tapered option is available for circular or box culverts and is shown below. A side-tapered inlet is designed to increase culvert performance by providing a more efficient inlet control section. A side-tapered, circular inlet has an enlarged elliptical face section with a transition (taper) to the circular culvert barrel. The side-tapered dimensions are entered as follows:

- **Face Width** -- Width of enlarged face section, denoted W_f in the drawing below.
- **Side Taper** -- (4:1 to 6:1) ($_:$ 1) Flare of walls of circular transition. Value that is input should be the number of units of wall length for every 1 unit of flare.
- **Face Height** -- Shown as H_f in the drawing below, can be no smaller than the barrel height and no larger than 1.1 times the barrel height.

A side-tapered, rectangular inlet has an enlarged rectangular face section with transition (taper) to the culvert barrel. The side-tapered dimensions are entered as follows:

- **Face Width** -- width of enlarged face section.
- **Side Taper** -- (4:1 to 6:1) ($_:$ 1) flare of walls of rectangular transition. Value that is input should be the number of units of wall length for every 1 unit of flare.

If the selected face width is not wide enough the face section will produce a higher headwater elevation than the culvert throat as shown in the "Improved Inlet Table." The user must continue to increase the face width and run the analysis until the headwater depth ceases to change with increasing face width. Once this occurs the face section no longer controls and may be used in analysis and construction. Detailed information pertaining to side-tapered inlets can be found in FHWA Publication HDS 5, bundled with the HY-8 program and accessed from the Help menu.

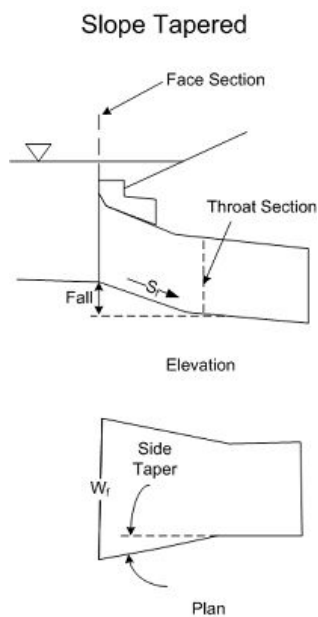


Slope Tapered

A slope tapered inlet is designed to increase the culvert performance by providing a depression and a more efficient control section at the throat, designated to represent the location of the culvert where a constant size begins (see drawing below). Slope tapered dimensions are entered as follows:

- **Face Width** -- Width of enlarged face section, denoted W_f in the drawing below.
- **Side Taper** -- (4:1 to 6:1) ($_:$ 1) Slope of walls of tapered transition. Value that is input should be the number of units of wall length for every 1 unit of flare.
- **Depression Slope** -- (2:1 to 3:1) ($_:$ 1) Slope between the entrance and throat invert, shown as S_t in the drawing below.
- **Throat Depression** -- Depression of inlet control section below stream bed. Measured from stream bed to throat invert.
- **Mitered Face** (Y/N) -- Face of culvert cut to conform to embankment slope.
- **Crest Length** -- Length of the upstream paved crest at the stream bed. This length is only used when the culvert face is mitered.

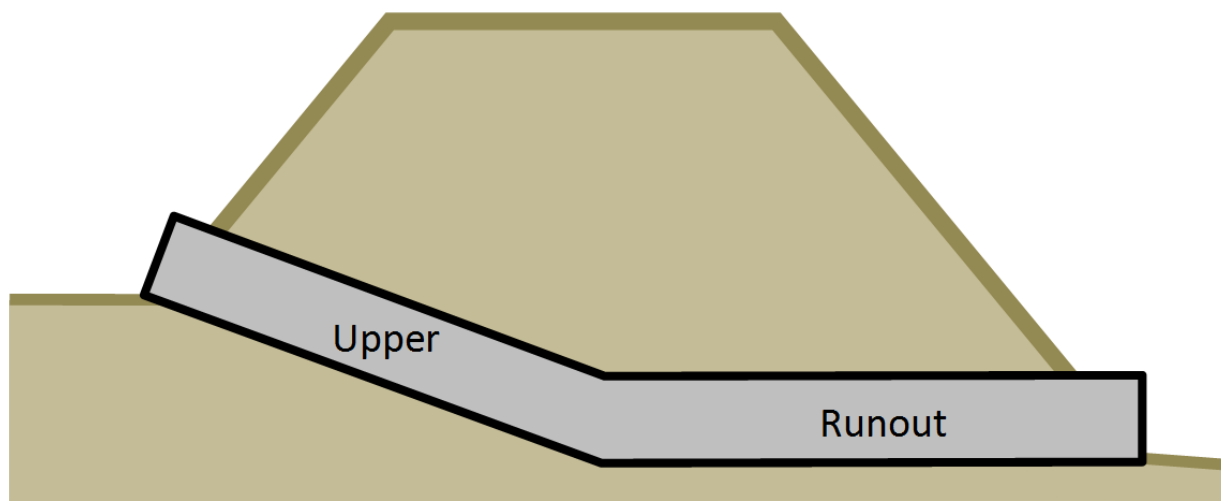
If the selected face width (and crest width in the case of a mitered face) is not wide enough the face (or crest) section will produce a higher headwater elevation than the culvert throat. The user must continue to increase the face width (and/or the crest width in the case of a mitered face) and run the analysis until the headwater depth ceases to change with increasing face width (and crest width in the case of a mitered face). Once this occurs the face section (and/or the crest section) no longer controls and may be used in analysis and construction. Detailed information pertaining to slope tapered inlets can be found in FHWA Publication HDS 5 and accessed from the Help menu.

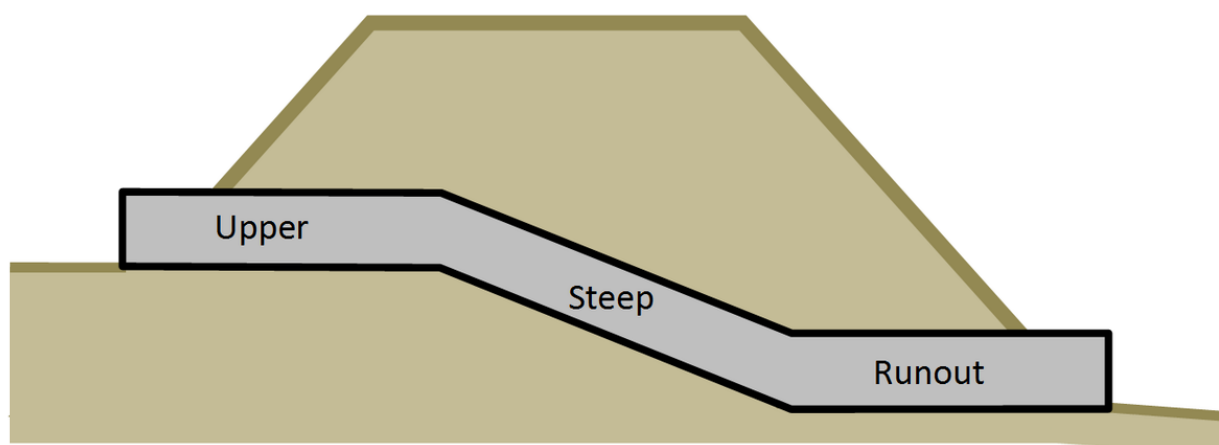


Broken Back Culverts

Overview of Broken Back Culverts

Broken-back culverts have one or more changes in slope along the length of the culvert. HY-8 supports single and double broken-back culverts, meaning one or two changes in slope. In this manual, the sections for a single broken-back culvert are referred to as 'Upper' and 'Runout' sections. The sections for a double broken-back culvert are referred to as 'Upper', 'Steep', and 'Runout' sections. Broken-back culverts are used to save on excavation costs or to force a hydraulic jump for energy dissipation and prevent scour in the channel downstream from the culvert.





Broken Back Culvert Computation Approach

To analyze a broken-back culvert, HY-8 computes each section as a single culvert. HY-8 determines the order that each section is calculated based on the slopes of each section. A culvert is steep if the normal depth of flow is less than critical depth and it is mild if normal depth is greater than critical depth.

The following table shows the computational order for single broken-back culverts. Please note that the order is only the initial computation. If necessary, some sections are recomputed with updated boundary conditions. The computation order is shown with the following abbreviations: U = Upper and R = Runout.

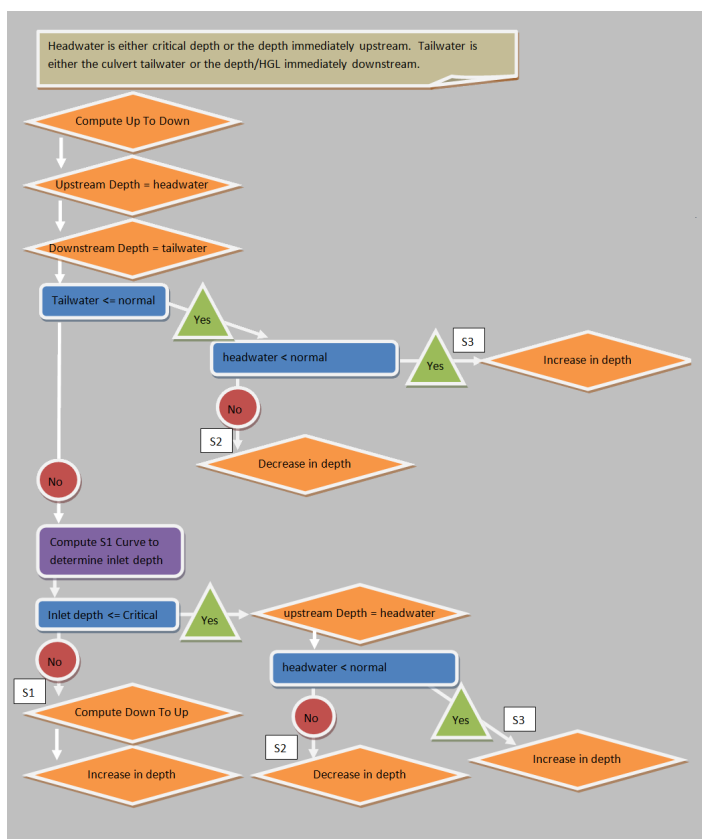
Slope (Steep or Mild)		Check for Hydraulic Jumps		Order
Upper	Lower	Upper	Lower	
Steep	Steep	X	X	UR
Steep	Mild	X	X	UR
Mild	Steep		X	RU
Mild	Mild			RU

The following table shows the computational order for double broken-back culverts. Please note that the order is only the initial computation. If necessary, some sections are recomputed with updated boundary conditions. The computation order is shown with the following abbreviations: U = Upper, S = Steep, and R = Runout.

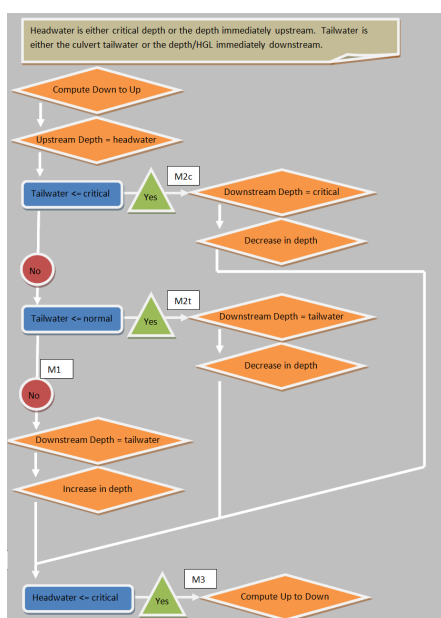
Slope (Steep or Mild)			Check for Hydraulic Jumps			Order
Upper	Middle	Lower	Upper	Middle	Lower	
Steep	Steep	Steep	X	X	X	USR
Steep	Steep	Mild	X	X	X	USR
Steep	Mild	Steep	X	X	X	RSU
Steep	Mild	Mild	X	X	X	URS
Mild	Steep	Steep		X	X	SRU
Mild	Steep	Mild		X	X	SRU
Mild	Mild	Steep			X	RSU
Mild	Mild	Mild				RSU

To determine the water surface profile of each section, HY-8 determines starting conditions for each section of a broken back culvert so the direct step method can be computed. The starting conditions HY-8 determines include the

water depth at the beginning and end of each section, the computation direction for each section, and whether the water surface increases or decreases in depth in the downstream direction for each section. The starting conditions for steep broken-back culvert sections are initialized based on the flowchart below.



The starting conditions for mild broken-back culvert sections are initialized based on the flowchart below.



Once HY-8 computes a profile for one section, it updates the water surface profile depth for the section(s) that it is next to. HY-8 pieces the profiles for each section together to create a seamless water surface profile through the broken-back culvert.

Broken Back Culvert Results

When analyzing broken back culverts in HY-8, the normal and critical depth in the **Culvert Summary Table** is not shown because it can vary by section. The flow type reported is the flow type of the upper section.

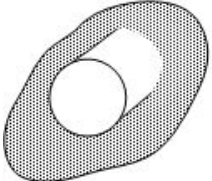
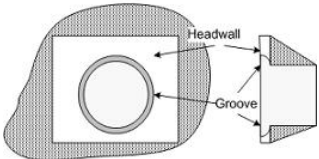
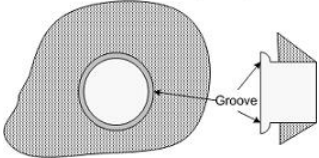
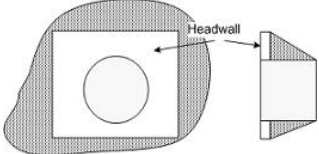
The option to display the **Tapered inlet table** is not available and instead there is a **Broken-Back Section** option. After selecting this option, select **Upper** or **Runout** if it is a single broken-back culvert or select **Upper**, **Steep**, or **Runout**. This option displays a table that is similar to the **Culvert Summary Table**, displaying the flow type, normal depth, and critical depth of the selected culvert section.

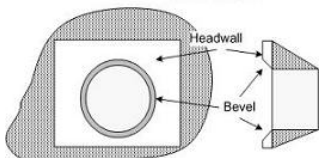
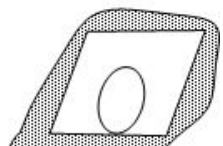
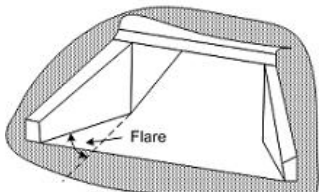
Inlet Configurations

You can select from the following inlet configurations which are available according to the selected culvert shape. The following inlet conditions are available (see drawing), but may not apply to all shapes or materials:

- Projecting
- Grooved end with headwall (0.05 X 0.07D)
- Grooved end projecting (0.05 X 0.07D)
- Square edge with headwall
- Beveled
- Mitered to conform with fill slope
- Headwall

The user can select only one inlet condition for each culvert. Detailed explanations of these inlet conditions can be found in FHWA Publication HDS No. 5 (2001) bundled with the program.

<p>Projecting</p> 	<p>This configuration results in the end of the culvert barrel projecting out of the embankment.</p>
<p>Grooved Pipe with Headwalls</p> 	<p>The grooved pipe is for concrete culverts and decreases the loss through the culvert entrance.</p>
<p>Grooved Pipe Projecting</p> 	<p>This option is for concrete pipe culverts.</p>
<p>Square Edge with Headwalls</p> 	<p>Square edge with headwall is an entrance condition where the culvert entrance is flush with the headwall.</p>

<p style="text-align: center;">Beveled Edge with Headwalls</p> 	<p>'Beveled edges' is a tapered inlet edge that decreases head loss as flow enters the culvert barrel.</p>
<p style="text-align: center;">Mitered</p> 	<p>A mitered entrance is when the culvert barrel is cut so it is flush with the embankment slope.</p>
<p style="text-align: center;">Wingwalls</p> 	<p>Wingwalls are used when the culvert is shorter than the embankment and prevents embankment material from falling into the culvert</p>

- NOTE: HDS-5 notes that "Flared end sections made of either metal or concrete, are the sections commonly available from manufacturers. From limited hydraulic tests they are equivalent in operation to a headwall in both inlet and outlet control. Some end sections, incorporating a closed taper in their design have a superior hydraulic performance. These latter sections can be designed using the information given for the beveled inlet"

Inlet Depression

The depression of a culvert is the vertical drop of the inlet control section below the stream bed. An inlet depression is defined by entering a value for each of the following items (see drawing below):

- Depression
- Depression Slope
- Crest Width

DEPRESSION

The vertical drop of inlet control section below the stream bed.

DEPRESSION SLOPE

Slope between the stream bed and the face invert. The depression slope must be set between 2:1 and 3:1.

CREST WIDTH

Length of weir crest at the top of the depression slope. Designing the crest width becomes an iterative process in HY-8 as the user must select a crest width wide enough so that it does not control the headwater calculations. If the selected crest width is not wide enough the crest section will produce a higher headwater elevation than the culvert throat. The user must continue to increase the crest width and run the analysis until the headwater depth ceases to change with increasing crest width. Once this occurs the crest section no longer controls and may be used in analysis and construction.

Embedment Depth

“Embedment Depth” is the depth the culvert is embedded from the invert of the culvert barrel to the top of the embedding material.

If an Embedment Depth greater than zero is entered, HY-8 will run the culvert analysis as if the input parameters were entered as a User Defined shape. If the culvert is embedded, HY-8 will determine the coordinates of the shape and use these coordinates in the User Defined equation. Because of this, if the culvert is embedded, only the User Defined Inlet Types and Inlet Configurations will be available. This is a significant difference from the computations for non-embedded culverts for the Circular, Concrete Box, Elliptical, and Pipe Arch shapes. For these shapes, non-embedded culverts use 5th-degree polynomial coefficients to compute the inlet control depth. However, if the culvert is embedded, the inlet control depth is interpolated based on a set of interpolation coefficients for User Defined culverts.

In HY-8 version 7.3 for embedded circular culverts, HY-8 uses the 5th-degree polynomial to determine the inlet control depth. The coefficients used are derived from the NCHRP 15-24 report. This report gives coefficients for a circular culvert that is embedded 20%, 40%, and 50%. HY-8 will linearly interpolate between the coefficients for the level of embedment specified; however, if the embedment is outside the range of data, the closest set of coefficients is used. The polynomial coefficients are available here: [Polynomial Coefficients](#).

You can define top and bottom Manning's n values to handle the embedding material properties and HY-8 uses these values to run the culvert analysis.

Finally, if you enter an embedment depth, all the materials for the selected shape will still be available. However, the material you select will be converted to one of the two user-defined materials using the following chart:

Shape	Material	Equivalent User-Defined Material (for embedded culverts)
Circular	Concrete	Concrete
	Any other material	
	Corrugated Steel	Corrugated Metal Riveted or welded
	Corrugated Aluminum	
Concrete Box	Concrete	Concrete
Elliptical	Steel or Aluminum	Corrugated Metal Riveted or Welded
	Concrete	Concrete
	Any other material	
Pipe Arch	Steel or Aluminum	Corrugated Metal Riveted or Welded
	Steel Structural Plate	
	Aluminum Structural Plate	
	Concrete	Concrete
	Any other material	
User Defined	Corrugated Metal Riveted or Welded	Corrugated Metal Riveted or Welded
	Concrete	Concrete
Arch, Open Bottom	Corrugated Steel	Corrugated Metal Riveted or Welded
	Corrugated Aluminum	
Low-Profile Arch	Corrugated Steel	Corrugated Metal Riveted or Welded
	Corrugated Aluminum	
High-Profile Arch	Corrugated Steel	Corrugated Metal Riveted or Welded
	Corrugated Aluminum	
Metal Box	Corrugated Steel	Corrugated Metal Riveted or Welded
Arch-Box, Concrete	Concrete	Concrete
Any other Shape	Any other material	Corrugated Metal Riveted or Welded

4.2. Site Data

Site Data Input Option

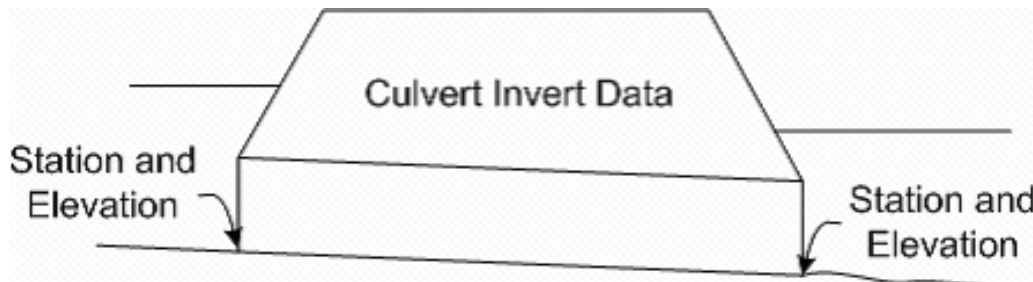
Site data describe the positioning and length of the culvert within an embankment. The program adjusts culvert length according to site data, culvert type, culvert height, and depression. The following options are available for entering site data:

- Culvert Invert Data
- Embankment Toe Data

Culvert Invert Data

The culvert invert data option is used to enter known coordinates of culvert inverts. This option is generally used to analyze known, existing culverts. Coordinates are defined by the following input as seen in the figure below:

- **Inlet Station** -- station of culvert inlet invert
- **Inlet Elevation** -- elevation at culvert inlet invert
- **Outlet Station** -- station of culvert outlet invert, must be greater than the inlet station
- **Outlet Elevation** -- elevation at culvert outlet invert
- **Number of Barrels** -- the program default is 1, although this may be changed by the user.

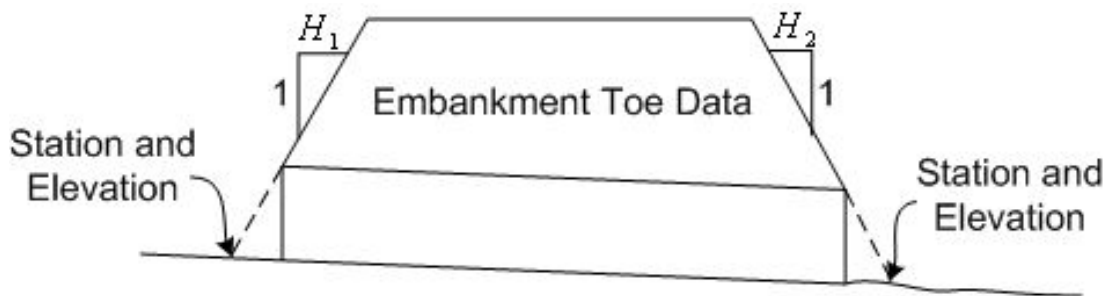


Once the user defines the culvert invert data, the program computes the culvert barrel length along the culvert barrel, rather than horizontally between the inlet and outlet stations. If a horizontal slope (0%) is desired with inlet and outlet stations at the same elevation the program will automatically assign a slope value of 0.000001 (ft/ft, m/m) for computational purposes. The slope will be shown as zero in all output tables.

Embankment Toe Data

Embankment toe data are used to describe the fill into which a culvert will be placed. No culvert dimensions are provided at this point, and the goal of the designer is to fit the culvert in the designed roadway cross section when geometry is provided from design drawings. Once the culvert height has been entered, the program will calculate the culvert invert station and elevation data (see the diagram below). The following parameters are defined by the user and are shown in the figure below:

- **Upstream Station** -- Station (m or ft) of the upstream intersection of the stream bed or drainage channel and embankment slope
- **Upstream Elevation** -- Stream bed elevation (m or ft) at upstream station
- **Upstream Embankment Slope** -- Embankment slope on the upstream side of the roadway (m/m or ft/ft)
- **Downstream Station** -- Station (m or ft) of downstream intersection of the stream bed or drainage channel and embankment slope. Must be greater than the upstream station.
- **Downstream Elevation** -- Stream bed elevation (m or ft) at downstream station
- **Downstream Embankment Slope** -- Embankment slope on the downstream side of the roadway (m/m or ft/ft)
- **Number of Barrels** -- Program default is 1 barrel, although the user may place multiple barrels with the same characteristics



5. Analysis

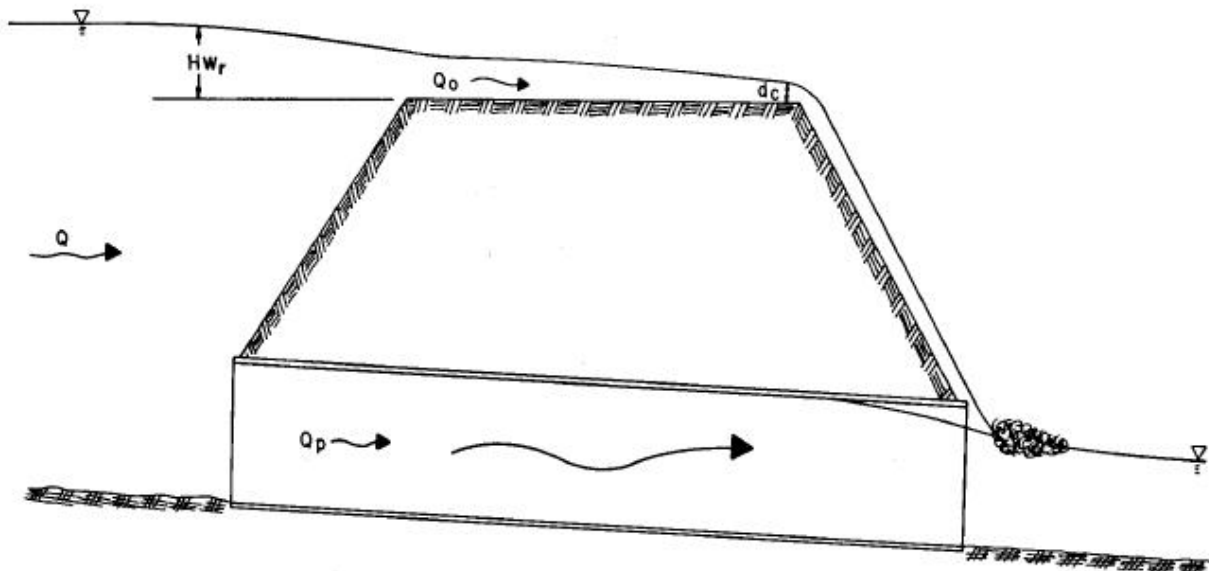
5.1. General

Project Units

The user has the option of entering data in US Customary or SI units. HY-8 performs all calculations in US Customary units, but the user may enter data and view results in SI units; HY-8 will perform the necessary conversions. When switching the units control all existing input parameters are converted appropriately.

Roadway Overtopping

When the headwater elevation exceeds the elevation of the roadway, overtopping will occur as shown below. When overtopping is simulated, the program computes the discharge for each culvert and for the roadway that will result in the same headwater elevation. An overtopping analysis will be completed for every crossing, and, if overtopping occurs, the corresponding flow values will be displayed.

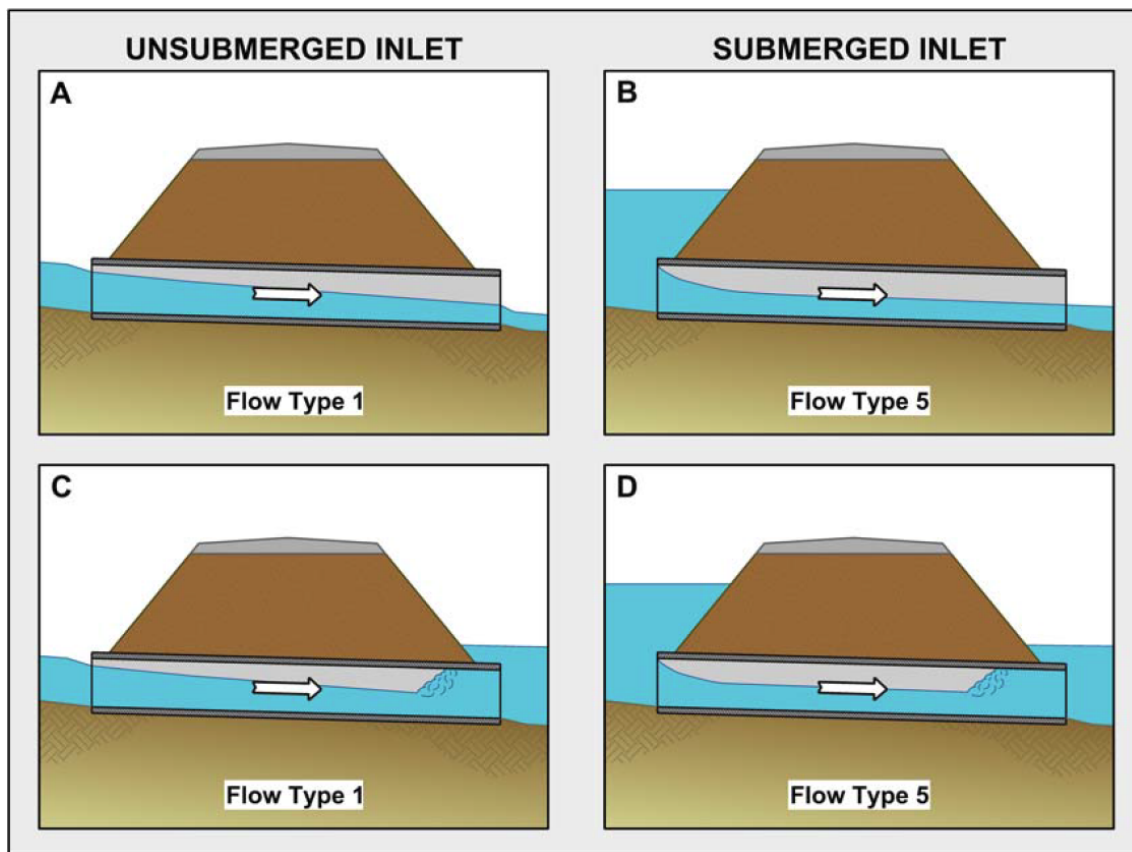


5.2. Head Water Computations

5.2.1. Inlet Control

Inlet Control Computations

Inlet control means that the amount of water the culvert barrel can carry is limited by the culvert entrance. Flow passes through critical depth at the culvert entrance and is supercritical in the barrel. There are several flow profiles possible, HY-8 simulates so-called Type A, B, C, and D conditions as shown below and as described in HDS-5. These profiles are known as Type 1 (A, C) and Type 5 (B, D) within HY-8. The various flow type properties may be found in HY-8 by selecting the **Flow Types** button from the Culvert Summary Table and are shown below. Because the flow in the barrel is supercritical, outlet losses and friction losses are not reflected in the headwater elevation. The headwater elevation is a function of the entrance size, shape, and culvert type. The computed inlet control headwater elevation is found by accessing the results of scaled physical model tests. The logic for determining what inlet flow control type prevails is shown below (from the original HY-8 help file).



Inlet Control Logic

DETERMINE APPLICABLE INLET CONTROL EQUATION

1. IF circle or box with IMPROVED INLETS then use INLET equations.
2. For Straight (previously called conventional) INLETS
 - A. If Q is $< Q$ at .5D, then assume LOW FLOW INLET CONTROL:
 - i. calculate CRITICAL DEPTH (DCO)
 - ii. calculate Section Properties
 - iii. $VH = (Q / AC)^2 / 64.4$
 - iv. $IH = DCO * LMULT + (1 + KELOW) * VH * VHCOEF$
 - IF no Depression THEN $IHI = IH + IIE$
 - For Depression, $HF = IH$ and check head on CREST.
 - B. If $Q > Q$ at .5D, but $< Q$ at 3D, then use INLET REGRESSION EQUATIONS.
 - C. If $Q > Q$ at 3D, then assume HIGH FLOW INLET CONTROL.
 - i. $IH = (Q / CDAHI)^2 + .5 * RISE$
 - ii. IF no Depression THEN $IHI = IH + IIE$
 - For Depression, $HF = IH$ and check head on CREST.

INLET REGRESSION EQUATIONS (Q between Q at .5D and Q at 3D)

1. CIRCULAR
 - A. See Straight inlet equations
 - B. SIDE TAPERED ELLIPTICAL TRANSITION, THROAT CONTROL

$$ZZ = Q / \text{SQR}(\text{RISE} \wedge 5), Y = \text{LOG}(ZZ) / 2.30258$$
 - i. IF $n < .015$ THEN SMOOTH PIPE IMPROVRD INLET.
 - ii. If $n \geq .015$ then ROUGH PIPE IMPROVED INLET.
 - iii. Calculate THROAT CONTROL
 - iv. Calculate FACE CONTROL
 - v. IF Depression Then $CW = CWF$, calculate CREST control.
 - C. SIDE TAPERED RECTANGULAR TRANSITION or SLOPE TAPERED
 - i. Calculate THROAT CONTROL
 - ii. Calculate FACE CONTROL
 - iii. IF Depression Then $CW = CWF$, calculate CREST control.
2. BOX CULVERTS
 - A. See Straight inlet equations
 - B. SIDE TAPERED RECTANGULAR TRANSITION or SLOPE TAPERED
 - i. Calculate THROAT CONTROL
 - ii. Calculate FACE CONTROL
 - iii. IF Depression Then $CW = CWF$, calculate CREST control.
3. PIPE ARCHES AND ELLIPSES
 - A. See Straight inlet equations
4. IRREGULAR SHAPE

A. See Straight inlet equations

Straight Inlet Equations

1. For IRREGULAR shape, $X = Q / (AC * \text{SQR}(\text{RISE}))$
 $\text{IF } X \leq .5 \text{ THEN } IH = (A(1) * (X / .5)) * \text{RISE}$
 $\text{ELSE } IH = (A(J - 1) + (A(J) - A(J - 1)) * ((X - J + 2) / \text{INC})) * \text{RISE}$
2. For all others shapes, $X = Q / (\text{SPAN} * \text{SQR}(\text{RISE}^3))$; $\text{SR} = \text{SR}(\text{IC})$
 $IH = (A + (B + (C + (D + (E + F * X) * X) * X) * X) * X - \text{SR} * S0) * \text{RISE}$
3. Headwater elevation (IHI) = IH + IIE if no Depression.
4. For Depression, CREST headwater is checked.

THROAT CONTROL TAPERED INLET

1. $X = Q / (\text{SPAN} * \text{SQR}(\text{RISE}^3))$
2. $\text{HT} = \text{RISE} * (.1295033 + (.3789944 + (-.0437778 + (4.26329\text{E-}03 - 1.06358\text{E-}04 * X) * X) * X) * X)$

FACE CONTROL-SIDE TAPERED INLET

1. $ZZ = Q / (BF * \text{SQR}(\text{RISE}^3))$
2. Calculate UNSUBMERGED: $\text{HF1} = (.56 * \text{RISE}) * (ZZ ^ .66667)$
3. Calculate SUBMERGED
 - A. For bevels: $\text{HF3} = (.0378 * (ZZ * ZZ) + .86) * \text{RISE}$
 $\text{IF } \text{HF1} > \text{RISE} \text{ THEN } \text{HF} = \text{HF3}$
 $\text{IF } \text{HF1} < \text{RISE} \text{ THEN } \text{HF} = \text{HF1}$
 $\text{IF } \text{HF1} \geq \text{HF3} \text{ THEN } \text{HF} = \text{HF1}$
 - B. For other edges: $\text{HF2} = (.0446 * (ZZ * ZZ) + .84) * \text{RISE}$
 $\text{IF } \text{HF1} > \text{RISE} \text{ THEN } \text{HF} = \text{HF2}$
 $\text{IF } \text{HF1} < \text{RISE} \text{ THEN } \text{HF} = \text{HF1}$
 $\text{IF } \text{HF1} \geq \text{HF2} \text{ THEN } \text{HF} = \text{HF1}$

FACE CONTROL FOR SLOPE TAPERED INLET

1. $ZZ = Q / (BF * \text{SQR}(\text{RISE}^3))$
2. Calculate UNSUBMERGED: $\text{HF1} = (.5 * \text{RISE}) * (ZZ ^ .66667)$
 - A. For bevels: $\text{HF3} = (.0378 * (ZZ * ZZ) + .7) * \text{RISE}$
 $\text{IF } \text{HF1} > \text{RISE} \text{ THEN } \text{HF} = \text{HF3}$
 $\text{IF } \text{HF1} < \text{RISE} \text{ THEN } \text{HF} = \text{HF1}$
 $\text{IF } \text{HF1} > \text{HF3} \text{ THEN } \text{HF} = \text{HF1}$
 - B. For other edges: $\text{HF2} = (.0446 * (ZZ * ZZ) + .64) * \text{RISE}$
 $\text{IF } \text{HF1} > \text{RISE} \text{ THEN } \text{HF} = \text{HF2}$
 $\text{IF } \text{HF1} < \text{RISE} \text{ THEN } \text{HF} = \text{HF1}$
 $\text{IF } \text{HF1} > \text{HF2} \text{ THEN } \text{HF} = \text{HF1}$

CREST CONTROL

$$1. HC = .5 * (Q / CW) ^ .66667$$

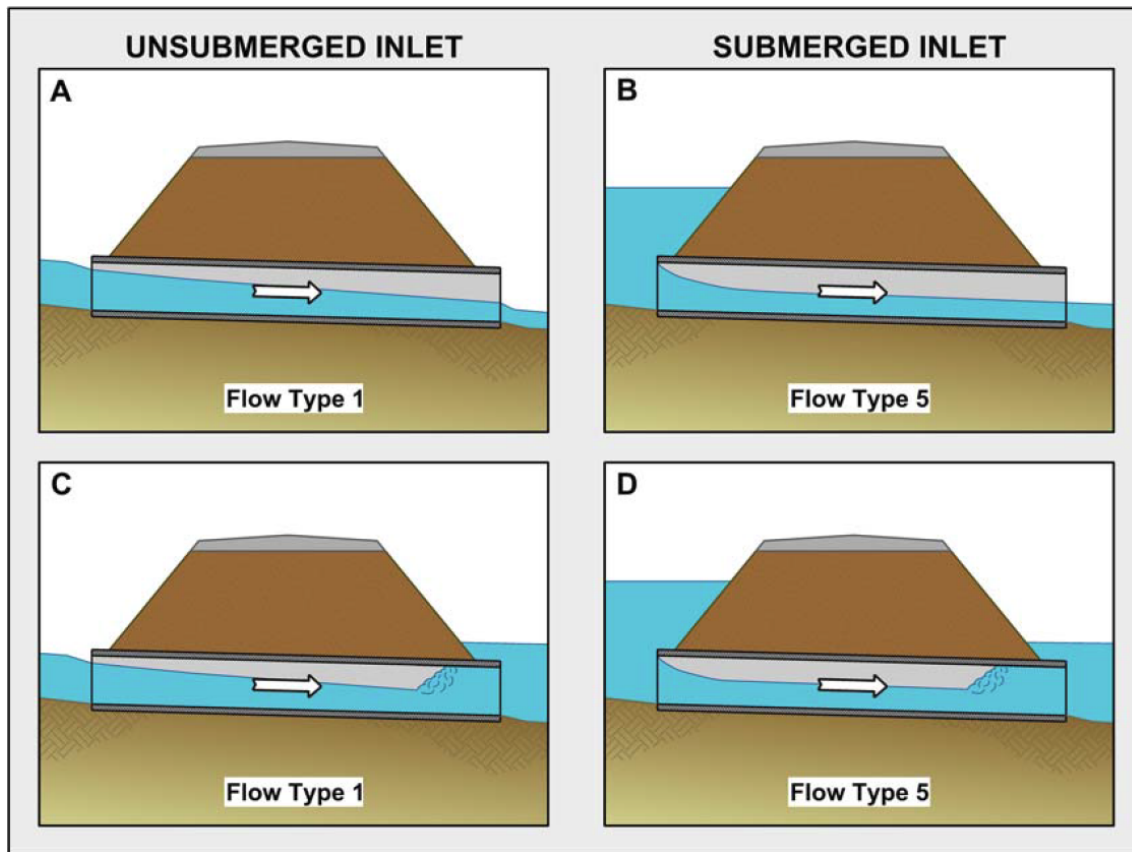
OUTLET CONTROL PROCEDURES THAT PRODUCE AN INLET CONTROL PROFILE

STEP

1. Compute critical depth (dco)
2. Compute normal depth (dno)
3. Compute fullflow if nomograph solution assumed "6-FFt or FFc".
4. If dno > .95(rise), assume fullflow "6-FFn".
5. If dno > dco, assume mild slope (SEE OUTLET.DAT).
6. If dno <= dco, assume steep slope.
 - A. If twh is >= So(L) + rise, assume fullflow "4-FFt".\
 - B. If twh is >= rise, outlet submerged, assume inlet unsubmerged.
 - C. If twh is < rise, outlet is unsubmerged, assume inlet unsubmerged.
 - i. Assume headwater (oh) = inlet control headwater (ih)
 Calculate S2 curve "1-S2n" for outlet depth.
 If oh >= rise, inlet submerged "5-S2n"
 - ii. If twh > headwater, tailwater drowns out jump.
 Calculate M1 curve "3-M1t".
 If culvert flows part full, "7-Mit".

STEP	FLOW TYPE	FLOW CONTROL	SUBMERGED		LENGTH FULL	LOSS CALC	OUTLET DEPTH
			INLET	OUTLET			
6C1	1	Inlet	No	No	None	S2n	Normal
6B3b	1	Inlet	No	Yes	Part	S1f	Full
6C1	5	Inlet	Yes	No	None	S2n	Normal
6B3b	5	Inlet	Yes	Yes	Part	S1f	Full

Inlet control means that the amount of water the culvert barrel can carry is limited by the culvert entrance. Flow passes through critical depth at the culvert entrance and is supercritical in the barrel. There are several flow profiles possible, HY-8 simulates so-called Type A, B, C, and D conditions as shown below and as described in HDS-5. These profiles are known as Type 1 (A, C) and Type 5 (B, D) within HY-8. The various flow type properties may be found in HY-8 by selecting the **Flow Types** button from the Culvert Summary Table and are shown below. Because the flow in the barrel is supercritical, outlet losses and friction losses are not reflected in the headwater elevation. The headwater elevation is a function of the entrance size, shape, and culvert type. The computed inlet control headwater elevation is found by accessing the results of scaled physical model tests. The logic for determining what inlet flow control type prevails is shown below (from the original HY-8 help file).



Inlet Control Logic

DETERMINE APPLICABLE INLET CONTROL EQUATION

1. IF circle or box with IMPROVED INLETS then use INLET equations.
2. For Straight (previously called conventional) INLETS
 - A. If Q is $< Q$ at $.5D$, then assume LOW FLOW INLET CONTROL:
 - i. calculate CRITICAL DEPTH (DCO)
 - ii. calculate Section Properties
 - iii. $VH = (Q / AC)^2 / 64.4$
 - iv. $IH = DCO * LMULT + (1 + KELOW) * VH * VHCOEF$
 - IF no Depression THEN $IHI = IH + I1E$
 - For Depression, $HF = IH$ and check head on CREST.
 - B. If $Q > Q$ at $.5D$, but $< Q$ at $3D$, then use INLET REGRESSION EQUATIONS.
 - C. If $Q > Q$ at $3D$, then assume HIGH FLOW INLET CONTROL.
 - i. $IH = (Q / CDAHI)^2 + .5 * RISE$
 - ii. IF no Depression THEN $IHI = IH + I1E$
 - For Depression, $HF = IH$ and check head on CREST.

INLET REGRESSION EQUATIONS (Q between Q at .5D and Q at 3D)

1. CIRCULAR

A. See Straight inlet equations

B. SIDE TAPERED ELLIPTICAL TRANSITION, THROAT CONTROL

$$ZZ = Q / \text{SQR}(\text{RISE}^5), Y = \text{LOG}(ZZ) / 2.30258$$

i. IF $n < .015$ THEN SMOOTH PIPE IMPROVRD INLET.

ii. If $n \geq .015$ then ROUGH PIPE IMPROVED INLET.

iii. Calculate THROAT CONTROL

iv. Calculate FACE CONTROL

v. IF Depression Then $CW = CWF$, calculate CREST control.

C. SIDE TAPERED RECTANGULAR TRANSITION or SLOPE TAPERED

i. Calculate THROAT CONTROL

ii. Calculate FACE CONTROL

iii. IF Depression Then $CW = CWF$, calculate CREST control.

2. BOX CULVERTS

A. See Straight inlet equations

B. SIDE TAPERED RECTANGULAR TRANSITION or SLOPE TAPERED

i. Calculate THROAT CONTROL

ii. Calculate FACE CONTROL

iii. IF Depression Then $CW = CWF$, calculate CREST control.

3. PIPE ARCHES AND ELLIPSES

A. See Straight inlet equations

4. IRREGULAR SHAPE

A. See Straight inlet equations

Straight Inlet Equations

1. For IRREGULAR shape, $X = Q / (AC * \text{SQR}(\text{RISE}))$

$$\text{IF } X \leq .5 \text{ THEN } IH = (A(1) * (X / .5)) * \text{RISE}$$

$$\text{ELSE } IH = (A(J - 1) + (A(J) - A(J - 1)) * ((X - J + 2) / \text{INC})) * \text{RISE}$$

2. For all others shapes, $X = Q / (\text{SPAN} * \text{SQR}(\text{RISE}^3))$; $SR = SR(\text{IC})$

$$IH = (A + (B + (C + (D + (E + F * X) * X) * X) * X) * X - SR * S0) * \text{RISE}$$

3. Headwater elevation (IHI) = IH + IIE if no Depression.

4. For Depression, CREST headwater is checked.

THROAT CONTROL TAPERED INLET

1. $X = Q / (\text{SPAN} * \text{SQR}(\text{RISE}^3))$
2. $\text{HT} = \text{RISE} * (.1295033 + (.3789944 + (-.0437778 + (4.26329\text{E-}03 - 1.06358\text{E-}04 * X) * X) * X) * X)$

FACE CONTROL-SIDE TAPERED INLET

1. $\text{ZZ} = Q / (\text{BF} * \text{SQR}(\text{RISE}^3))$
2. Calculate UNSUBMERGED: $\text{HF1} = (.56 * \text{RISE}) * (\text{ZZ} ^ .66667)$
3. Calculate SUBMERGED
 - A. For bevels: $\text{HF3} = (.0378 * (\text{ZZ} * \text{ZZ}) + .86) * \text{RISE}$
 - IF $\text{HF1} > \text{RISE}$ THEN $\text{HF} = \text{HF3}$
 - IF $\text{HF1} < \text{RISE}$ THEN $\text{HF} = \text{HF1}$
 - IF $\text{HF1} \geq \text{HF3}$ THEN $\text{HF} = \text{HF1}$
 - B. For other edges: $\text{HF2} = (.0446 * (\text{ZZ} * \text{ZZ}) + .84) * \text{RISE}$
 - IF $\text{HF1} > \text{RISE}$ THEN $\text{HF} = \text{HF2}$
 - IF $\text{HF1} < \text{RISE}$ THEN $\text{HF} = \text{HF1}$
 - IF $\text{HF1} \geq \text{HF2}$ THEN $\text{HF} = \text{HF1}$

FACE CONTROL FOR SLOPE TAPERED INLET

1. $\text{ZZ} = Q / (\text{BF} * \text{SQR}(\text{RISE}^3))$
2. Calculate UNSUBMERGED: $\text{HF1} = (.5 * \text{RISE}) * (\text{ZZ} ^ .66667)$
 - A. For bevels: $\text{HF3} = (.0378 * (\text{ZZ} * \text{ZZ}) + .7) * \text{RISE}$
 - IF $\text{HF1} > \text{RISE}$ THEN $\text{HF} = \text{HF3}$
 - IF $\text{HF1} < \text{RISE}$ THEN $\text{HF} = \text{HF1}$
 - IF $\text{HF1} > \text{HF3}$ THEN $\text{HF} = \text{HF1}$
 - B. For other edges: $\text{HF2} = (.0446 * (\text{ZZ} * \text{ZZ}) + .64) * \text{RISE}$
 - IF $\text{HF1} > \text{RISE}$ THEN $\text{HF} = \text{HF2}$
 - IF $\text{HF1} < \text{RISE}$ THEN $\text{HF} = \text{HF1}$
 - IF $\text{HF1} > \text{HF2}$ THEN $\text{HF} = \text{HF1}$

CREST CONTROL

1. $\text{HC} = .5 * (Q / \text{CW}) ^ .66667$

OUTLET CONTROL PROCEDURES THAT PRODUCE AN INLET CONTROL PROFILE**STEP**

1. Compute critical depth (dco)
2. Compute normal depth (dno)
3. Compute fullflow if nomograph solution assumed "6-FFt or FFc".
4. If $\text{dno} > .95(\text{rise})$, assume fullflow "6-FFn".
5. If $\text{dno} > \text{dco}$, assume mild slope (SEE OUTLET.DAT).
6. If $\text{dno} \leq \text{dco}$, assume steep slope.
 - A. If twh is $\geq \text{So(L)} + \text{rise}$, assume fullflow "4-FFt".\

- B. If twh is \geq rise, outlet submerged, assume inlet unsubmerged.
- C. If twh is $<$ rise, outlet is unsubmerged, assume inlet unsubmerged.
- i. Assume headwater (oh) = inlet control headwater (ih)
- Calculate S2 curve "1-S2n" for outlet depth.
- If $oh \geq$ rise, inlet submerged "5-S2n"
- ii. If $twh >$ headwater, tailwater drowns out jump.
- Calculate M1 curve "3-M1t".
- If culvert flows part full, "7-Mit".

STEP	FLOW TYPE	FLOW CONTROL	SUBMERGED		LENGTH FULL	LOSS CALC	OUTLET DEPTH
			INLET	OUTLET			
6C1	1	Inlet	No	No	None	S2n	Normal
6B3b	1	Inlet	No	Yes	Part	S1f	Full
6C1	5	Inlet	Yes	No	None	S2n	Normal
6B3b	5	Inlet	Yes	Yes	Part	S1f	Full

Template loop detected: WMS:HY-8 Flow Types

Polynomial Generation

Inlet control means that flow within the culvert barrel is supercritical and not capable of transmitting losses upstream. The determination of the headwater depth, therefore, is not found using the energy equation, but is the result of many scaled model tests. In HDS-5 (Appendix A), submerged and unsubmerged equations developed by the National Bureau of Standards from the scaled model tests were originally used to determine headwater depths. These equations required four coefficients, K, M, c, and Y. Unfortunately, once plotted, the transition zone between unsubmerged and submerged flow was not well defined. For the purposes of the HY-8 program, a fifth degree polynomial curve was fitted through the three regions of flow: unsubmerged, transition, and submerged (see equation below). Fifth degree polynomial coefficients were obtained for all combinations of culvert shape and inlet configurations.

$$\frac{HW}{D} = a + b \left[\frac{Q}{BD^{1.5}} \right] + c \left[\frac{Q}{BD^{1.5}} \right]^2 + d \left[\frac{Q}{BD^{1.5}} \right]^3 + e \left[\frac{Q}{BD^{1.5}} \right]^4 + f \left[\frac{Q}{BD^{1.5}} \right]^5$$

Polynomial Coefficients

Overview

For circular, box, elliptical, pipe arch, concrete open-bottom arch (commonly called CON/SPAN), and South Dakota Concrete Box culverts, polynomial coefficients, found in Tables 1-6, are utilized in the inlet control headwater computations. Other culvert shapes use Table 7, which shows the HW/D points A(1) through A(10) for interpolation. Each row of coefficients represents different inlet configurations for different culvert shapes.

Note About Coefficient Changes in HY-8 7.3 and Higher

In HY-8 7.3 and later versions of HY-8, several significant changes were made to the coefficients used in HY-8. A summary of the changes to the HY-8 coefficients in this version follows:

Changes to Shapes Using Polynomial Coefficients

Changed the slope correction coefficient, SR, used for all the mitered inlet configurations to the recommended -0.7

Changes to Box Culverts

Changed the 1.5:1 Bevel Wingwall inlet configuration from HY-8 Equation 6 to equation 2. For HY-8 Equations 2, 3, and 6, added 0.01 to the "A" Coefficient in the shape database to account for the fact that the equations were derived using a 2% slope (a 2% slope was used to derive the polynomial equations, meaning 0.5(0.02) was subtracted from each of the polynomial curves and needed to be added back into the equations before correcting for slopes).

Changes to Shapes using A(1) to A(10) Interpolation Coefficients

Added the slope correction term $SR \cdot \text{Slope}$ to the interpolation equations in the code and added 0.01 to the interpolation coefficients for thin, square, and bevel inlets. Subtracted 0.01 for the mitered inlet. Added the SR coefficients (All = 0.5 except for mitered which = -0.7) to the coefficient database and the documentation on this page.

Table 1. Polynomial Coefficients - Circular

HY-8 Equation	Inlet Configuration	KE	SR	A	BS	C	DIP	EE	F
1	Thin Edge Projecting	0.9	0.5	0.187321	0.56771	-0.156544	0.0447052	-0.00343602	8.96610E-05
2	Mitered to Conform to Slope	0.7	-0.7	0.107137	0.757789	-0.361462	0.1233932	-0.01606422	0.00076739
3	Square Edge with Headwall (Steel/Aluminum/Corrugated PE)	0.5	0.5	0.167433	0.538595	-0.149374	0.0391543	-0.00343974	0.000115882
4	Grooved End Projecting	0.2	0.5	0.108786	0.662381	-0.233801	0.0579585	-0.0055789	0.000205052
5	Grooved End in Headwall	0.2	0.5	0.114099	0.653562	-0.233615	0.0597723	-0.00616338	0.000242832
6	Beveled Edge (1:1)	0.2	0.5	0.063343	0.766512	-0.316097	0.0876701	-0.009836951	0.00041676
7	Beveled Edge (1.5:1)	0.2	0.5	0.08173	0.698353	-0.253683	0.065125	-0.0071975	0.000312451
8	sq. proj.	0.2	0.5	0.167287	0.558766	-0.159813	0.0420069	-0.00369252	0.000125169
9	Square Edge with Headwall (Concrete/PVC/HDPE)	0.5	0.5	0.087483	0.706578	-0.253295	0.0667001	-0.00661651	0.000250619

10	end sect.	0.4	0.5	0.120659	0.630768	-0.218423	0.0591815	-0.00599169	0.000229287
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EQ #'s: REFERENCE

1-9 : Calculator Design Series (CDS) 3 for TI-59, FHWA, 1980, page 60

1-10: Hydraulic Computer Program (HY) 1, FHWA, 1969, page 18

Table 2. Polynomial Coefficients - Embedded Circular

HY-8 Equation	Inlet Configuration	KE	SR	A	BS	C	DIP	EE	F
1	20% Embedded, Projecting End, Pond	1.0	0.5	0.0608834861787302	0.485734308768152	-0.138194248908661	0.027539172439404	-0.00214546773150856	0.0000642768838741702
2	40% Embedded, Projecting End, Pond	1.0	0.5	0.0888877561313819	0.431529135749154	-0.073866511532321	0.0159200223783949	-0.00103390288198853	0.0000262133369282047
3	50% Embedded, Projecting End, Pond	1.0	0.5	0.0472950768985916	0.59879374328307	-0.191731763062064	0.0480749069653899	-0.00424418228907681	0.00014115316932528
4	20% Embedded, Square Headwall	0.55	0.5	0.0899367985347424	0.363046722229086	-0.0683746513605387	0.0109593856642167	-0.000706535544154146	0.0000189546410047092
5	40% Embedded, Square Headwall	0.55	0.5	0.074298531535586	0.4273662972292	-0.0849120530113796	0.0157965200237501	-0.00102651687866388	0.0000260155937601425
6	50% Embedded, Square Headwall	0.55	0.5	0.212469378699735	0.511461899639209	-0.174199884499934	0.0410961018431149	-0.00366309685788592	0.000123085395227651
7	20% Embedded, 45 degree Beveled End	0.35	0.5	0.0795781442396077	0.373319755852658	-0.0821508852481996	0.0148670702428601	-0.00121876746632593	0.0000406896111847521
8	40% Embedded, 45 degree Beveled End	0.35	0.5	0.0845740029462746	0.389113662011417	-0.0685090654986062	0.0117190357464366	-0.000790440416133214	0.0000226453591207209
9	50% Embedded, 45 degree Beveled End	0.35	0.5	0.0732498224366533	0.426296207882289	-0.0825309806843494	0.0158108288973248	-0.00103586921012557	0.0000265873062363919
10	20% Embedded, Mitered End 1.5H:1V	0.9	0.5	0.075018832861494	0.404532870578638	-0.0959305677963978	0.0172402567402576	-0.00121896053512953	0.0000338251697138414

11	40% Embedded, Mitered End 1.5H:1V	0.9	0.5	0.086819906748455	0.362177446931189	-0.048309284166457	0.00870598247307798	-0.000359506993503941	2.89144278309283E-06
12	50% Embedded, Mitered End 1.5H:1V	0.9	0.5	0.0344461003984492	0.574817400258578	-0.204079127155295	0.0492721656480291	-0.00436372397619383	0.000144794982321005

EQ #'s: REFERENCE

1-12: NCHRP 15-24 report

Table 3. Polynomial Coefficients - Box

HY-8 Equation	Inlet Configuration	KE	SR	A	BS	C	DIP	EE	F
1	Square Edge (90 degree) Headwall, Square Edge (90 & 15 degree flare) Wingwall	0.5	0.5	0.122117	0.505435	-0.10856	0.0207809	-0.00136757	0.00003456
2	1.5:1 Bevel (90 degree) Headwall, 1.5:1 Bevel (19-34 degree flare) Wingwall	0.2	0.5	0.1067588	0.4551575	-0.08128951	0.01215577	-0.00067794	0.0000148
3	1:1 Bevel Headwall	0.2	0.5	0.1666086	0.3989353	-0.06403921	0.01120135	-0.0006449	0.000014566
4	Square Edge (30-75 degree flare) Wingwall	0.4	0.5	0.0724927	0.507087	-0.117474	0.0221702	-0.00148958	0.000038
5	Square Edge (0 degree flare) Wingwall	0.7	0.5	0.144133	0.461363	-0.0921507	0.0200028	-0.00136449	0.0000358
6	1:1 Bevel (45 degree flare) Wingwall	0.2	0.5	0.0995633	0.4412465	-0.07434981	0.01273183	-0.0007588	0.00001774

EQ #'s: REFERENCE

1-6: Hydraulic Computer Program (HY) 6, FHWA, 1969, subroutine BEQUA

1,4,5: Hydraulic Computer Program (HY) 3, FHWA, 1969, page 16

1,3,4,6: Calculator Design Series (CDS) 3 for TI-59, FHWA, 1980, page 16

Table 4. Polynomial Coefficients - Ellipse

HY-8 Equation	PIPE	Inlet Configuration	KE	SR	A	BS	C	DIP	EE	F
27	CSPE	headwall	0.5	0.5	0.01267	0.79435	-0.2944	0.07114	-0.00612	0.00015
28	CSPE	mitered	0.7	-0.7	-0.14029	1.437	-0.92636	0.32502	-0.04865	0.0027
29	CSPE	bevel	0.3	0.5	-0.00321	0.92178	-0.43903	0.12551	-0.01553	0.00073
30	CSPE	thin	0.9	0.5	0.0851	0.70623	-0.18025	0.01963	0.00402	-0.00052
31	RCPE	square	0.5	0.5	0.13432	0.55951	-0.1578	0.03967	-0.0034	0.00011
32	RCPE	grv. hdwl	0.2	0.5	0.15067	0.50311	-0.12068	0.02566	-0.00189	0.00005
33	RCPE	grv. proj	0.2	0.5	-0.03817	0.84684	-0.32139	0.0755	-0.00729	0.00027

EQ #'s: REFERENCE

27-30: Calculator Design Series (CDS) 4 for TI-59, FHWA, 1982, page 20

31-33: Calculator Design Series (CDS) 4 for TI-59, FHWA, 1982, page 22

Table 5. Polynomial Coefficients - Pipe Arch

HY-8 Equation	PIPE	Inlet Configuration	KE	SR	A	BS	C	DIP	EE	F
12	CSPA	proj.	0.9	0.5	0.08905	0.71255	-0.27092	0.07925	-0.00798	0.00029
13	CSPA	proj.	0.9	0.5	0.12263	0.4825	-0.00002	-0.04287	0.01454	-0.00117
14	CSPA	proj.	0.9	0.5	0.14168	0.49323	-0.03235	-0.02098	0.00989	-0.00086
15	CSPA	proj.	0.9	0.5	0.09219	0.65732	-0.19423	0.04476	-0.00176	-0.00012
16	CSPA	mitered	0.7	-0.7	0.0833	0.79514	-0.43408	0.16377	-0.02491	0.00141
17	CSPA	mitered	0.7	-0.7	0.1062	0.7037	-0.3531	0.1374	-0.02076	0.00117
18	CSPA	mitered	0.7	-0.7	0.23645	0.37198	-0.0401	0.03058	-0.00576	0.00045
19	CSPA	mitered	0.7	-0.7	0.10212	0.72503	-0.34558	0.12454	-0.01676	0.00081
20	CSPA	headwall	0.5	0.5	0.11128	0.61058	-0.19494	0.05129	-0.00481	0.00017
21	CSPA	headwall	0.5	0.5	0.12346	0.50432	-0.13261	0.0402	-0.00448	0.00021
22	CSPA	headwall	0.5	0.5	0.09728	0.57515	-0.15977	0.04223	-0.00374	0.00012
23	CSPA	headwall	0.5	0.5	0.09455	0.61669	-0.22431	0.07407	-0.01002	0.00054
24	RCPA	headwall	0.5	0.5	0.16884	0.38783	-0.03679	0.01173	-0.00066	0.00002
25	RCPA	grv. hdwl	0.2	0.5	0.1301	0.43477	-0.07911	0.01764	-0.00114	0.00002
26	RCPA	grv. proj	0.2	0.5	0.09618	0.52593	-0.13504	0.03394	-0.00325	0.00013


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




12-23: Calculator Design Series (CDS) 4 for TI-59, FHWA, 1982, page 17

24-26: Calculator Design Series (CDS) 4 for TI-59, FHWA, 1982, page 24

12,16,20: Hydraulic Computer Program (HY) 2, FHWA, 1969, page 17

Table 6. Polynomial Coefficients - Concrete Open-Bottom Arch

Span:Rise Ratio	Wingwall Angle (Inlet Configuration)	KE	SR	A	BS	C	DIP	EE	F	Diagram/Notes
2:1	0 Degrees (Mitered to Conform to Slope)	0.7	0.0	0.0389106557	0.6044131889	-0.1966160961	0.0425827445	-0.0035136880	0.0001097816	 <p>2:1 Coefficients are used if the span:rise ratio is less than or equal to 3:1.</p>

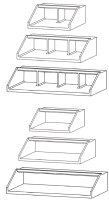
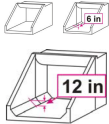


2:1	45 Degrees (45-degree Wingwall)	0.5	0.0	0.0580199163	0.5826504262	-0.1654982156	0.0337114383	-0.0026437555	0.0000796275	 <p>2:1 Coefficients are used if the span:rise ratio is less than or equal to 3:1.</p>
2:1	90 Degrees (Square Edge with Headwall)	0.5	0.0	0.0747688320	0.5517030198	-0.1403253664	0.0281511418	-0.0021405250	0.0000632552	 <p>2:1 Coefficients are used if the span:rise ratio is less than or equal to 3:1.</p>
4:1	0 Degrees (Mitered to Conform to Slope)	0.7	0.0	0.0557401882	0.4998819105	-0.1249164198	0.0219465031	-0.0015177347	0.0000404218	 <p>4:1 coefficients are used if the span:rise ratio is greater than 3:1</p>
4:1	45 Degrees (45-degree Wingwall)	0.5	0.0	0.0465032346	0.5446293346	-0.1571341119	0.0312822438	-0.0024007467	0.0000704011	 <p>4:1 coefficients are used if the span:rise ratio is greater than 3:1</p>
4:1	90 Degrees (Square Edge with Headwall)	0.5	0.0	0.0401619369	0.5774418238	-0.1693724912	0.0328323405	-0.0024131276	0.0000668323	 <p>4:1 coefficients are used if the span:rise ratio is greater than 3:1</p>

References for Concrete Open-bottom Arch polynomial coefficients:

- Thiele, Elizabeth A. Culvert Hydraulics: Comparison of Current Computer Models. (pp. 121-126), Brigham Young University Master's Thesis (2007).
- Chase, Don. Hydraulic Characteristics of CON/SPAN Bridge Systems. Submitted Study and Report (1999)

Table 7. Polynomial Coefficients - South Dakota Concrete Box

Description	KE	SR	A	BS	C	DIP	EE	F	Diagram/Notes
Sketch 1: 30 degree-flared wingwalls; top edge beveled at 45 degrees	0.5	0.5	0.0176998563	0.5354484847	-0.1197176702	0.0175902318	-0.0005722076	-0.0000080574	
Sketch 2: 30 degree-flared wingwalls; top edge beveled at 45 degrees; 2, 3, and 4 multiple barrels	0.5	0.5	0.0506647261	0.5535393634	-0.1599374238	0.0339859269	-0.0027470036	0.0000851484	
Sketch 3: 30 degree-flared wingwalls; top edge beveled at 45 degrees; 2:1 to 4:1 span-to-rise ratio	0.5	0.5	0.0518005829	0.5892384653	-0.1901266252	0.0412149379	-0.0034312198	0.0001083949	
Sketch 4: 30 degree-flared wingwalls; top edge beveled at 45 degrees; 15 degrees skewed headwall with multiple barrels	0.5	0.5	0.2212801152	0.6022032341	-0.1672369732	0.0313391792	-0.0024440549	0.0000743575	
Sketch 5: 30 degree-flared wingwalls; top edge beveled at 45 degrees; 30 degrees to 45 degrees skewed headwall with multiple barrels	0.5	0.5	0.2431604850	0.5407556631	-0.1267568901	0.0223638322	-0.0016523399	0.0000490932	
Sketches 6 & 7: 0 degree-flared wingwalls (extended sides); square-edged at crown and 0 degree-flared wingwalls (extended sides); top edge beveled at 45 degrees; 0- and 6-inch corner fillets	0.5	0.5	0.0493946080	0.7138391179	-0.2354755894	0.0473247331	-0.0036154348	0.0001033337	

Sketches 8 & 9: 0 degree-flared wingwalls (extended sides); top edge beveled at 45 degrees; 2, 3, and 4 multiple barrels and 0 degree-flared wingwalls (extended sides); top edge beveled at 45 degrees; 2:1 to 4:1 span-to-rise ratio	0.5	0.5	0.1013668008	0.6600937637	-0.2133066786	0.0437022641	-0.0035224589	0.0001078198	
Sketches 10 & 11: 0 degree-flared wingwalls (extended sides); crown rounded at 8-inch radius; 0- and 6-inch corner fillets and 0 degree-flared wingwalls (extended sides); crown rounded at 8-inch radius; 12-inch corner fillets	0.5	0.5	0.0745605288	0.6533033536	-0.1899798824	0.0350021004	-0.0024571627	0.0000642284	
Sketch 12: 0 degree-flared wingwalls (extended sides); crown rounded at 8-inch radius; 12-inch corner fillets; 2, 3, and 4 multiple barrels	0.5	0.5	0.1321993533	0.5024365440	-0.1073286526	0.0183092064	-0.0013702887	0.0000423592	
Sketch 13: 0 degree-flared wingwalls (extended sides); crown rounded at 8-inch radius; 12-inch corner fillets; 2:1 to 4:1 span-to-rise ratio.	0.5	0.5	0.1212726739	0.6497418331	-0.1859782730	0.0336300433	-0.0024121680	0.0000655665	

References for South Dakota Concrete Box polynomial coefficients:

- Thiele, Elizabeth A. Culvert Hydraulics: Comparison of Current Computer Models. (pp. 121-126), Brigham Young University Master's Thesis ^[1] (2007).
- Effects of Inlet Geometry on Hydraulic Performance of Box Culverts** ^[2] (FHWA Publication No. FHWA-HRT-06-138, October 2006)

Table 8. User Defined, Open Bottom Arch, Low-Profile Arch, High-Profile Arch, and Metal Box HW/D Values.

$Q/A \cdot D^{.5} =$				0.5	1	2	3	4	5	6	7	8	9
HY-8 Interpolation Coefficients	Inlet Configuration	KE	SR	A(1)	A(2)	A(3)	A(4)	A(5)	A(6)	A(7)	A(8)	A(9)	A(10)
1	Thin Edge Projecting	0.9	0.5	0.31	0.48	0.81	1.11	1.42	1.84	2.39	3.03	3.71	4.26
2	Mitered to Conform to Slope	0.7	-0.7	0.34	0.49	0.77	1.04	1.45	1.91	2.46	3.06	3.69	4.34
3	Square Edge with Headwall	0.5	0.5	0.31	0.46	0.73	0.96	1.26	1.59	2.01	2.51	3.08	3.64
4	Beveled Edge	0.2	0.5	0.31	0.44	0.69	0.89	1.16	1.49	1.81	2.23	2.68	3.18

Reference for User-defined interpolation coefficients: FHWA HDS-5, Appendix D, Chart 52B

References

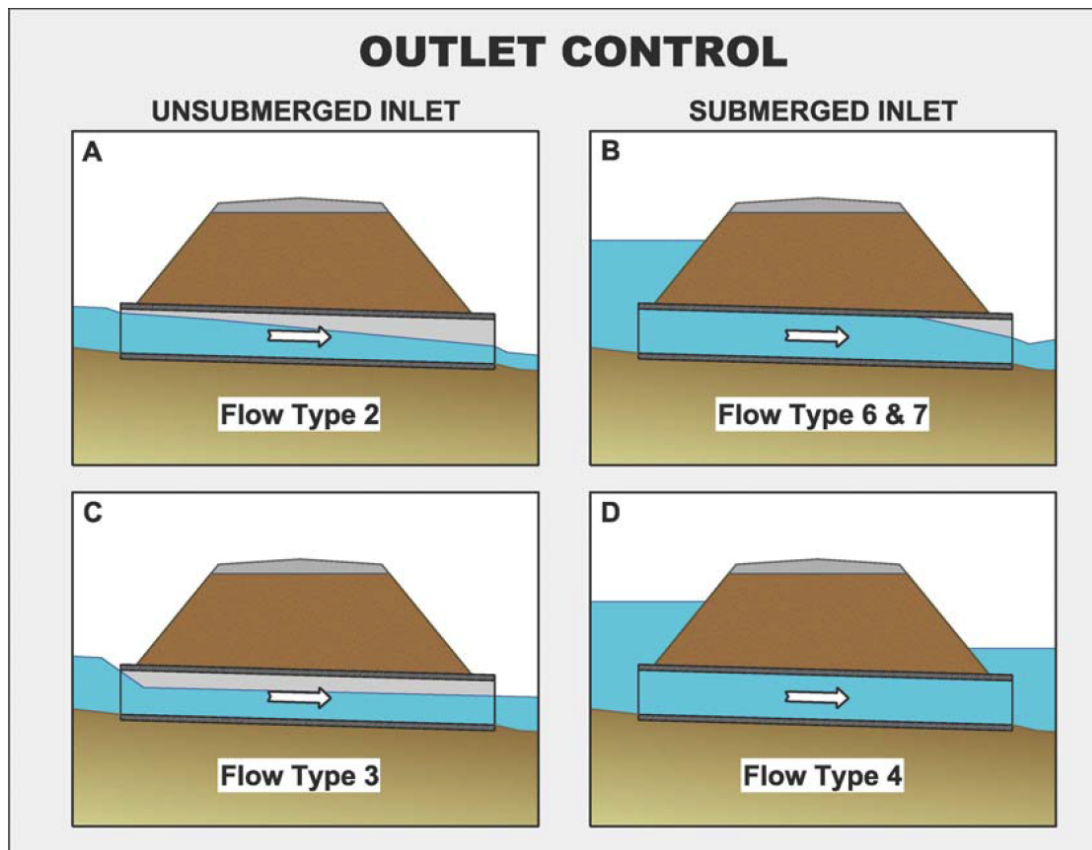
- [1] <http://etd.byu.edu>
- [2] <http://fhwicsint01.fhwa.dot.gov/publications/research/infrastructure/hydraulics/06138/>

5.2.2. Outlet Control

Outlet Control Computations

Outlet Control Flow Types

Outlet control means that the amount of water the culvert barrel can carry is limited by the barrel and/or tailwater conditions downstream. As a result, the flow in the barrel is subcritical, and the energy equation may be used to find the upstream headwater depth. Several flow profiles are possible as are shown below and as described in HDS-5. HY-8 flow types 2, 3, 4, 6, and 7 are all outlet control flow types and are shown in the figure below. The various flow type properties may be found in HY-8 by selecting the **Flow Types** button from the *Culvert Summary Table* and are shown below.



Outlet Control Computations

The logic for determining flow type due to outlet control is shown in the figure below:

This flowchart uses the following terms:

HJ = Check for Hydraulic Jumps

Full flow = Check if the culvert is flowing full

TWH = Depth of the tailwater from the invert of the tailwater channel at the culvert outlet

twOutletDepth = Depth of the tailwater from the invert of the culvert at the culvert outlet. If the culvert is buried, this value is taken from the top of the embedment material.

IH = Inlet control headwater depth measured at the inlet invert of the culvert

OH = Outlet control headwater depth measured at the inlet invert of the culvert

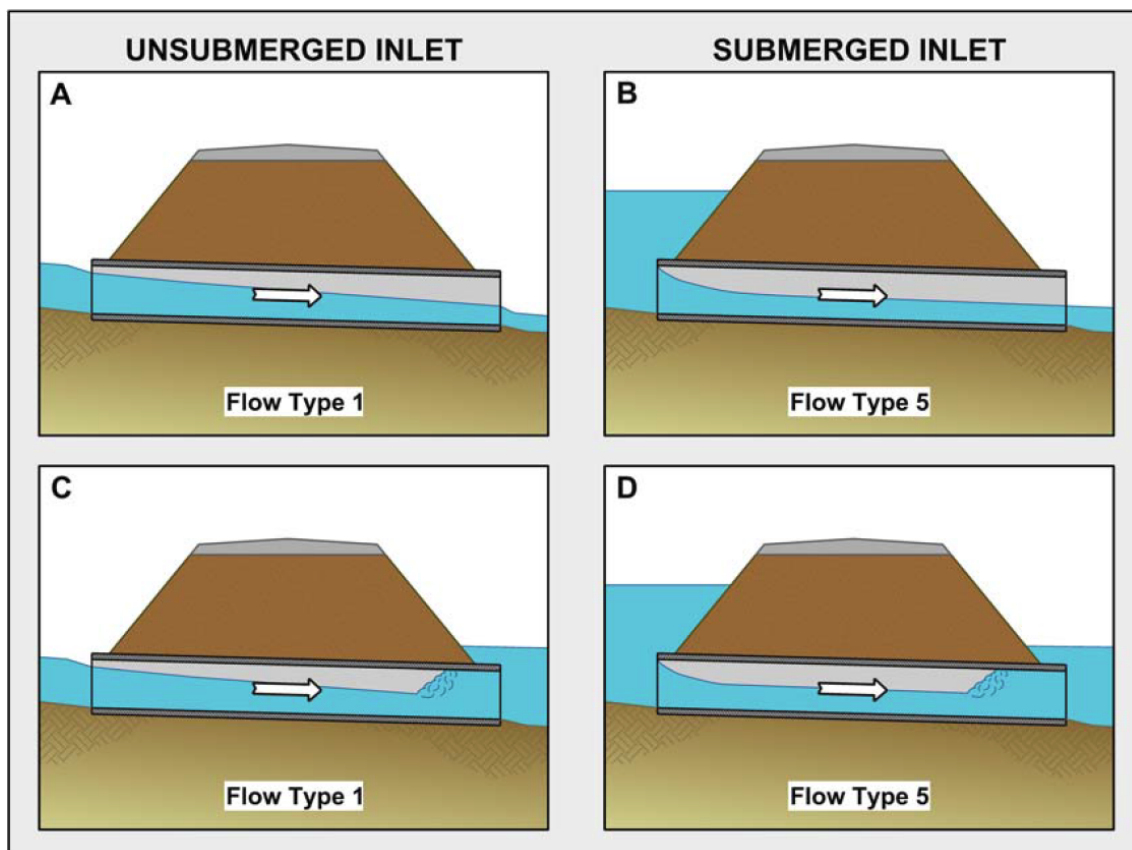
RISE = Height of the culvert. If the culvert is buried, this value is taken from the top of the embedment material.

Inlet Depth = The depth computed at the entrance to the culvert using the direct step profile computation method

Critical = The critical depth in the culvert

Normal = The normal depth in the culvert

Inlet control means that the amount of water the culvert barrel can carry is limited by the culvert entrance. Flow passes through critical depth at the culvert entrance and is supercritical in the barrel. There are several flow profiles possible, HY-8 simulates so-called Type A, B, C, and D conditions as shown below and as described in HDS-5. These profiles are known as Type 1 (A, C) and Type 5 (B, D) within HY-8. The various flow type properties may be found in HY-8 by selecting the **Flow Types** button from the Culvert Summary Table and are shown below. Because the flow in the barrel is supercritical, outlet losses and friction losses are not reflected in the headwater elevation. The headwater elevation is a function of the entrance size, shape, and culvert type. The computed inlet control headwater elevation is found by accessing the results of scaled physical model tests. The logic for determining what inlet flow control type prevails is shown below (from the original HY-8 help file).



Inlet Control Logic

DETERMINE APPLICABLE INLET CONTROL EQUATION

1. IF circle or box with IMPROVED INLETS then use INLET equations.
2. For Straight (previously called conventional) INLETS
 - A. If Q is $< Q$ at .5D, then assume LOW FLOW INLET CONTROL:
 - i. calculate CRITICAL DEPTH (DCO)
 - ii. calculate Section Properties
 - iii. $VH = (Q / AC)^2 / 64.4$
 - iv. $IH = DCO * LMULT + (1 + KELOW) * VH * VHCOEF$
 - IF no Depression THEN $IHI = IH + IIE$
 - For Depression, $HF = IH$ and check head on CREST.
 - B. If $Q > Q$ at .5D, but $< Q$ at 3D, then use INLET REGRESSION EQUATIONS.
 - C. If $Q > Q$ at 3D, then assume HIGH FLOW INLET CONTROL.
 - i. $IH = (Q / CDAHI)^2 + .5 * RISE$
 - ii. IF no Depression THEN $IHI = IH + IIE$
 - For Depression, $HF = IH$ and check head on CREST.

INLET REGRESSION EQUATIONS (Q between Q at .5D and Q at 3D)

1. CIRCULAR
 - A. See Straight inlet equations
 - B. SIDE TAPERED ELLIPTICAL TRANSITION, THROAT CONTROL

$$ZZ = Q / \text{SQR}(\text{RISE} \wedge 5), Y = \text{LOG}(ZZ) / 2.30258$$
 - i. IF $n < .015$ THEN SMOOTH PIPE IMPROVRD INLET.
 - ii. If $n \geq .015$ then ROUGH PIPE IMPROVED INLET.
 - iii. Calculate THROAT CONTROL
 - iv. Calculate FACE CONTROL
 - v. IF Depression Then $CW = CWF$, calculate CREST control.
 - C. SIDE TAPERED RECTANGULAR TRANSITION or SLOPE TAPERED
 - i. Calculate THROAT CONTROL
 - ii. Calculate FACE CONTROL
 - iii. IF Depression Then $CW = CWF$, calculate CREST control.
2. BOX CULVERTS
 - A. See Straight inlet equations
 - B. SIDE TAPERED RECTANGULAR TRANSITION or SLOPE TAPERED
 - i. Calculate THROAT CONTROL
 - ii. Calculate FACE CONTROL
 - iii. IF Depression Then $CW = CWF$, calculate CREST control.
3. PIPE ARCHES AND ELLIPSES
 - A. See Straight inlet equations
4. IRREGULAR SHAPE

A. See Straight inlet equations

Straight Inlet Equations

1. For IRREGULAR shape, $X = Q / (AC * \text{SQR}(\text{RISE}))$
 $\text{IF } X \leq .5 \text{ THEN } IH = (A(1) * (X / .5)) * \text{RISE}$
 $\text{ELSE } IH = (A(J - 1) + (A(J) - A(J - 1)) * ((X - J + 2) / \text{INC})) * \text{RISE}$
2. For all others shapes, $X = Q / (\text{SPAN} * \text{SQR}(\text{RISE}^3))$; $\text{SR} = \text{SR}(\text{IC})$
 $IH = (A + (B + (C + (D + (E + F * X) * X) * X) * X) * X - \text{SR} * S0) * \text{RISE}$
3. Headwater elevation (IHI) = IH + IIE if no Depression.
4. For Depression, CREST headwater is checked.

THROAT CONTROL TAPERED INLET

1. $X = Q / (\text{SPAN} * \text{SQR}(\text{RISE}^3))$
2. $\text{HT} = \text{RISE} * (.1295033 + (.3789944 + (-.0437778 + (4.26329\text{E-}03 - 1.06358\text{E-}04 * X) * X) * X) * X)$

FACE CONTROL-SIDE TAPERED INLET

1. $ZZ = Q / (BF * \text{SQR}(\text{RISE}^3))$
2. Calculate UNSUBMERGED: $\text{HF1} = (.56 * \text{RISE}) * (ZZ ^ .66667)$
3. Calculate SUBMERGED
 - A. For bevels: $\text{HF3} = (.0378 * (ZZ * ZZ) + .86) * \text{RISE}$
 $\text{IF } \text{HF1} > \text{RISE} \text{ THEN } \text{HF} = \text{HF3}$
 $\text{IF } \text{HF1} < \text{RISE} \text{ THEN } \text{HF} = \text{HF1}$
 $\text{IF } \text{HF1} \geq \text{HF3} \text{ THEN } \text{HF} = \text{HF1}$
 - B. For other edges: $\text{HF2} = (.0446 * (ZZ * ZZ) + .84) * \text{RISE}$
 $\text{IF } \text{HF1} > \text{RISE} \text{ THEN } \text{HF} = \text{HF2}$
 $\text{IF } \text{HF1} < \text{RISE} \text{ THEN } \text{HF} = \text{HF1}$
 $\text{IF } \text{HF1} \geq \text{HF2} \text{ THEN } \text{HF} = \text{HF1}$

FACE CONTROL FOR SLOPE TAPERED INLET

1. $ZZ = Q / (BF * \text{SQR}(\text{RISE}^3))$
2. Calculate UNSUBMERGED: $\text{HF1} = (.5 * \text{RISE}) * (ZZ ^ .66667)$
 - A. For bevels: $\text{HF3} = (.0378 * (ZZ * ZZ) + .7) * \text{RISE}$
 $\text{IF } \text{HF1} > \text{RISE} \text{ THEN } \text{HF} = \text{HF3}$
 $\text{IF } \text{HF1} < \text{RISE} \text{ THEN } \text{HF} = \text{HF1}$
 $\text{IF } \text{HF1} > \text{HF3} \text{ THEN } \text{HF} = \text{HF1}$
 - B. For other edges: $\text{HF2} = (.0446 * (ZZ * ZZ) + .64) * \text{RISE}$
 $\text{IF } \text{HF1} > \text{RISE} \text{ THEN } \text{HF} = \text{HF2}$
 $\text{IF } \text{HF1} < \text{RISE} \text{ THEN } \text{HF} = \text{HF1}$
 $\text{IF } \text{HF1} > \text{HF2} \text{ THEN } \text{HF} = \text{HF1}$

CREST CONTROL

$$1. HC = .5 * (Q / CW) ^ .66667$$

OUTLET CONTROL PROCEDURES THAT PRODUCE AN INLET CONTROL PROFILE

STEP

1. Compute critical depth (dco)
2. Compute normal depth (dno)
3. Compute fullflow if nomograph solution assumed "6-FFt or FFc".
4. If dno > .95(rise), assume fullflow "6-FFn".
5. If dno > dco, assume mild slope (SEE OUTLET.DAT).
6. If dno <= dco, assume steep slope.
 - A. If twh is >= So(L) + rise, assume fullflow "4-FFt".\
 - B. If twh is >= rise, outlet submerged, assume inlet unsubmerged.
 - C. If twh is < rise, outlet is unsubmerged, assume inlet unsubmerged.
 - i. Assume headwater (oh) = inlet control headwater (ih)
 Calculate S2 curve "1-S2n" for outlet depth.
 If oh >= rise, inlet submerged "5-S2n"
 - ii. If twh > headwater, tailwater drowns out jump.
 Calculate M1 curve "3-M1t".
 If culvert flows part full, "7-Mit".

STEP	FLOW TYPE	FLOW CONTROL	SUBMERGED		LENGTH FULL	LOSS CALC	OUTLET DEPTH
			INLET	OUTLET			
6C1	1	Inlet	No	No	None	S2n	Normal
6B3b	1	Inlet	No	Yes	Part	S1f	Full
6C1	5	Inlet	Yes	No	None	S2n	Normal
6B3b	5	Inlet	Yes	Yes	Part	S1f	Full

Template loop detected: WMS:HY-8 Flow Types

Exit Loss Options

Introduction

HY-8 version 7.1 incorporates an alternative modified equation for defining culvert exit loss. The method described in HDS-5 uses the energy equation and several assumptions to compute the exit loss for a culvert. The equation that is given in HDS-5 ignores the velocity head downstream from a culvert barrel and is given as the following:

$$H_o = k_0 \frac{V^2}{2g}$$

where $k_0 = 1.0$

Where H_o is the exit loss, V is the velocity inside the culvert barrel, and g is gravity. However, exit losses obtained from this expression do not match exit losses obtained from experimental studies by the researchers at Utah State University. USU has formulated an alternative expression for determining exit losses that uses the “Borda-Carnot equation”. This equation was originally developed for sudden expansions in pressurized pipes, but was found to give an accurate representation of culvert exit losses by USU’s experimental studies. Two useful forms of this expression are:

$$H_o = 1.0 \frac{(V_p - V_c)^2}{2g}$$

and

$$H_o = k_0 \frac{V_p^2}{2g}$$

where

$$k_0 = \left(1 - \frac{A_p}{A_c}\right)^2$$

Where H_o is the exit loss, V_p is the velocity inside the culvert barrel, V_c is the velocity in the downstream channel, and g is gravity. In HY-8, we need to use the first form of the equation ($H_o = 1.0 \frac{V^2}{2g}$) to compute the exit loss and the corresponding outlet control depth. The only additional value required between this equation and the previous equation is the velocity in the downstream channel. We already compute the downstream channel velocity in HY-8, so we can just use this computed velocity with the Borda-Carnot equation to compute the modified exit loss.

Modified Exit Loss Option

To access this equation in HY-8 use *Exit Loss* combo box in the *Macros* toolbar in HY-8. This combo box will have two options: 1) *Exit Loss: Standard Method* and 2) *Exit Loss: USU Method*.

If the *Standard Method* is selected, HY-8 will use the current method for computing exit losses. If the *USU Method* is selected, HY-8 will use the USU (Borda-Carnot) equation to compute exit losses.

Hydraulic Jump Calculations

Determining if a Hydraulic Jump Exists and its Location

A hydraulic jump is created in a rapidly varied flow situation where supercritical flow rapidly becomes subcritical flow. As the flow changes, energy is lost to turbulence. However, momentum is conserved across the jump. The two depths of flow just prior to and after a hydraulic jump are called sequent depths.

To determine if a hydraulic jump exists, HY-8 determines the supercritical and subcritical water surface profiles that form within the culvert using a direct step profile computation. At each location along the two profiles, HY-8 computes the sequent depths of the supercritical profile and compares these sequent depths to the subcritical profile's computed depth.

While HY-8 computes the supercritical profile, a hydraulic jump forms if either of the following two conditions occurs: (1) the sequent depth profile intersects the subcritical profile, or (2) the Froude number is reduced to approximately 1.7 in a decelerating flow environment (M3, S3, H3, or A3 flow) (See the section in FHWA's HEC-14 on broken back culverts, 7.4).

If the outlet is submerged, HY-8 uses the energy equation to determine the hydraulic grade line. Once the hydraulic grade line falls below the crown of the culvert, HY-8 uses the direct step method to determine the remainder of the profile.

The equations used to determine the sequent depth vary by shape and are detailed in Nathan Lowe's thesis (Lowe, 2008). Sequent Depths are not adjusted for slope or hydraulic jump type (see Hydraulic Jump Types).

An example of a profile set and sequent depth calculations from a box culvert is given in Table 1 and plotted in Figure 1. The subcritical depth is shown extending above the crown of the culvert to show the hydraulic grade line for comparison purposes. Once HY-8 concludes the hydraulic jump calculations, the flow profile is modified to be contained within the culvert barrel.

Table 1: Parameters of culvert used for example

Parameter	Value	Units
Culvert Shape	Box	
Rise:	6.0	ft
Span:	6.0	ft
Length:	100.0	ft
Flow:	80.0	cfs

Table 2: HY-8 Water Surface Profile and Sequent Depth Calculations

Computation Direction: Upstream to Downstream		
Location (ft)	S2 Water Depth (ft)	Sequent Depth (ft)
0	1.767423128	1.767423128
0.029316423	1.717423128	1.818384336
0.121221217	1.667423128	1.871344458
0.284143628	1.617423128	1.926427128
0.528025114	1.567423128	1.983769228
0.86466911	1.517423128	2.043522893
1.308192917	1.467423128	2.105857905
1.87561876	1.417423128	2.17096453
2.587657601	1.367423128	2.239056945
3.469764745	1.317423128	2.310377355
4.553586554	1.267423128	2.385201009
5.878983069	1.217423128	2.463842333
7.496921363	1.167423128	2.546662495
9.473726216	1.117423128	2.634078814
11.89752361	1.067423128	2.726576563
14.88838	1.017423128	2.824723925
18.61499626	0.967423128	2.929191151
23.32377651	0.917423128	3.040775386
29.3931714	0.867423128	3.160433253
37.44519272	0.817423128	3.289324251
48.60550709	0.767423128	3.42886946
65.23610698	0.717423128	3.580832395
93.76009585	0.667423128	3.747432593
100	0.663122364	3.762533062

Computation Direction: Downstream to Upstream	
Location (ft)	S1 Water Depth (ft)
100	7.78884205
76.62538619	6
76.01536408	5.95
75.40596369	5.9
74.79697048	5.85
74.18839865	5.8
73.58026305	5.75
72.97257915	5.7
72.36536314	5.65
71.75863195	5.6

71.15240324	5.55
70.54669552	5.5
69.94152813	5.45
69.33692135	5.4
68.73289638	5.35
68.12947544	5.3
67.52668185	5.25
66.92454003	5.2
66.3230756	5.15
65.72231547	5.1
65.12228788	5.05
64.5230225	5
63.92455054	4.95
63.32690478	4.9
62.73011975	4.85
62.13423177	4.8
61.5392791	4.75
60.94530208	4.7
60.35234323	4.65
59.76044741	4.6
59.16966197	4.55
58.58003695	4.5
57.9916252	4.45
57.40448266	4.4
56.81866848	4.35
56.23424533	4.3
55.6512796	4.25
55.06984171	4.2
54.49000634	4.15
53.91185285	4.1
53.33546552	4.05
52.76093401	4
52.18835372	3.95
51.61782627	3.9
51.04946001	3.85
50.48337049	3.8
49.91968113	3.75
49.35852381	3.7
48.80003962	3.65

48.24437962	3.6
47.69170569	3.55
47.1421915	3.5
46.59602356	3.45
46.05340235	3.4
45.51454362	3.35
44.97967983	3.3
44.44906168	3.25
43.92295991	3.2
43.40166723	3.15
42.88550053	3.1
42.37480328	3.05
41.86994835	3
41.37134098	2.95
40.87942233	2.9
40.39467334	2.85
39.91761912	2.8
39.44883402	2.75
38.98894719	2.7
38.53864914	2.65
38.09869903	2.6
37.66993312	2.55
37.25327445	2.5
36.84974393	2.45
36.46047324	2.4
36.08671965	2.35
35.72988334	2.3
35.39152756	2.25
35.07340226	2.2
34.77747182	2.15
34.50594783	2.1
34.26132798	2.05
34.04644235	2
33.86450893	1.95
33.71920038	1.9
33.61472501	1.85
33.55592549	1.8

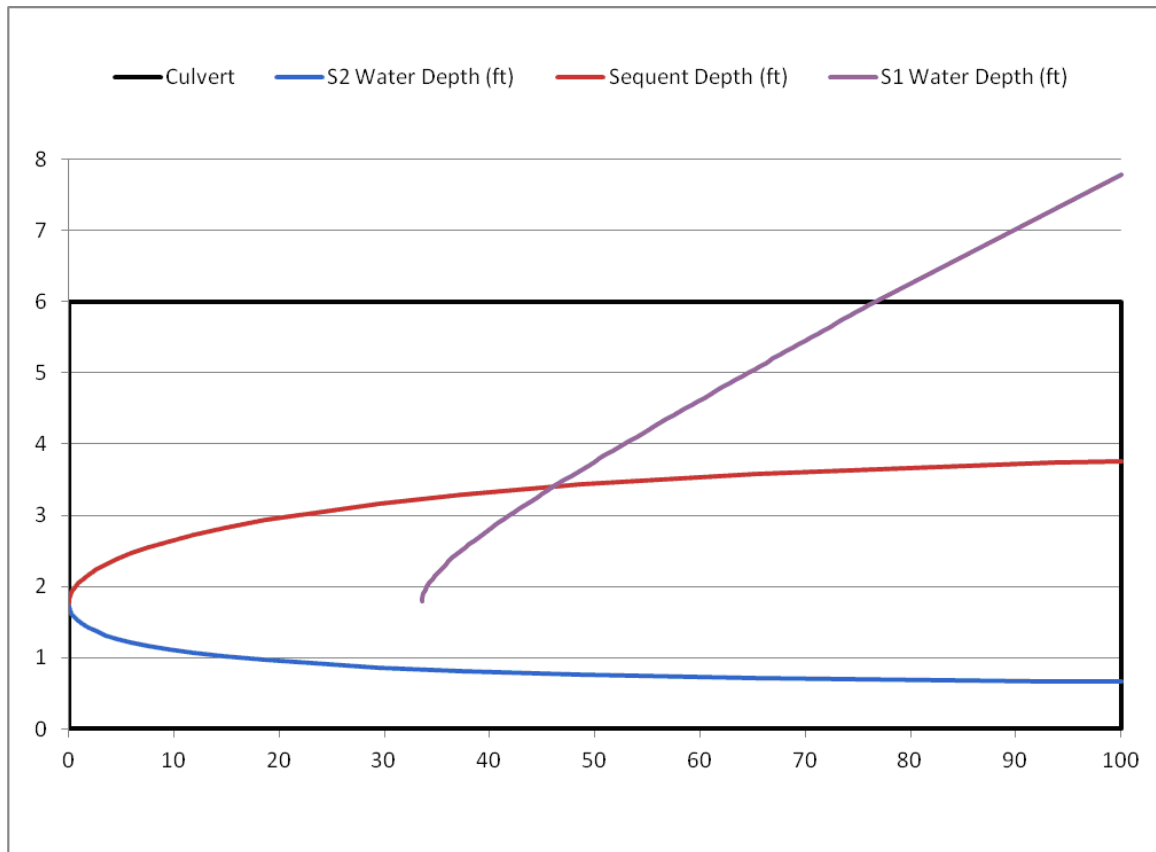


Figure 1: HY-8 Water Surface Profile and Sequent Depth Calculations

In Figure 1, the sequent depth shown by the red line crosses the S1 water depth shown by the purple line. The point of intersection is where a hydraulic jump occurs and is located at approximately 46' downstream of the inlet of the culvert. HY-8 creates a combined water surface profile from the two profiles. If you assume that the length of the hydraulic jump is zero, the jump would be a vertical line. An example of a water surface profile for a hydraulic jump assuming zero jump length is shown in Figure 2.

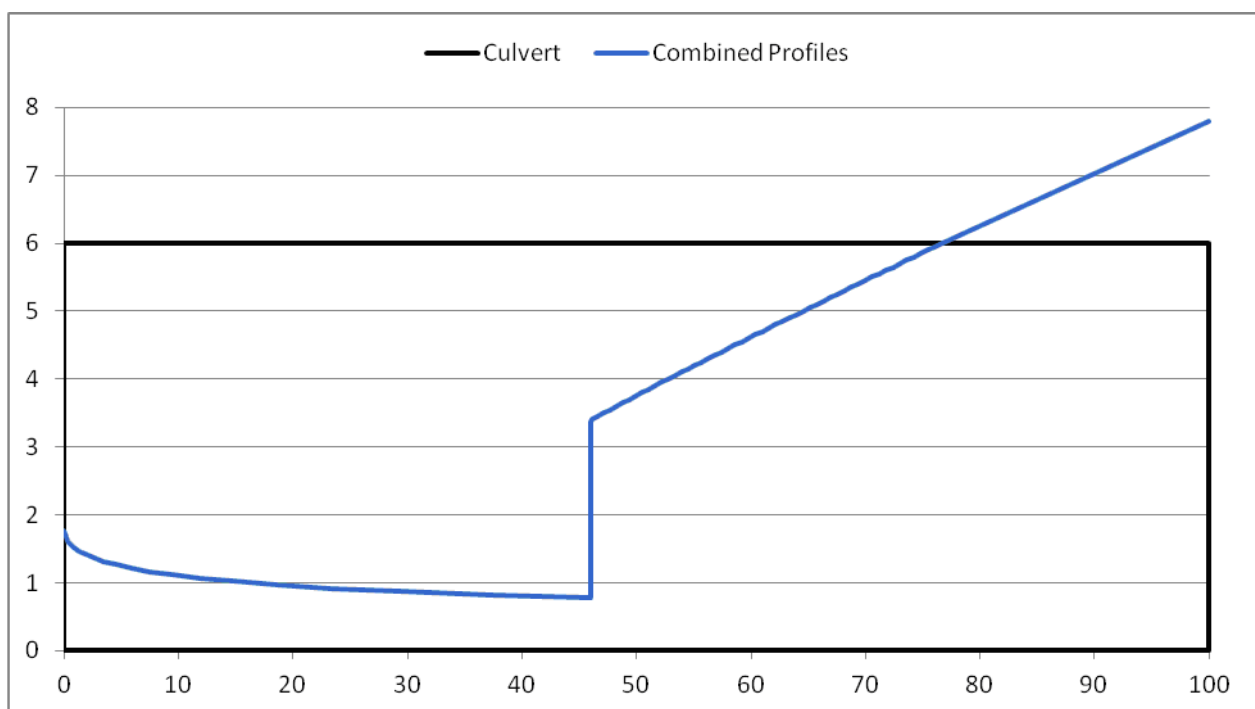


Figure 2: Water Surface Profile Assuming a Jump Length of Zero

Once HY-8 determines that a jump occurs and the jump's location, HY-8 determines the length of the jump and applies that length to the profile. Before determining the length, however, HY-8 must first determine the type of hydraulic jump so the appropriate equation can be used for computing the length.

Hydraulic Jump Types

In HY-8, hydraulic jumps are divided into 3 different types: A, B, and C (See Figure 3). Type A jumps occur on a flat slope, and this condition often occurs at the downstream section of a broken back culvert if a hydraulic jump did not occur in the steep section of the culvert. Type B jumps only occur in broken back culverts where the jump starts in the steep section of the culvert but finishes in the downstream section of the culvert. Type C jumps could occur in any sloped culverts.

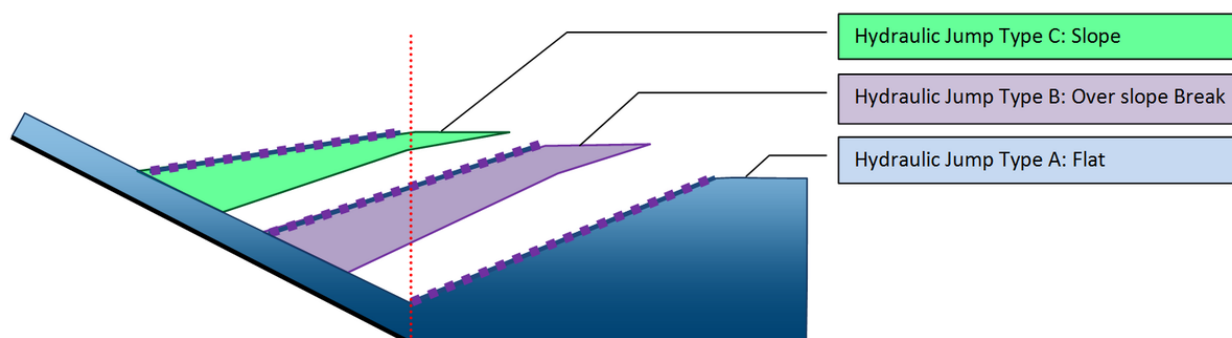


Figure 3: Hydraulic Jump Types used in HY-8

Determining the Length of a Hydraulic Jump

HY-8 uses equations determined by Bradley and Peterka (1957) and Hager (1992) as shown in the following table. Complete information about the lengths of hydraulic jumps does not exist in the literature. These portions of the table, where equations representing the hydraulic jump length are not available, are denoted with a "-". In instances where an equation has not been determined, an explanation of how HY-8 computes the length is shown.

Table 3: HY-8 Hydraulic Jump Length Equations

Culvert Shape	Flat Slope (Type A)	Sloped Culvert (Type C)	Jump Over Slope Break (Type B)
Circular	$L_j^* = 6y_2$	- (Use box equation)	- (Use box equation)
Box	$L_j^* = 220(y_1) \left(\tanh \left(\frac{Fr_1 - 1}{22} \right) \right)$	$L_j = L_j^* \exp \left(-\frac{4}{3}\theta \right)$	First solve for Fr_{1t} $Fr_{1t} = 11.3 \left(1 - \frac{2}{3}[(h_2 - z_1)/h_2] \right)$ Then, if $Fr_1 > Fr_{1t}$ $L_j = L_j^*$ Otherwise, if $Fr_1 \leq Fr_{1t}$ $L_j = h_2 \left[\frac{7}{3}(2 + [6E * \exp(1 - 6E)]) - \frac{1}{20}(1 + 5[6E * \exp(1 - 6E)])(Fr_1 - 2) \right]$ where: $E = (h_2 - z_1)/h_2$
Ellipse	Use longer of circular and box equations	- (Use box equation)	- (Use box equation)
Pipe Arch	Use longer of circular and box equations	- (Use box equation)	- (Use box equation)
User Defined/Other	Use longer of circular and box equations	- (Use box equation)	- (Use box equation)

In the above table, you can see that the literature is incomplete for the jump lengths of several of the shapes supported in HY-8. Further research is required for a more accurate analysis. The following variables are used in the above table and are shown in Figure 4:

L_j^* = Length of the hydraulic jump on a flat slope (ft or m)

y_1 = Sequent depth at the upstream end of the hydraulic jump (ft or m)

y_2 = Sequent depth at the downstream end of the hydraulic jump (ft or m)

Fr_1 = Froude number at the upstream end of the hydraulic jump

θ = Channel angle of repose (in radians, = Arctan(channel slope))

L_j = Length of the hydraulic jump on a sloping channel (ft or m)

z_1 = Distance from the invert of the flat part of the channel to the channel invert at the beginning of the jump (ft or m)

h_2 = Depth of water on a flat slope after the jump (ft or m)

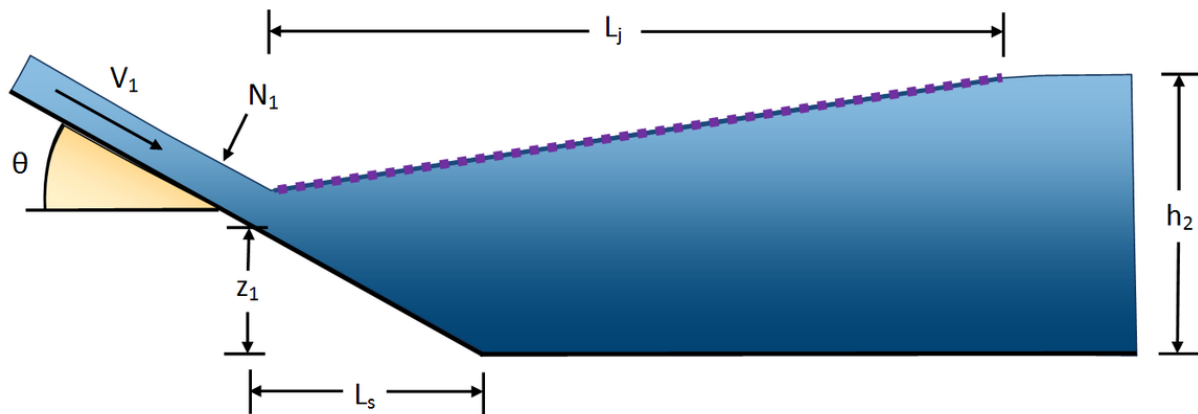


Figure 4: Variable definitions used in hydraulic jump length computations

HY-8 determines the length of the jump and modifies the profile to an angled transition to the subcritical flow rather than a vertical transition. The beginning of the jump is assumed to be the location previously determined as the jump location. The end of the jump is the beginning of the jump plus the jump length. If the end of the jump is outside of the culvert, the jump is assumed to be swept out. This may or may not happen, but is considered to be conservative. This assumption means HY-8 reports less hydraulic jumps than may actually occur. Example hydraulic jump length calculations are shown in Table 4. The profile showing the hydraulic jump with the jump length applied is shown in Figure 5.

Table 4: Sample Hydraulic Jump Length Calculations

Parameter	Value	Units
Culvert Shape	Box	
Froude Number 1:	3.4229	
Depth 1:	0.7778	ft
Length of Jump:	18.77	ft
Station 1:	46.0	ft
Station 2:	64.8	ft

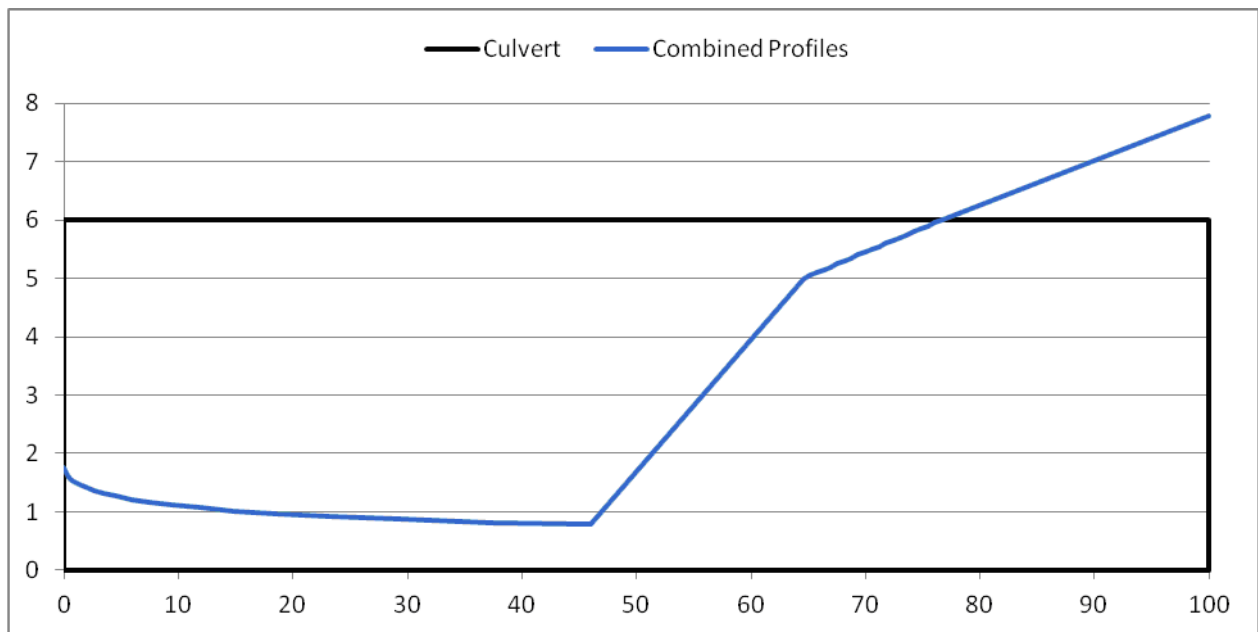


Figure 5: Water Profile with Hydraulic Jump with Calculated Jump Length

When HY-8 finishes computing the hydraulic jump length, and has applied it to the profile, HY-8 trims the profile to stay within the culvert barrel. The completed profile is shown in Figure 6.

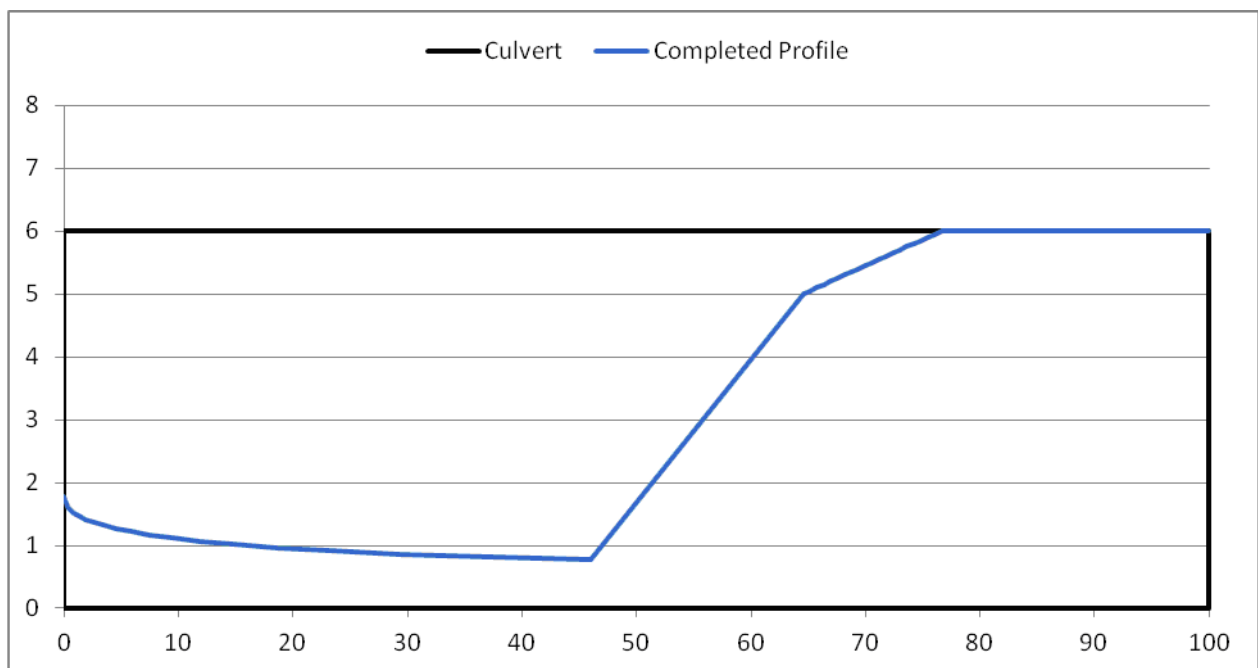


Figure 6: Completed Water Surface Profile

References

Lowe, N. J. (2008). THEORETICAL DETERMINATION OF SUBCRITICAL SEQUENT DEPTHS FOR COMPLETE AND INCOMPLETE HYDRAULIC JUMPS IN CLOSED CONDUITS OF ANY SHAPE. ^[1] Provo, Utah: Brigham Young University.

Bradley, J.N. and Peterka, A.J., The hydraulic design of stilling basins: hydraulic jumps on a horizontal apron (Basin I), Journal of the Hydraulics Division, ASCE, 83 (HY5), pp. 1401 (1-24), 1957.

Hager, W.H. Energy Dissipators and Hydraulic Jump. Kluwer Academic Publishers, Dordrecht, Netherlands, 1992.

References

[1] <http://contentdm.lib.byu.edu/u?/ETD,1623>

5.3. Tables and Plots

Tables and Plots

After analyzing the culvert crossing, the user can view the following tables and plots:

- Crossing Summary Table
- Culvert Summary Table
- Water Surface Profiles
- Tapered Inlet Table
- Customized Table

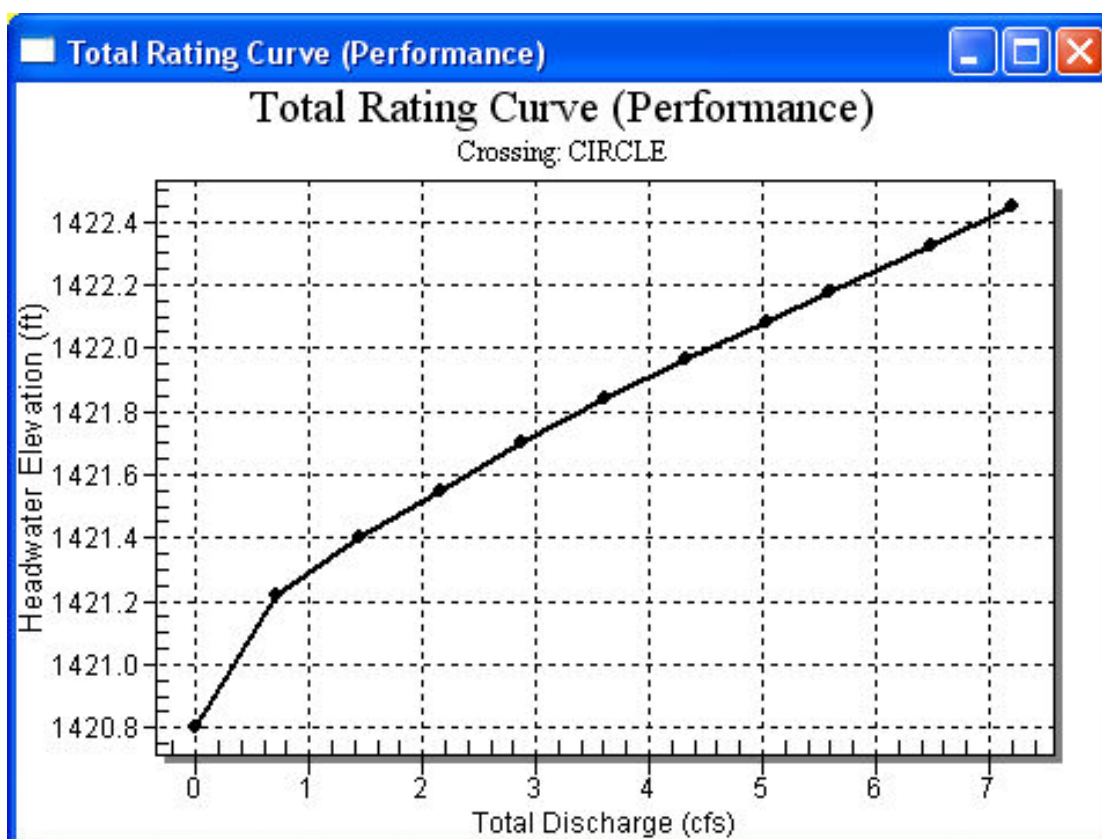
The appearance of plots within HY-8 can be controlled by the user using the Plot Display Options.

Crossing Summary

The crossing summary table is important in showing the balance of discharge moving through the culvert(s) at the crossing and over the roadway. The following variables are displayed in the table:

- **Headwater Elevation:** the elevation of the headwater when the flow is balanced between the culvert(s) and roadway.
- **Total Discharge:** the sum of the discharge through the culvert barrel(s) and over the roadway.
- **Culvert(1) Discharge:** the balance discharge through all the barrels in the first culvert.*
- **Roadway Discharge:** total discharge overtopping the roadway.
- **Iteration:** displays the number of iterations required to reach the convergence limit.
- Note: there will be a column for the discharge through each culvert in the crossing.

When the crossing summary table option is selected, the user may also view the total rating curve for all culverts in the crossing. A sample rating curve is shown in the figure below.

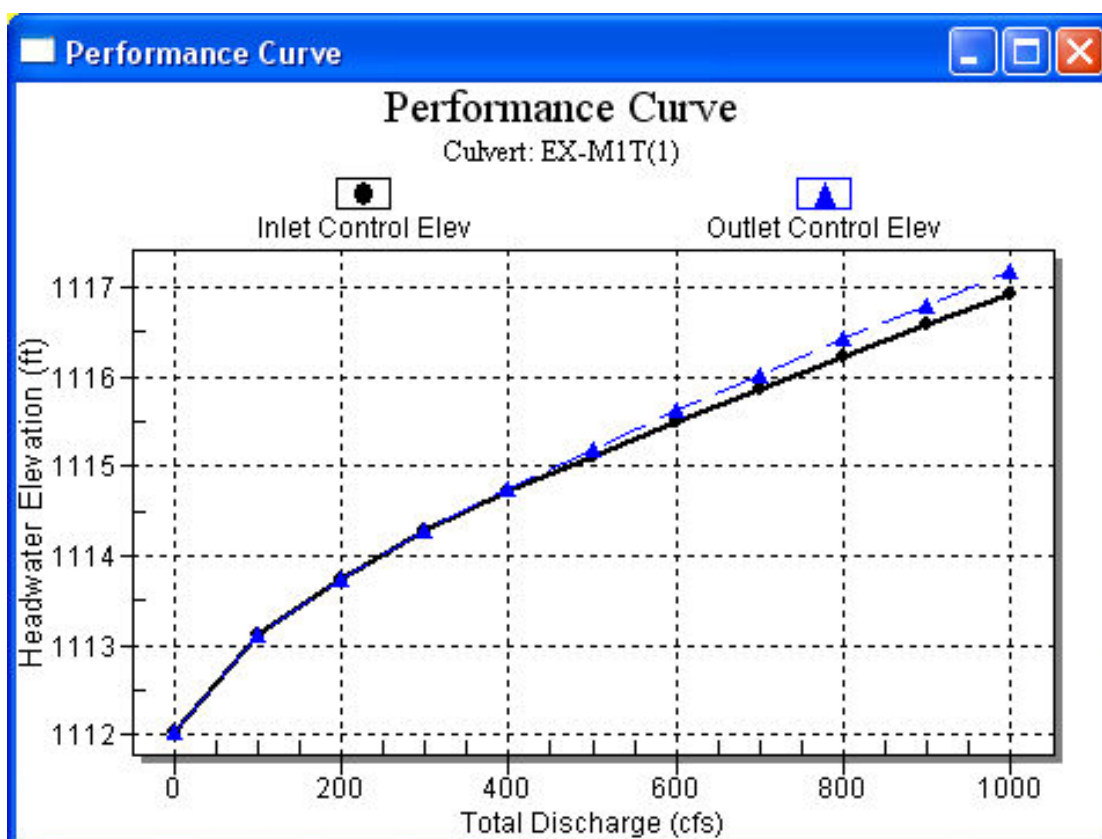


Culvert Summary

The culvert summary table shows the performance table for each culvert in the crossing. Each culvert's properties can be viewed by selecting the desired culvert from the drop-down list. The following properties are represented in the table:

- **Total Discharge:** Total discharge at the culvert crossing
- **Culvert Discharge:** Amount of discharge that passes through the selected culvert barrel(s)
- **Headwater Elevation:** Computed headwater elevation at the inlet of the culvert(s)
- **Inlet Control Depth:** Inlet control headwater depth above inlet invert
- **Outlet Control Depth:** Outlet control headwater depth above inlet invert
- **Flow Type:** USGS flow type 1 through 7 is indicated and the associated profile shape and boundary condition. Press the *Flow Types* button for a summary of Flow Types.
- **Normal Depth:** Normal depth in the culvert. If the culvert capacity is insufficient to convey flow at normal depth, normal depth is set equal to the barrel height.
- **Critical Depth:** Critical depth in culvert. If the culvert capacity is insufficient to convey flow at critical depth, critical depth is set equal to the barrel height.
- **Outlet Depth:** Depth at culvert outlet
- **Tailwater Depth:** Depth in downstream channel
- **Outlet Velocity:** Velocity at the culvert outlet
- **Tailwater Velocity:** Velocity in downstream channel

In the table, bold values indicate inlet or outlet controlling depths. Within the culvert summary option, the user may plot the performance curve for each culvert in the crossing. A sample performance curve is displayed in the figure below.

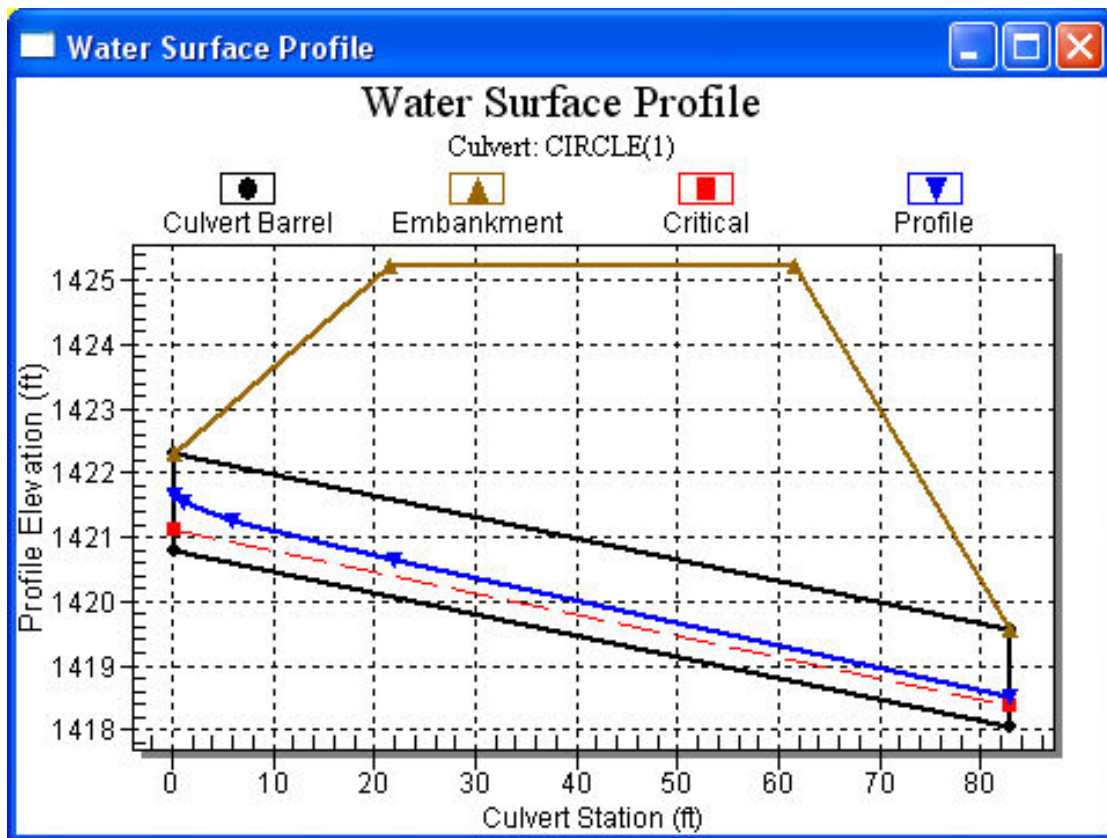


Water Surface Profiles

Water surface profile information is displayed in a table format for each of the discharge values. Once a profile is selected, the user may then plot and view the profile. The following parameters are displayed in the water surface profiles table:

- **Total Discharge:** Total discharge at the culvert crossing
- **Culvert Discharge:** Amount of discharge that passes through the culvert barrel(s)
- **Headwater Elevation:** Computed headwater elevation at the inlet of the culvert
- **Inlet Control Depth:** Headwater depth above inlet invert assuming inlet control
- **Outlet Control Depth:** Headwater depth above inlet invert assuming outlet control
- **Flow Type:** USGS flow type 1 through 7 is indicated and the associated profile shape and boundary condition.
Press the *Flow Types* button for a summary of Flow Types
- **Length Full:** Length of culvert that is flowing full.
- **Length Free:** Length of culvert that has free surface flow.
- **Last Step:** Last length increment calculated in profile.
- **Mean Slope:** Last mean water surface slope calculated.
- **First Depth:** Starting depth for water surface profile.
- **Last Depth:** Ending depth for the water surface profile.

While viewing the water surface profiles table, the user may plot any of the profiles by selecting the desired profile in the table and clicking the water profile button in the window. Below is a sample water surface profile for a circular culvert.



Tapered Inlet

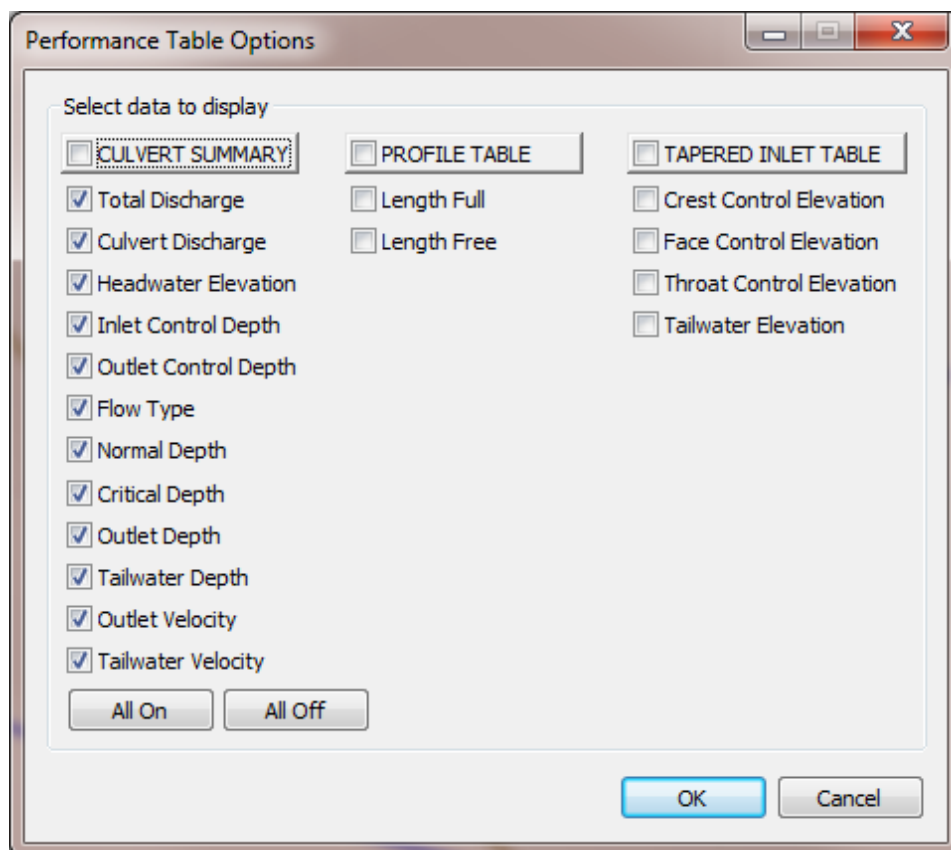
The tapered inlet table is designed to be used with tapered inlets and shows the headwater elevation at the culvert inlet based on different controls such as the crest, face, and throat. The following parameters are computed and displayed:

- **Total Discharge:** Total discharge at the culvert crossing
- **Culvert Discharge:** Amount of discharge that passes through the culvert barrel(s)
- **Headwater Elevation:** Computed headwater elevation at the inlet(s) of the culvert(s)
- **Inlet Control Depth:** Inlet control headwater depth above inlet invert
- **Outlet Control Depth:** Outlet control headwater depth above inlet invert
- **Flow Type:** USGS flow type "Full Flow HDS-5" is shown if full flow outlet control option is selected
- **Crest Control Elevation:** Headwater elevation calculated assuming crest control.
- **Face Control Elevation:** Headwater elevation calculated assuming face control.
- **Throat Control Elevation:** Headwater elevation calculated assuming throat control.
- **Tailwater Elevation:** Tailwater elevation at culvert outlet from downstream channel.

The tapered inlet table also provides the option of plotting and viewing the culvert performance curve.

Customized

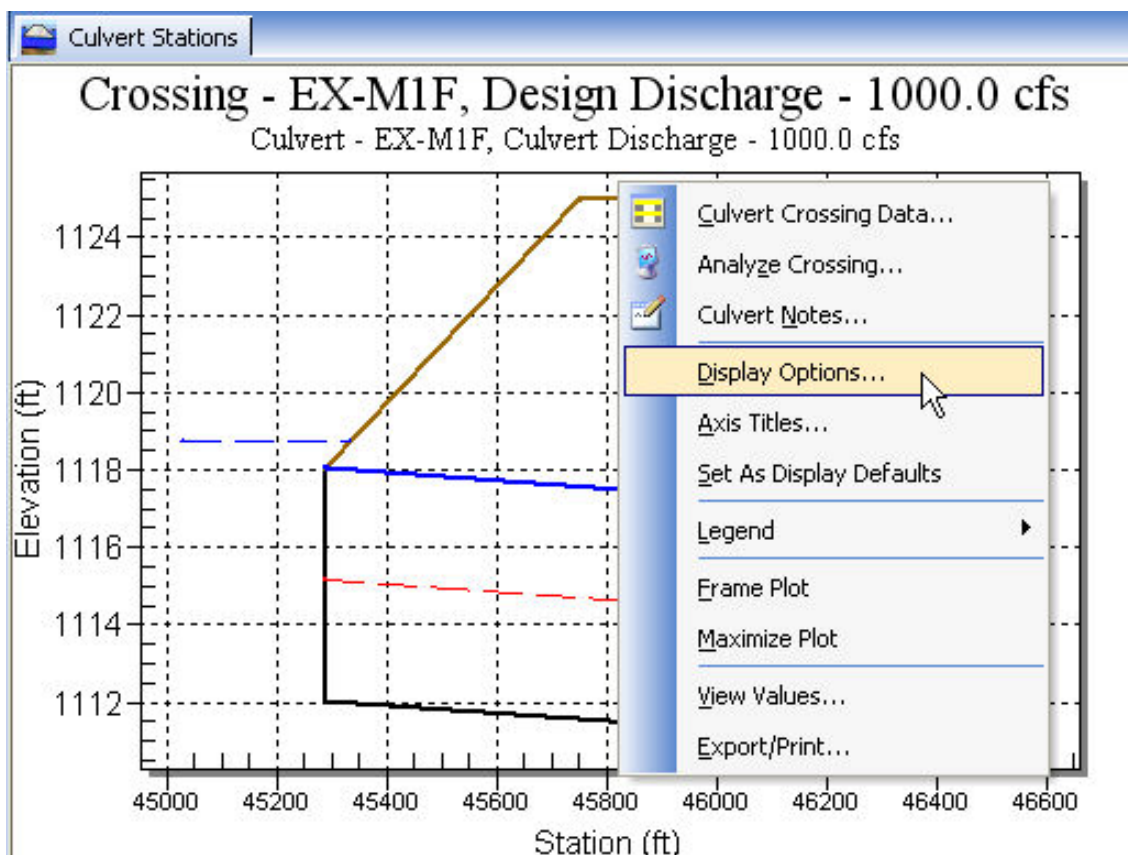
The customized table is set up by the user by clicking on the options button when the customized table feature is selected. The figure below shows the different variables that can be displayed in the culvert summary, profile, and tapered inlet tables.



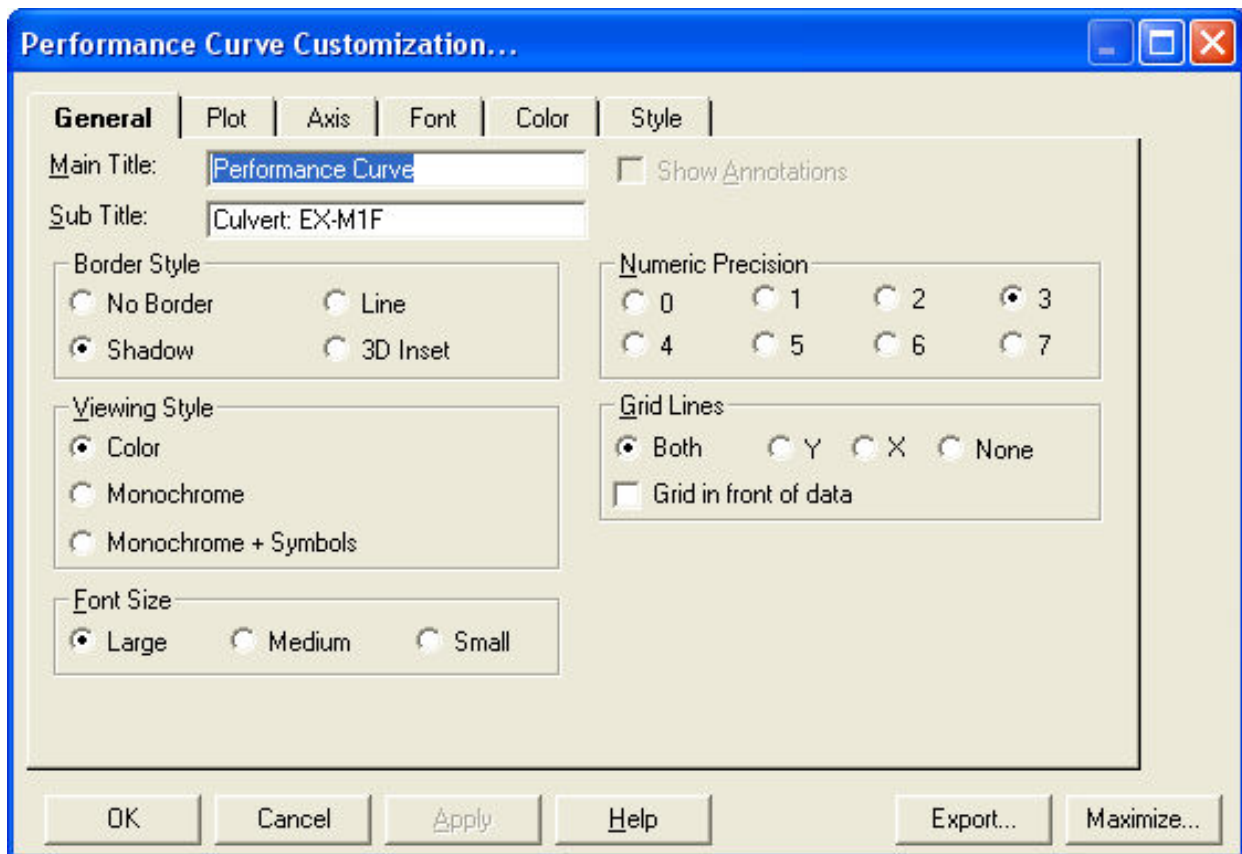
Controlling Plot Display Options

The available plots in HY-8 are managed by the user through right-clicking in the plot window. Because the same plot library is used for all plots (culvert profiles, front views, performance curves, etc.) they can all be controlled in the same fashion, but the menus are slightly different depending on the plot. For example the right-click menu for the front and side views of the main HY-8 window include menus for editing the culvert crossing data, analyzing the culvert crossing, and defining culvert notes. The right-click menu for a performance curve would not include these menus.

However, it should be emphasized that changing the display options of a plot window DOES NOT alter the hydraulic computations, it only modifies the display of currently computed values.



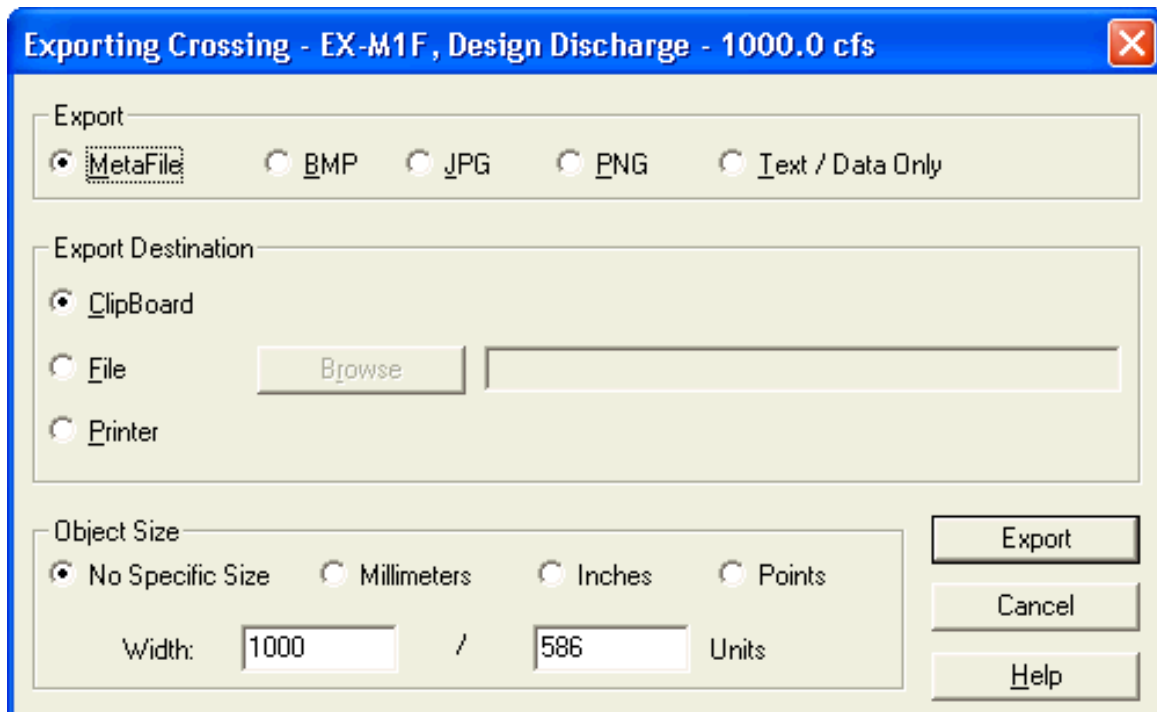
The right-click menu provides options for the user to control the *Display Options* of the plot. These options include the ability to modify fonts, symbols, colors, axis ranges and titles, legends, exporting, and more as shown in the *Display Options* dialog below.



Some of the more commonly used options like axis titles, legends, and exporting are available directly from the right-click menu.

Exporting and Printing

The plot may be exported to three different locations: the system clipboard, a file, or printer. You can also export to the following formats: MetaFile, BMP, JPG, PNG, Text. The text format is a table of the values that are plotted. These can be viewed by right-clicking on the plot, and selecting View Values. If you are exporting a MetaFile, BMP, JPG, or PNG, You can select the size of the image you wish to export.



Exporting Crossing - EX-M1F, Design Discharge - 1000.0 cfs

Export

☒ MetaFile ☐ BMP ☐ JPG ☐ PNG ☐ Text / Data Only

Export Destination

☒ Clipboard

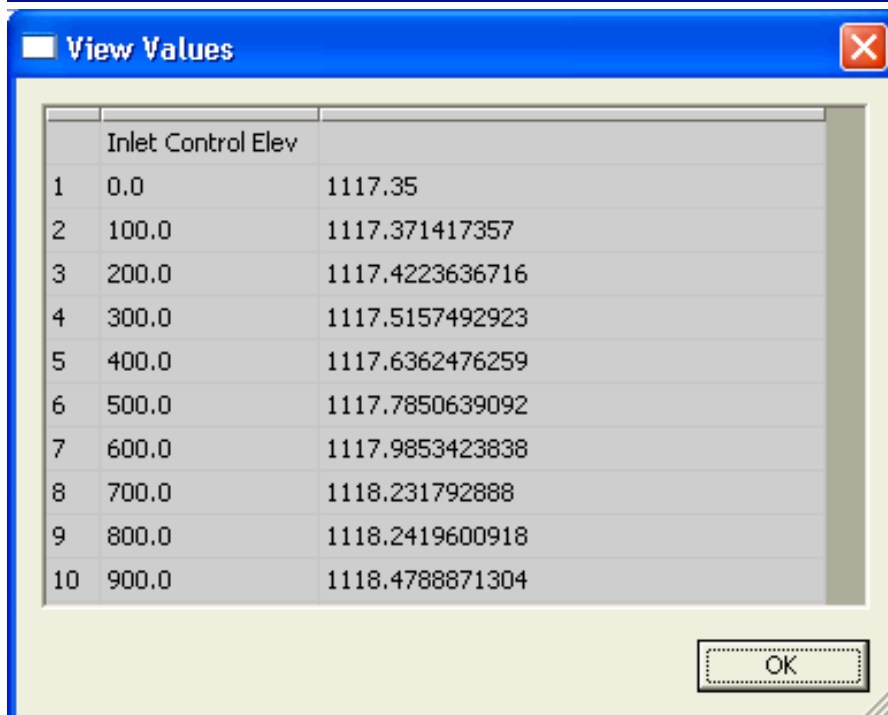
☐ File

☐ Printer

Object Size

☒ No Specific Size ☐ Millimeters ☐ Inches ☐ Points

Width: / Units



View Values

	Inlet Control Elev	
1	0.0	1117.35
2	100.0	1117.371417357
3	200.0	1117.4223636716
4	300.0	1117.5157492923
5	400.0	1117.6362476259
6	500.0	1117.7850639092
7	600.0	1117.9853423838
8	700.0	1118.231792888
9	800.0	1118.2419600918
10	900.0	1118.4788871304

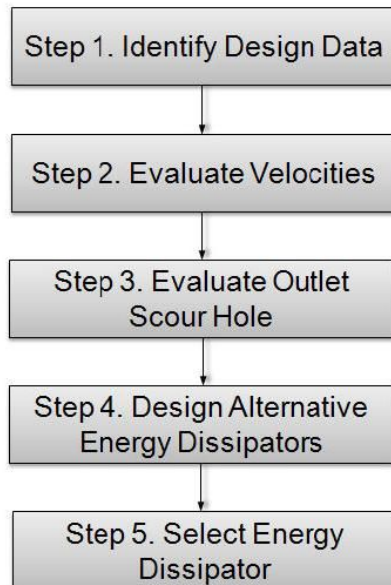
Zooming and Panning

To zoom in on a part of a plot, drag a box over the area you wish to see. There is no zoom out tool. To view the entire image, right-click on the plot and select *Frame Plot*. You can also view the plot in Full-Screen mode by right-clicking on the plot and selecting *Maximize Plot*. To exit Full-Screen mode, press escape.

6. Energy Dissipation

Energy Dissipators

Hydraulic Engineering Circular No. 14 (HEC-14) describes several energy dissipating structures that can be used with culverts. HEC-14 describes procedures that can be used to compute scour hole sizes and design internal and external dissipators. It outlines the following steps that can be used when designing a culvert:



HEC-14 also describes the energy dissipators and their limitations as follows:

Chapter	Dissipator Type	Froude Number ^[1] (Fr)	Allowable Debris ^[2]			Tailwater (TW)
			Silt/Sand	Boulders	Floating	
4	Flow transitions	na	H	H	H	Desirable
5	Scour hole	na	H	H	H	Desirable
6	Hydraulic jump	> 1	H	H	H	Required
7	Tumbling flow ^[3]	> 1	M	L	L	Not needed
7	Increased resistance ^[4]	na	M	L	L	Not needed
7	USSBR Type IX baffled apron	< 1	M	L	L	Not needed
7	Broken-back culvert	> 1	M	L	L	Desirable
7	Outlet weir	2 to 7	M	L	M	Not needed
7	Outlet drop/weir	3.5 to 6	M	L	M	Not needed
8	USBR Type II stilling basin	4.5 to 17	M	L	M	Required
8	USBR Type IV stilling basin	2.5 to 4.5	M	L	M	Required
8	SAF stilling basin	1.7 to 17	M	L	M	Required
9	CSU rigid boundary basin	< 3	M	L	M	Not needed
9	Contra Costa basin	< 3	H	M	M	< 0.5D

9	Hook basin	1.8 to 3	H	M	M	Not needed
9	USBR Type VI impact basin ^[5]	na	M	L	L	Desirable
10	Riprap basin	< 3	H	H	H	Not needed
10	Riprap apron ^[6]	na	M	L	L	Desirable
11	Straight drop structure ^[7]	< 1	H	L	M	Required
11	Box inlet drop structure ^[8]	< 1	H	L	M	Required
12	USACE stilling well	na	M	L	N	Desirable

[1] At release point from culvert or channel

[2] Debris notes: N = none, L = low, M = moderate, H = heavy

[3] Bed slope must be in the range $4\% < S_o < 25\%$

[4] Check headwater for outlet control

[5] Discharge, $Q < 11 \text{ m}^3/\text{s}$ (400 ft³/s) and Velocity, $V < 15 \text{ m/s}$ (50 ft/s)

[6] Culvert rise less than or equal to 1500 mm (60 in)

[7] Drop < 4.6 m (15 ft)

[8] Drop < 3.7 m (12 ft)

na = not applicable.

6.1. Scour Hole Geometry

Scour Hole Geometry

The scour hole geometry presented in this screen represents the local scour at the outlet of structures based on soil and flow data and culvert geometry. Chapter 5 of FHWA publication HEC 14, Hydraulic Design of Energy Dissipators for Culverts and Channels, dated July 2006, presents the general concept and equations used by the program to compute the scour hole geometry for cohesive and cohesionless materials.

NOTE—A soil analysis should be performed prior to running this option of the program.

For Cohesive soils, the program requires the following parameters:

- Time to Peak—Enter the value obtained in the 'HYDROLOGY' option of HY-8 (If unknown enter 30 minutes).
- Saturated Shear Strength—Obtained by performing test no. ASTM D211-66-76.
- Plasticity Index—Obtained by performing test no. ASTM D423-36.

For Cohesionless soils, the program requires the following parameters:

- Time to Peak—Enter the value obtained in the 'HYDROLOGY' option of HY-8 (If unknown enter 30 minutes).
- D16, D84—Soil particle diameters which represent percent of particles finer.

Note on Time to Peak

The time of scour is estimated based upon knowledge of peak flow duration. Lacking this knowledge, it is recommended that a time of 30 minutes be used in Equation 5.1. The tests indicate that approximately 2/3 to 3/4 of the maximum scour depth occurs in the first 30 minutes of the flow duration. The exponents for the time parameter in Table 5.1 reflect the relatively flat part of the scour-time relationship ($t > 30$ minutes) and are not applicable for the first 30 minutes of the scour process.

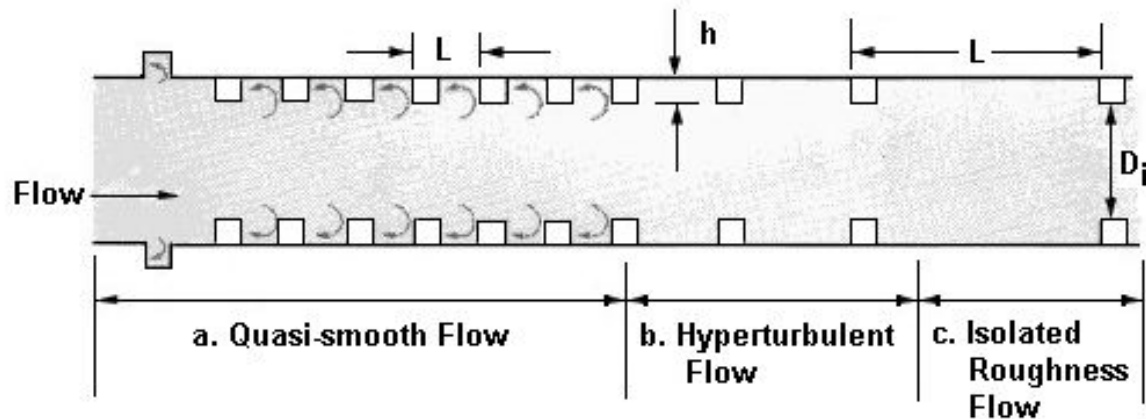
6.2. Internal Energy Dissipators

Increased Resistance in Box Culverts

The input variables required for this calculation are the following:

- h/r_i —Ratio of roughness element height divided by hydraulic radius taken about the top of the roughness element.
- Height of the roughened section (h)

The following figure shows the flow regimes and variables for an increased resistance energy dissipator implemented in a circular culvert.



Variables from the figure

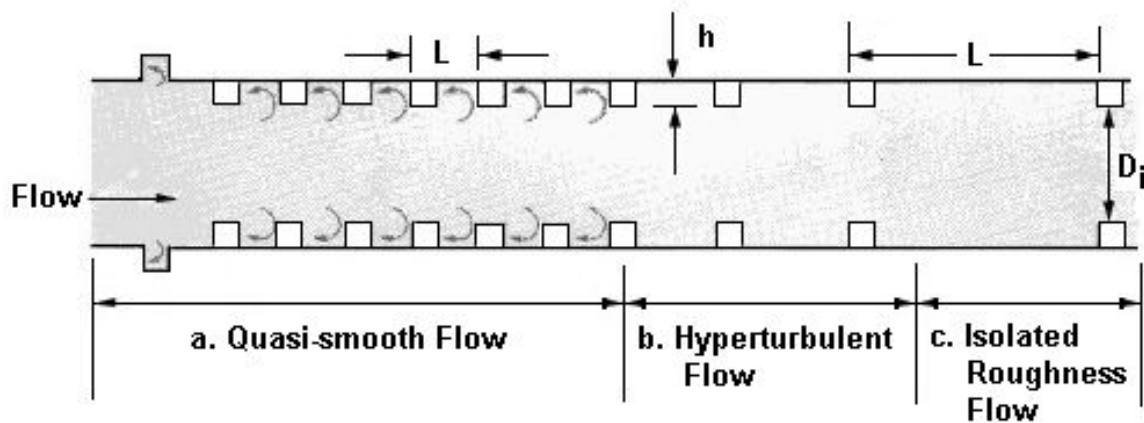
- L —Length from beginning of one roughness element to the beginning of the next roughness element.
- h —height of roughness element
- D_i —diameter of roughened section (opening)

Increased Resistance in Circular Culverts

The input variables required for this calculation is the following:

- L/D_i — Ratio of roughness element spacing divided by the diameter of the culvert opening at the roughness element. (Range = .05 to 1.5)
- h/D_i — Ratio of roughness element height divided by the diameter of the culvert opening at the roughness element. (Range = .005 to .1).
- L_r/P_i — Ratio of the roughness length to inside perimeter (Range = 0.0 to 1.0)
- Diameter of roughened section (Opening, D_i)

The following figure shows the flow regimes and variables for an increased resistance energy dissipator implemented in a circular culvert.



Variables from the figure

- L — Length from beginning of one roughness element to the beginning of the next roughness element.
- h — height of roughness element
- D_i — diameter of roughened section (opening)

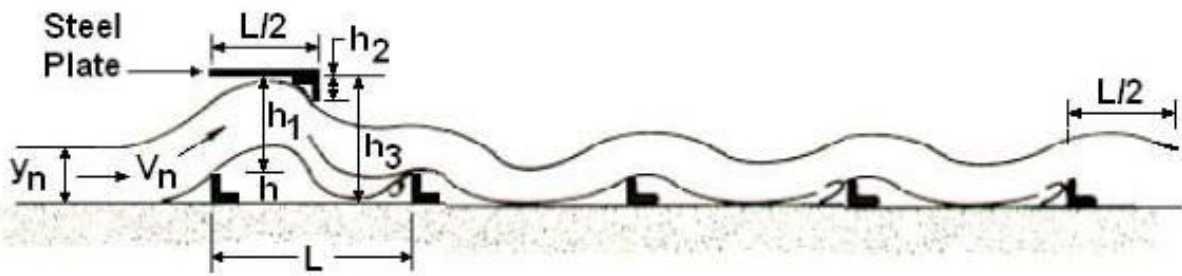
Tumbling Flow in Box Culverts

The input variables required for this calculation is the following:

Roughness Spacing to Height Ratio — The user must select a value of either 8.5 or 10 for the ratio of roughness element spacing divided by roughness element height. If after calculations the flow through the roughened section of the culvert impacts on the culvert roof, then the minimum enlarged section height needed to correct this problem will be given and the user will be prompted to enter a value equal to or larger than this minimum value.

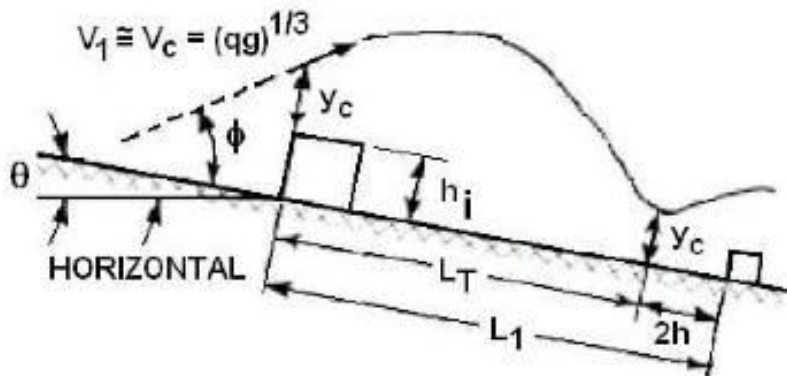
Height, which must be equal to or greater than the height of the culvert.

The following figures show two configurations of tumbling flow dissipators.



Variables from the figure

- L — Length from beginning of one roughness element to the beginning of the next roughness element.
- h — Height of roughness element
- h_1 — Distance from top of dissipator to ceiling of culvert
- h_2 — Height of splash shield on ceiling of culvert
- h_3 — Culvert rise
- y_n — Tailwater depth



Variables from the figure

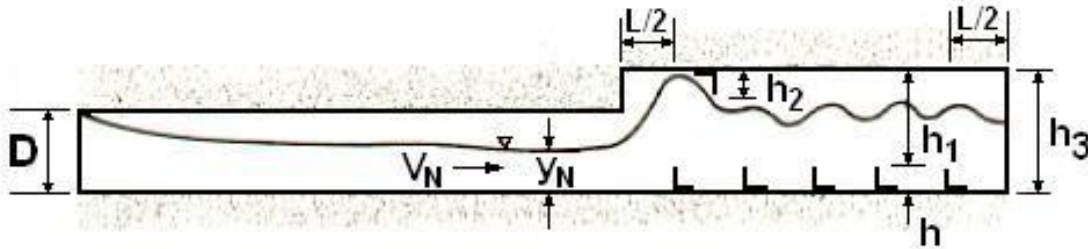
- L_1 — Length from beginning of one roughness element to the beginning of the next roughness element.
- L_T — Transition Length
- h_i — Height of roughness element
- y_c — Critical depth
- θ — slope of the culvert bottom expressed in degrees
- ϕ — jet angle, taken as 45 degrees

Tumbling Flow in Circular Culverts

The only input variable required for this calculation is the following:

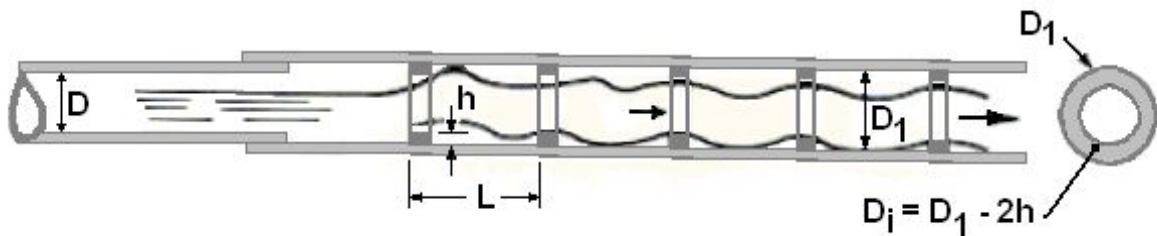
- Diameter of enlarged culvert

The following figures show implementations of tumbling flow within circular culverts along with the variables used to design the energy dissipator.



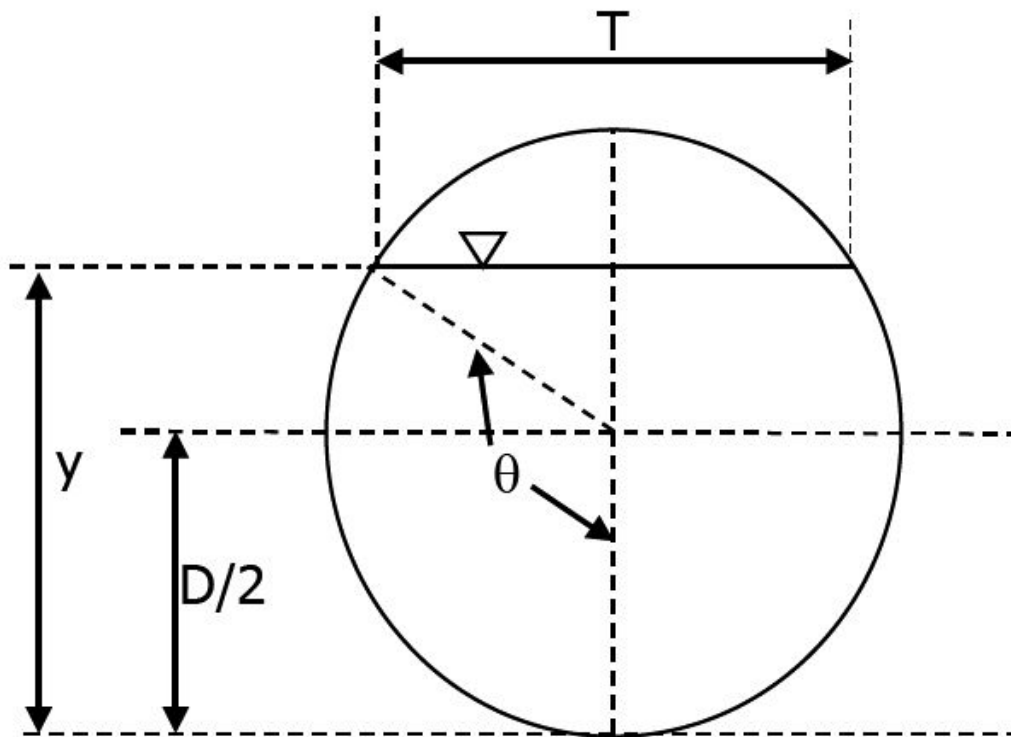
Variables from the figure

- D — Diameter of original culvert
- V_n — Tailwater velocity
- y_n — Tailwater depth
- L — Length from beginning of one roughness element to the beginning of the next roughness element.
- h — Height of roughness element
- h_1 — length from top of roughness element to enlarged culvert ceiling
- h_2 — height of splash shield on enlarged culvert ceiling.
- h_3 — rise of enlarged culvert.



Variables from the figure

- D — Diameter of original culvert
- D_1 — Diameter of enlarged culvert
- D_i — Diameter of roughened section
- h — Height of roughness element
- L — Length from beginning of one roughness element to the beginning of the next roughness element.



Variables from the figure

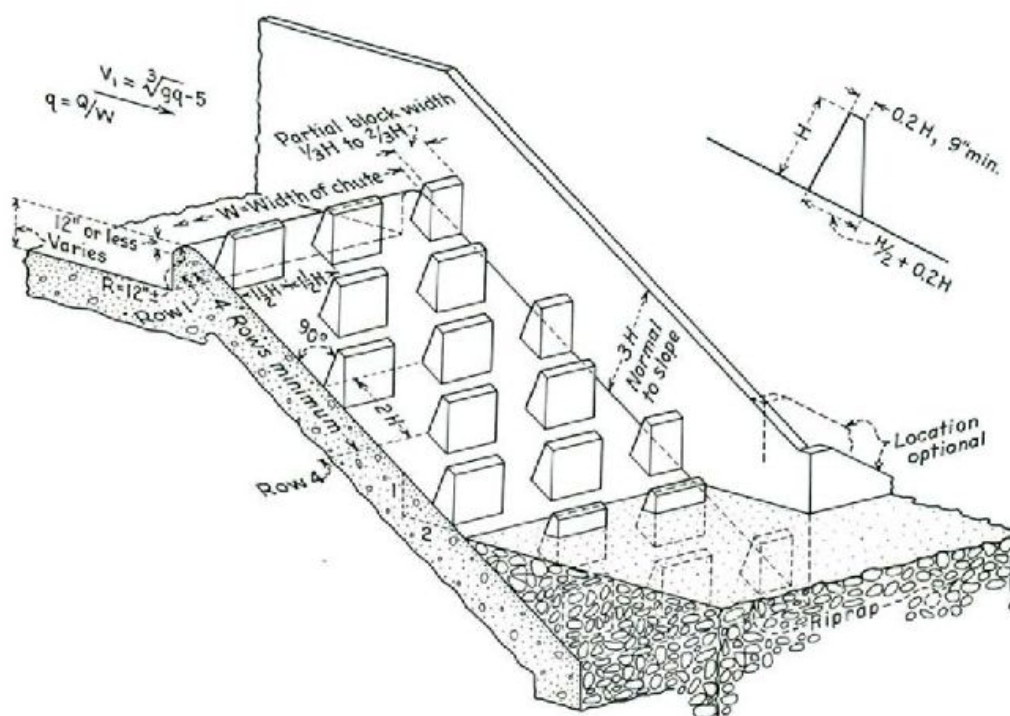
- D — Diameter of original culvert
- T — Water surface width at critical flow condition
- y — Depth of flow

USBR Type IX Baffled Apron

The input variables required for this calculation is the following:

- Approach Channel Slope
- Vertical Drop Height
- Baffled Apron Slope
- Baffled Apron Width

The following figure shows a USBR Type IX Baffled Apron.



Variables from the figure

- H — height of the dissipator
- W — Width of Chute

6.3. External Dissipators

6.3.1. Drop Structures

Drop Structures

Drop structures are commonly used for flow control and energy dissipation. Their main purpose is to change the slope from steep to mild by placing drop structures at intervals along the channel reach. Two types of Drop Structure External Dissipators are available:

- Box Inlet Drop Structure
- Straight Drop Structure

Box Inlet Drop Structure

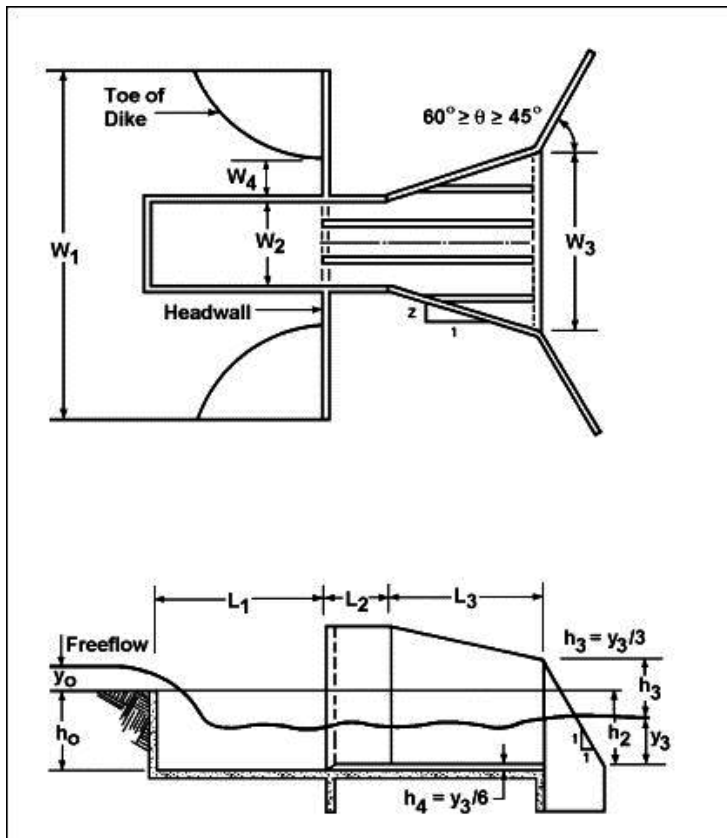
The input variables required for this calculation is the following:

- H_D — Desired drop height. Must be between 2 and 12 ft or between 0.6 and 3.7 m.
- New Slope — The slope that will exist on the channel once the drop structures are in place (The new slope must be subcritical).
- Box Length — Length of box inlet. (USER'S CHOICE)
- W_2 — Width of box inlet. Must fit criteria ($.25 < H_D/W_2 < 1$)
- W_3 — Width of the Downstream End of Stilling Basin. This must be equal to or larger than the culvert width.

Flare of Stilling Basin (1 Lateral: Z long) — This value must be greater than or equal to 2, which is to say 1 lateral: 2 Long)

Length from Toe of Dike to Box Inlet — If a dike is used, the distance from the toe of the dike to the box inlet must be entered. If no dike is used, enter a value of 100 ft or 30.48 m for this distance.

The following figure shows a plan and side view of a box inlet drop structure.



Variables from the figure

- W_1 — Width of the upstream end of the basin
- W_2 — Width of box inlet crest
- W_3 — Width of the downstream end of the basin
- W_4 — Distance from the toe of dike to the box inlet
- L_1 — Length of box inlet
- L_2 — Minimum length for the straight section
- L_3 — Minimum length for final section (potentially flared)
- H_0 — Drop from crest to stilling basin floor
- h_2 — Vertical distance of the tailwater below the crest
- h_3 — Height of the end sill
- y_0 — Required head on the weir crest to pass the design flow
- y_3 — Tailwater depth above the floor of the stilling basin
- h_4 — Sill height

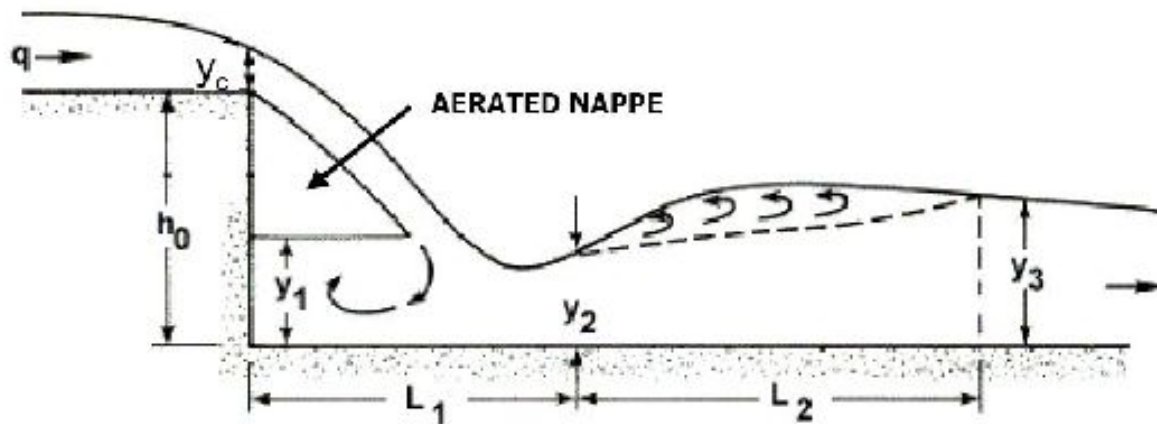
Straight Drop Structure

The input variables required for this calculation is the following:

Drop Height — The vertical drop height from structure crest to channel bottom. In the final design, the drop height to the basin bottom is given. The difference between the two is the amount the basin is suppressed below the channel bottom.

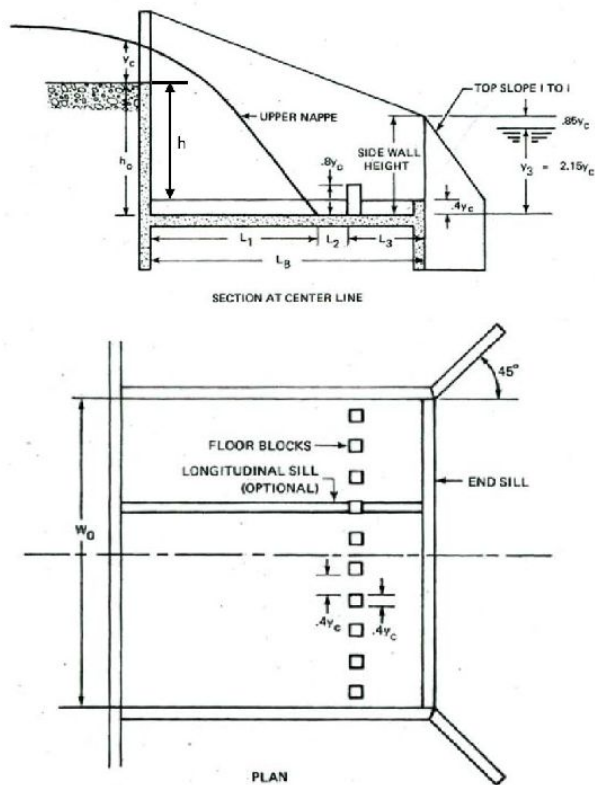
New Slope — The slope that will exist on the channel once the drop structures are in place (the new slope must be subcritical).

The following figures show straight drop structures.



Variables from the figure

- q — Design Discharge
- y_c — Critical depth
- h_0 — Drop from crest to stilling basin floor
- y_1 — Pool depth under the nappe
- y_2 — Depth of flow at the tow of the nappe or the beginning of the hydraulic jump
- y_3 — Tailwater depth sequent to y_2
- L_1 — Distance from the headwall to the point where the surface of the upper nappe strikes the stilling basin floor
- L_2 — Distance from the upstream face of the floor blocks to the end of the stilling basin



Variables from the figure

- y_c — Critical depth
- h_0 — Drop from crest to stilling basin floor
- h — Vertical drop between the approach and tailwater channels
- y_1 — Pool depth under the nappe
- y_2 — Depth of flow at the tow of the nappe or the beginning of the hydraulic jump
- y_3 — Tailwater depth sequent to y_2
- L_1 — Distance from the headwall to the point where the surface of the upper nappe strikes the stilling basin floor
- L_2 — Distance from the upstream face of the floor blocks to the end of the stilling basin
- L_3 — distance from the upstream face of the floor blocks to the end of the stilling basin
- L_B — Stilling basin length

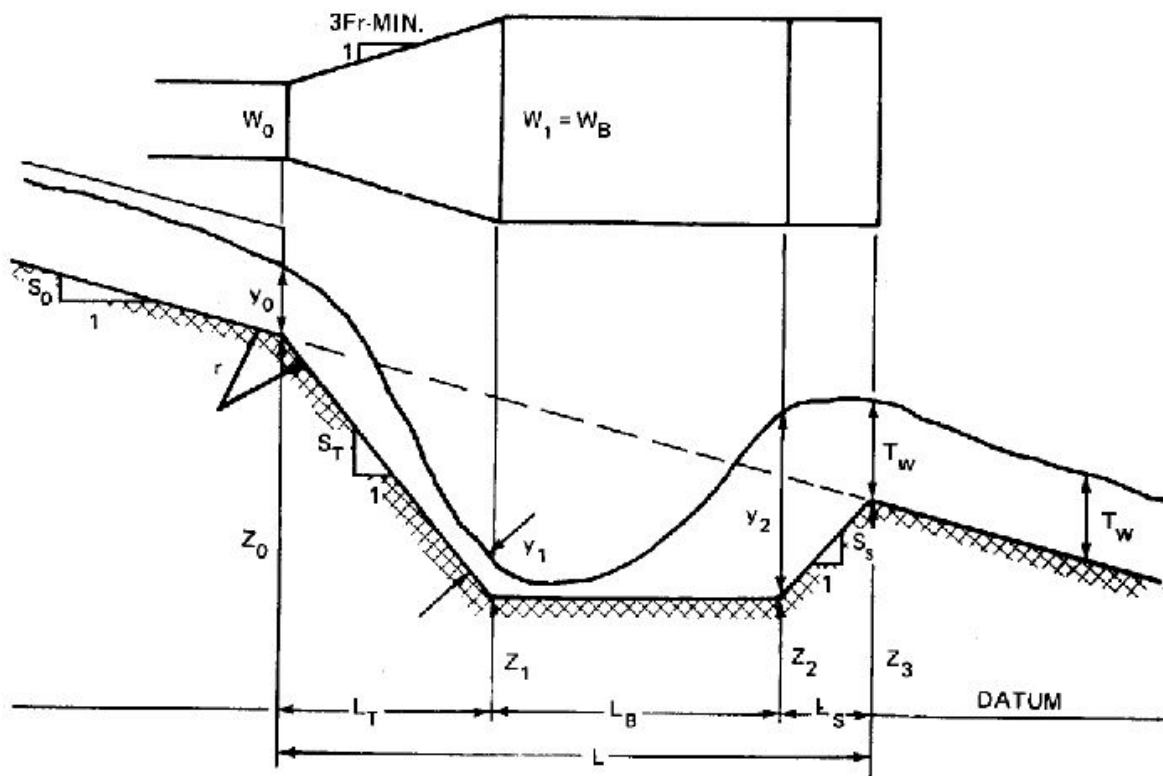
6.3.2. Stilling Basin

Stilling Basins

The four types of Stilling Basins External Energy Dissipators available in the program:

- USBR Type III Stilling Basin
- USBR Type IV Stilling Basin
- St. Anthony Falls (SAF) Stilling Basin

The maximum width of an efficient 'USBR' type stilling basin is limited by the width that a jet of water would flare naturally on the basin foreslope. The user is given the maximum flare value and is prompted to enter a basin width smaller than this value. If a 'SAF' basin is used, the basin width is set equal to the culvert width and the user is prompted to choose either a rectangular or flared basin depending on site conditions. Stilling Basins resemble the following illustration.



Variables from the figure

- W_0 — width of the channel
- W_B — Width of the basin
- y_0 — Culvert outlet depth
- y_1 — Depth entering the basin
- y_2 — Conjugate depth
- S_0 — Slope of the channel
- S_T — Slope of the transition
- S_S — Slope leaving the basin

- Z_0 — ground elevation at the culvert outlet
- Z_1 — ground elevation at the basin entrance
- Z_2 — ground elevation at the basin exit
- Z_3 — Elevation of basin at basin exit (sill)
- L_T — Length of transition from culvert outlet to basin
- L — Total basin length
- L_B — Length of the bottom of the basin
- L_S — Length of the basin from the bottom of the basin to the basin exit (sill)
- T_w — Tailwater depth leaving the basin

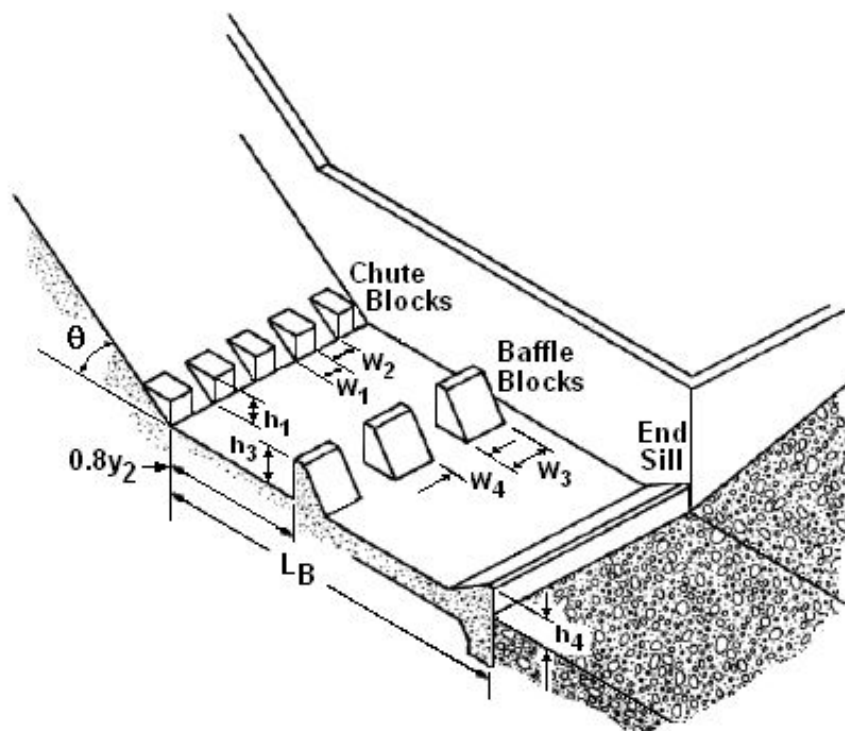
Warning for Stilling Basin Width

Since the maximum basin width is a function of basin depth, the maximum width may decrease as the program increases the basin depth while converging on a solution. Therefore the maximum basin width may fall below the user's first choice for basin width. In this case, the user will be prompted for a new basin width.

USBR Type III Stilling Basin

The only input variable required for this calculation is the following:

- Basin Width



Variables from the figure

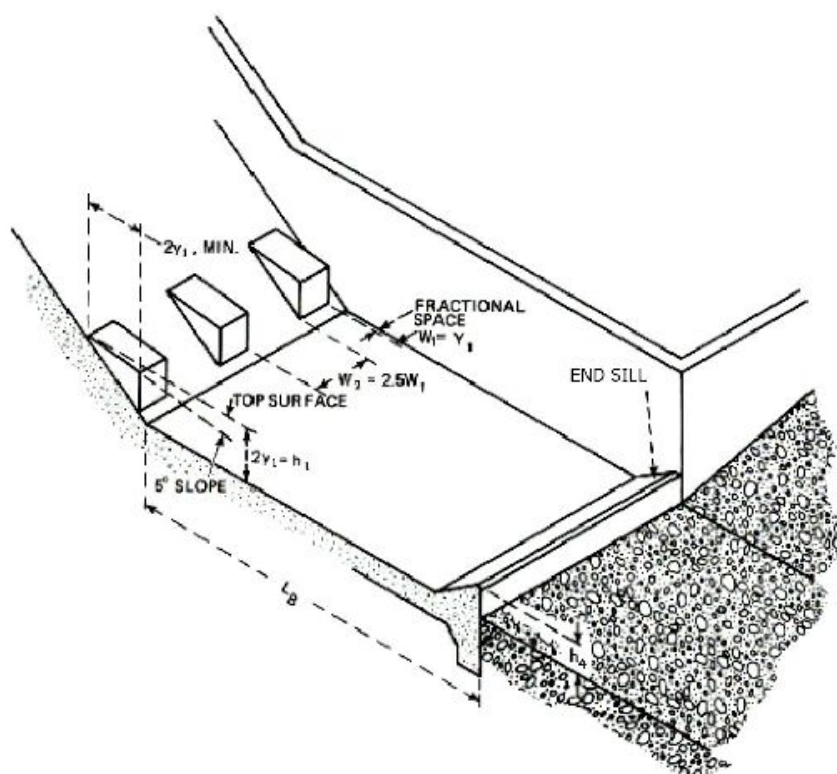
- W_1 — width of the chute blocks
- W_2 — space between chute blocks
- h_1 — height of the chute blocks
- W_3 — width of the baffle blocks

- W_4 — space between chute blocks
- h_3 — height of the baffle blocks
- h_4 — height of the end sill
- L_B — Length of the bottom of the basin
- y_2 — Conjugate depth

USBR Type IV Stilling Basin

The only input variable required for this calculation is the following:

- Basin Width



Variables from the figure

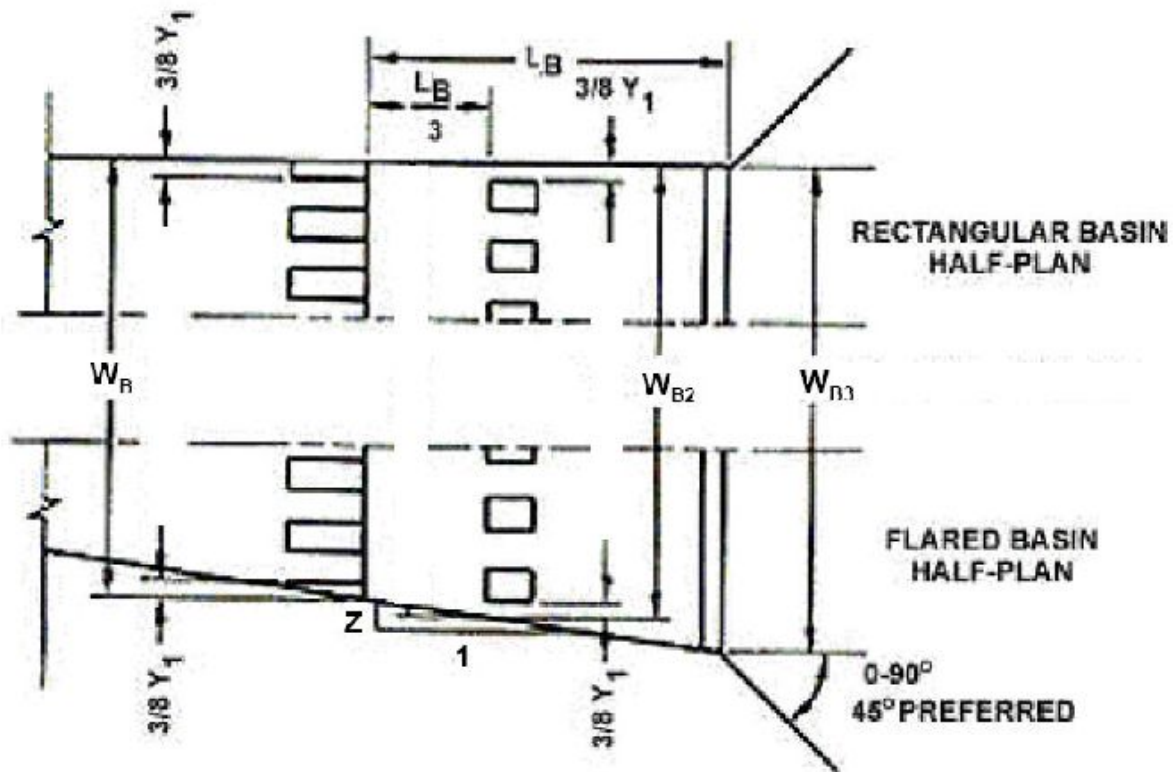
- y_1 — height of the chute blocks
- h_1 — width of the chute blocks
- h_4 — Height of the end sill
- W_1 — space between chute blocks
- W_2 — height of the end sill
- L_B — Length of the bottom of the basin

Saint Anthony Falls (SAF Stilling Basin)

The input variables required for this calculation is the following:

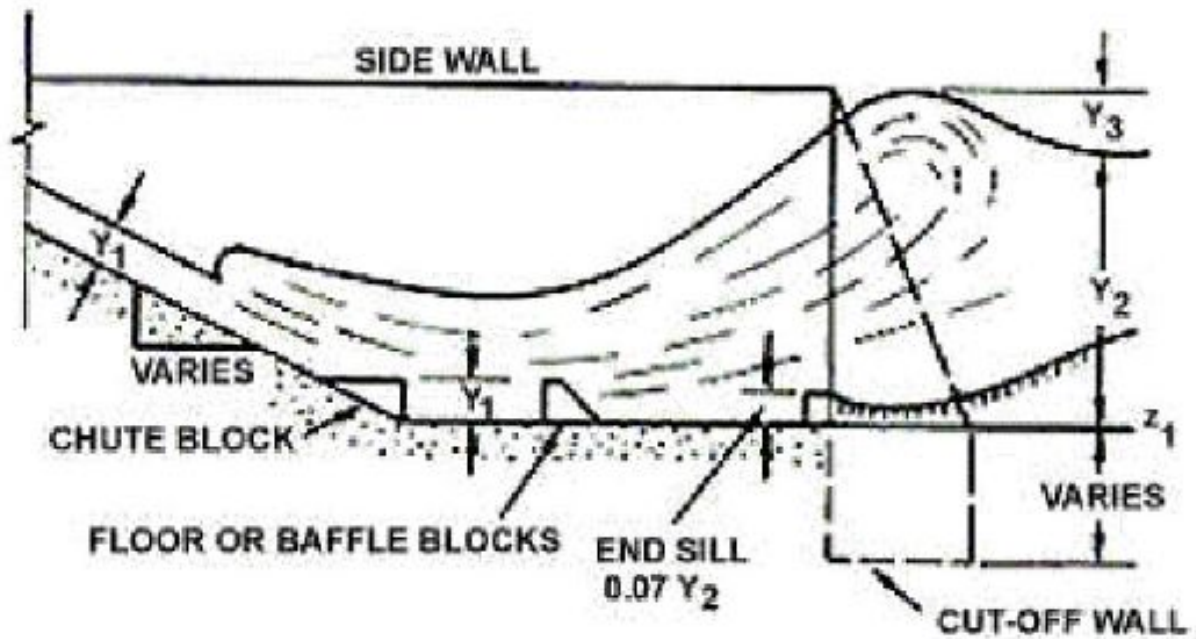
- Shape (Flared or Rectangular)
- Sidewall Flare — This will only apply if the basin has a flared shape

The following figure shows a Saint Anthony Falls stilling basin.



Variables from the figure

- W_B — Basin width
- W_{B2} — Basin width at the baffle row
- W_{B3} — Basin width at the sill
- Y_1 — height of the chute blocks
- L_B — Length of the basin
- Z -- basin flare



Variables from the figure

- Y_1 — height of the chute blocks
- Y_2 — Conjugate height
- Y_3 — height of the chute blocks
- z_1 — elevation of basin floor

6.3.3. Streambed level Structures

Streambed Level Structures

The five types of At-Stream-Bed Structure External Energy Dissipators are available in the program:

- Colorado State University (CSU) Rigid Boundary Basin
- Riprap Basin and Apron
- Contra Costa Basin
- Hook Basin
- USBR Type VI Impact Basin

Colorado State University (CSU) Rigid Boundary Basin

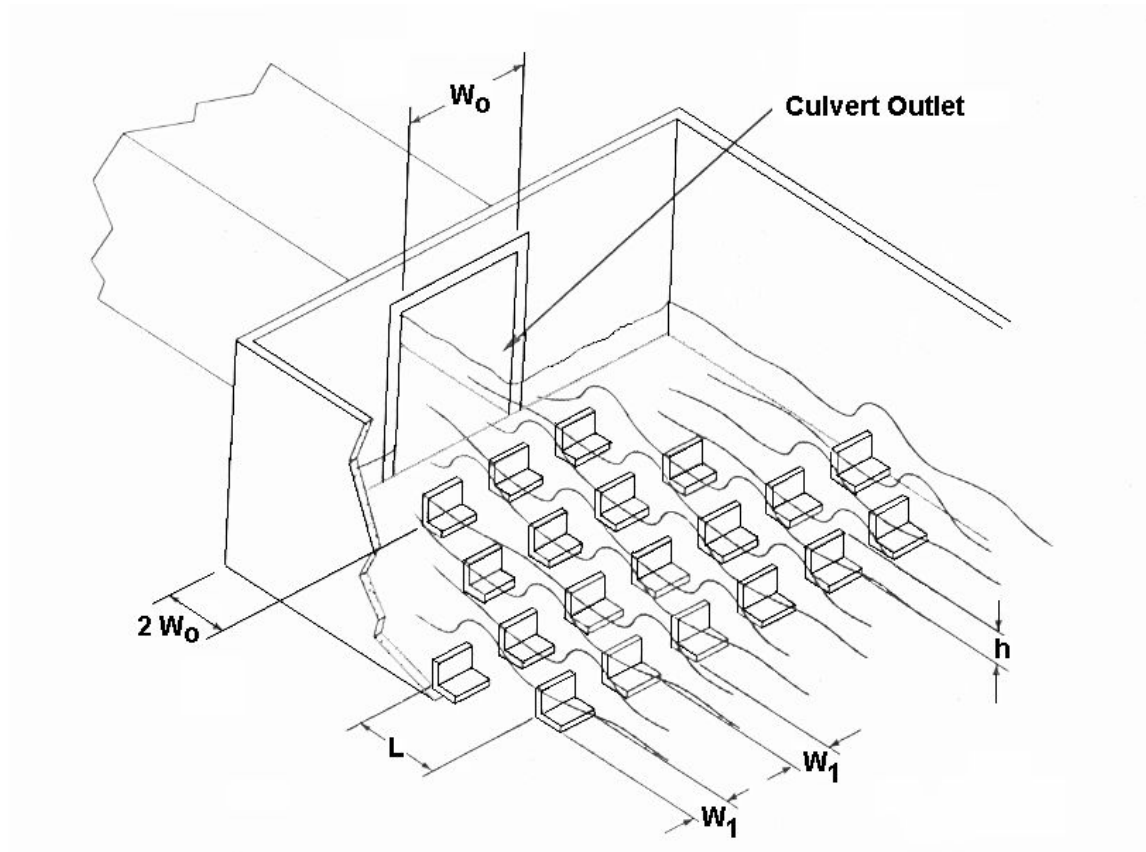
Colorado State University (CSU) Rigid Boundary Basin

No input variables are required for this calculation; however, one design is selected by the user.

All possible designs for CSU Rigid Boundary Basins are calculated for the given culvert and flow. Designs which do not dissipate sufficient energy are discarded. The criteria of the remaining designs are numbered and displayed one at a time.

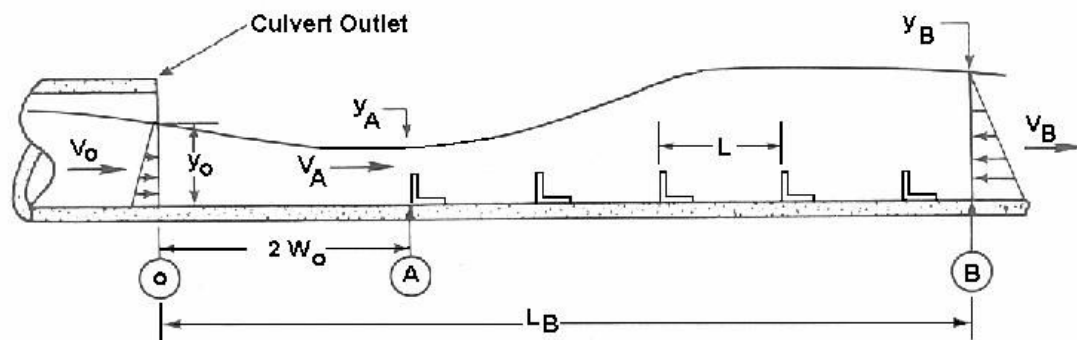
Designs are calculated and displayed in order of increasing width, increasing number of element rows, and increasing element height. As a result, smaller, less expensive designs are presented first.

The following figures show a Colorado State University (CSU) Rigid Boundary Basin



Variables from the figure

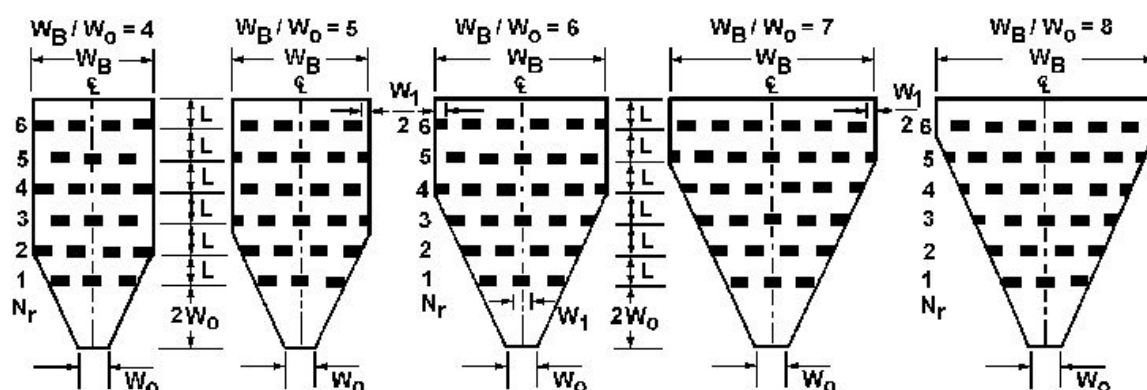
- W_0 — Culvert width at culvert outlet
- W_1 — Element width which is equal to element spacing
- h — Roughness element height



Variables from the figure

- V_0 — Velocity at the culvert outlet
- V_A — Approach velocity at two culvert widths downstream of the culvert outlet
- V_B — Exit velocity, just downstream of the last row of roughness elements
- y_0 — Depth at the culvert outlet
- y_A — Approach depth at two culvert widths downstream of the culvert outlet
- y_B — Depth at exit
- W_0 — Culvert width at the culvert outlet
- L_B — Total basin length

- L — Longitudinal spacing between rows of elements



Variables from the figure

- W_B — Width of basin
- W_0 — Culvert width at the culvert outlet
- L — Longitudinal spacing between rows of elements
- N_r — Row number

W_B/W_0			2 to 4			5			6			7		8
W_I/W_0			0.57			0.63			0.6			0.58		.62
Rows (N_r)			4	5	6	4	5	6	4	5	6	5	6	6
Elements (N)			14	17	21	15	19	23	17	22	27	24	30	30
Rectangular	h/y_A	L/h	Basin Drag Coefficient, C_B											
	.91	6	0.32	0.28	0.24	0.32	0.28	0.24	0.31	0.27	0.23	0.26	0.22	0.22
	.71	6	0.44	0.40	0.37	0.42	0.38	0.35	0.40	0.36	0.33	0.34	0.31	0.29
	.48	12	0.60	0.55	0.51	0.56	0.51	0.47	0.53	0.48	0.43	0.46	0.39	0.35
	.37	12	0.68	0.66	0.65	0.65	0.62	0.60	0.62	0.58	0.55	0.54	0.50	0.45
Circular	0.91	6	0.21	0.20	0.48	0.21	0.19	0.17	0.21	0.19	0.17	0.18	0.16	
	0.71	6	0.29	0.27	0.40	0.27	0.25	0.23	0.25	0.23	0.22	0.22	0.20	
	0.31	6	0.38	0.36	0.34	0.36	0.34	0.32	0.34	0.32	0.30	0.30	0.28	
	0.48	12	0.45	0.42	0.25	0.40	0.38	0.36	0.36	0.34	0.32	0.30	0.28	
	0.37	12	0.52	0.50	0.18	0.48	0.46	0.44	0.44	0.42	0.40	0.38	0.36	

Riprap Basin and Apron

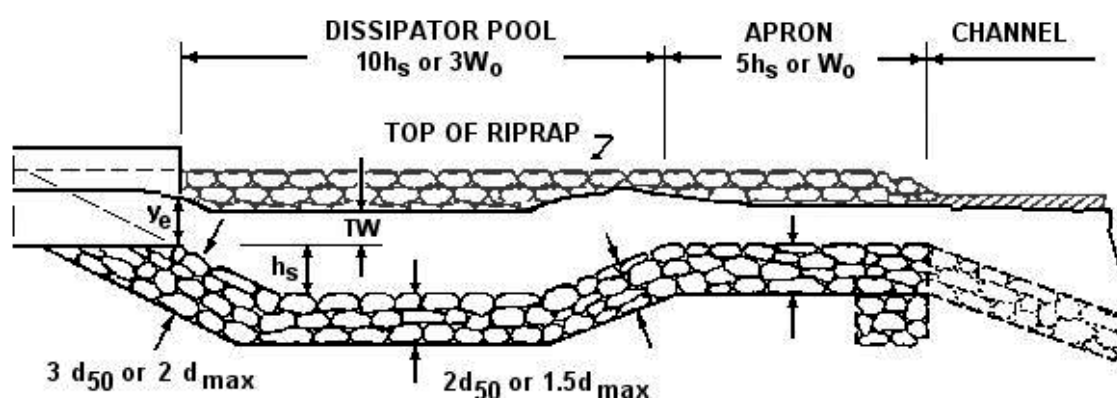
Riprap Basin and Apron

The input variables required for this calculation is the following:

- Condition to compute Basin Outlet Velocity — The user can select *Best Fit Curve* or *Envelope Curve*. The user should choose *Best Fit Curve* if the flow downstream of the basin is believed to be supercritical. If the flow downstream is believed to be subcritical, the user should choose *Envelope Curve*.
- D50 of the Riprap Mixture — Mean diameter (by weight) of the riprap to be used.
- DMax of the Riprap Mixture — Maximum diameter (by weight) of the riprap to be used.

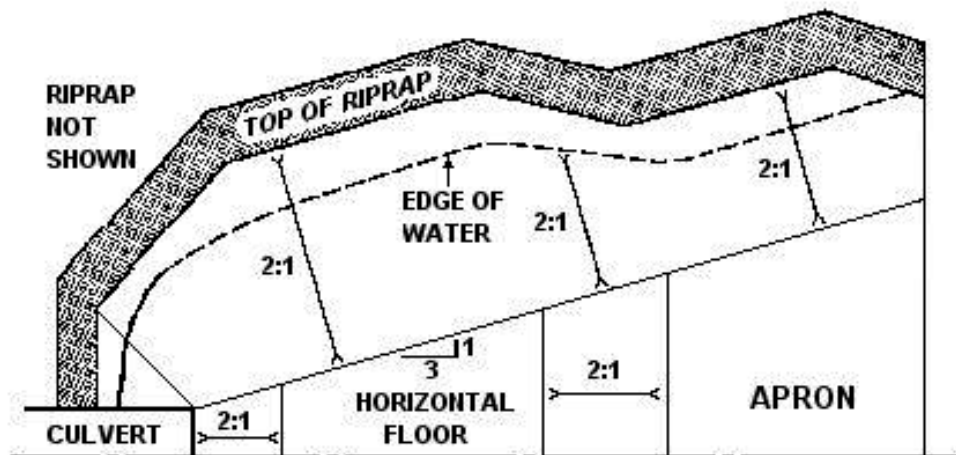
The design criteria for this basin was based on model runs in which D50/YE ranged from 0.1 to 0.7; values outside this range are rejected by the program.

The following figures show riprap basins and aprons.



Variables from the figure

- h_s — Dissipator pool depth
- W_0 — Culvert width
- TW — Tailwater depth
- y_e — Equivalent brink (outlet) depth
- d_{50} — Median rock size by weight
- d_{max} — Max rock size by weight



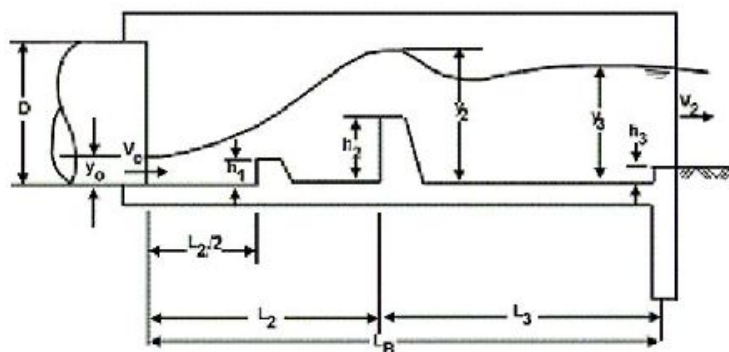
Contra Costa Basin

Contra Costa Basin

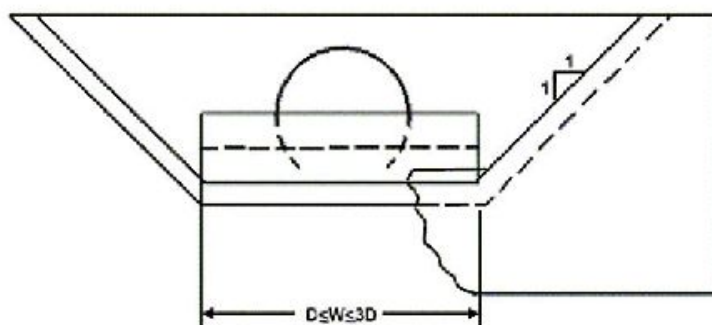
The input variables required for this calculation is the following:

- Baffle Block Height Ratio — The ratio of the baffle block height to baffle block distance from the culvert.
- End Sill Height to Maximum Depth Ratio — ratio to determine the end sill height from the maximum depth.
- Basin Width — The channel width is recommended for the basin width.

The following figures show the design of a Contra Costa basin.



Profile View



End View

Variables from the figure

- D — Diameter of culvert
- y_0 — Outlet depth
- y_2 — Approximate maximum water surface depth
- y_3 — Basin exit velocity
- V_0 — Outlet velocity
- V_2 — Exit velocity
- h_1 — Height of small baffle
- h_2 — Height of large baffle
- h_3 — Height of end sill
- L_2 — Length from culvert exit to large baffle
- L_3 — Length from large baffle to end sill
- L_B — Basin length

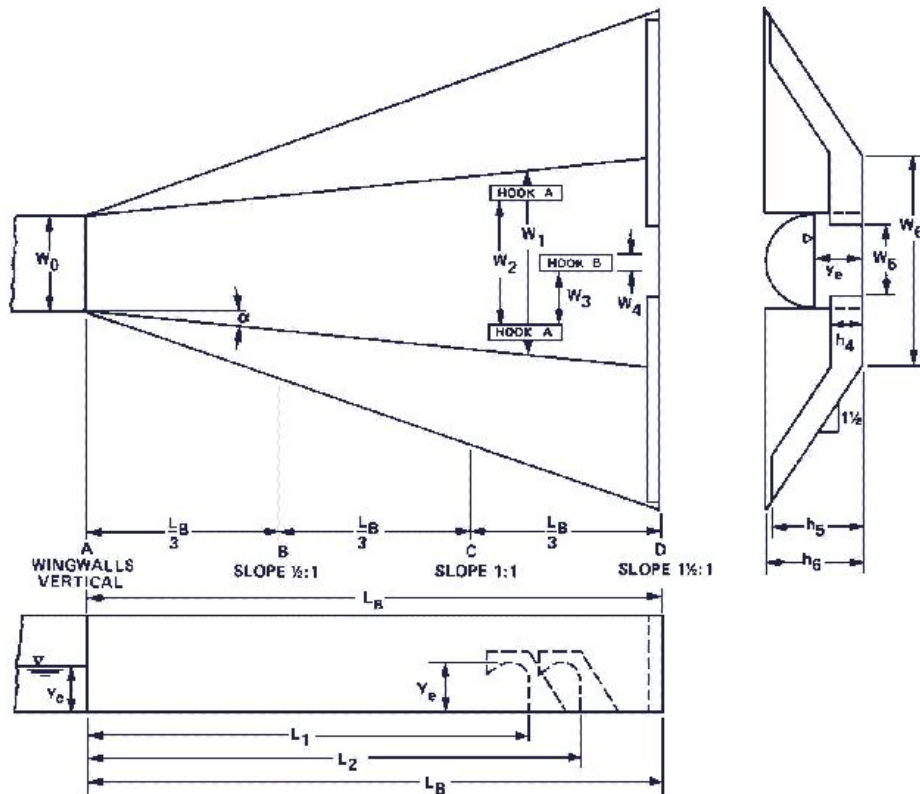
Hook Basin

Hook Basin

The input variables required for this calculation is the following:

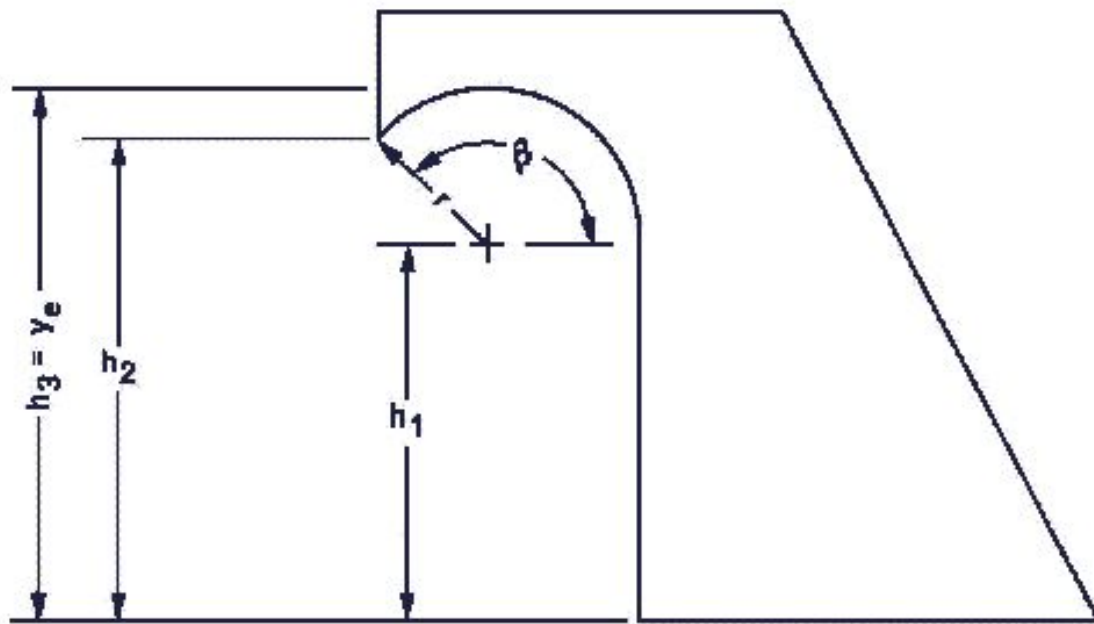
- Shape of Dissipator — The user can select 'Warped Wingwalls' or 'Trapezoidal'. See illustrations below for examples.
- Flare Angle (Warped Wingwalls only) — Flare angle per side of the basin.
- Ratio of Length to A-hooks over Total Basin Length (Warped Wingwalls only) — Distance from culvert exit to first row of hooks (A-HOOKS) divided by the total length of the basin.
- Ratio of Width to A-hooks over Total Basin Length (Warped Wingwalls only) — Distance between hooks in the first row divided by the basin width at the first row.
- Ratio of Length to B-Hooks over Total Basin Length (Warped Wingwalls only) — Distance from culvert exit to second row of hooks (B-HOOKS) divided by the total length of the basin.
- Width for the Downstream End of the Basin (Warped Wingwalls only)
- Basin Side Slope (Trapezoidal shape only) — The user can select either '1.5 : 1' or '2 : 1'.
- Basin Bottom Width (Trapezoidal shape only)

The next two figures show a hook basin with warped wingwalls:



Variables from the figure

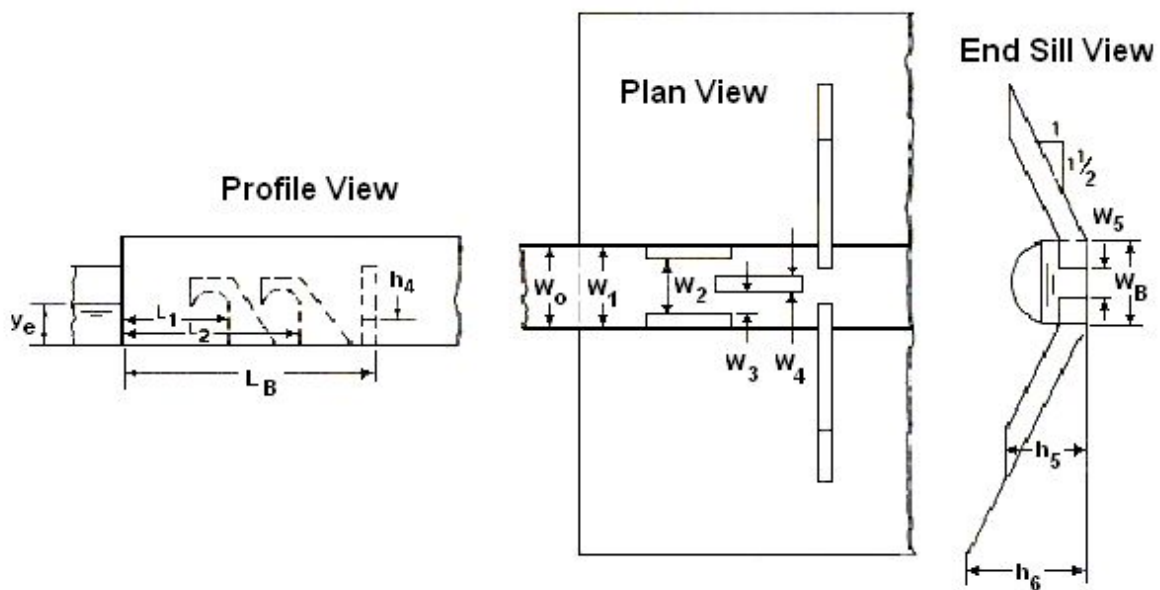
- W_0 — Outlet width
- W_1 — Width at first hooks
- W_2 — Distance between first hooks (row A)
- W_3 — lateral spacing between A and B hook
- W_4 — Width of hooks
- W_5 — Width of slot in end sill
- W_6 — approximately channel width
- h_4 — Height of end sill
- h_5 — Height to top of end sill
- h_6 — Height to top of warped wingwall
- y_e — Equivalent depth
- L_1 — Distance to first hooks
- L_2 — Distance to second hooks (row B)
- L_B — Basin length



Variables from the figure

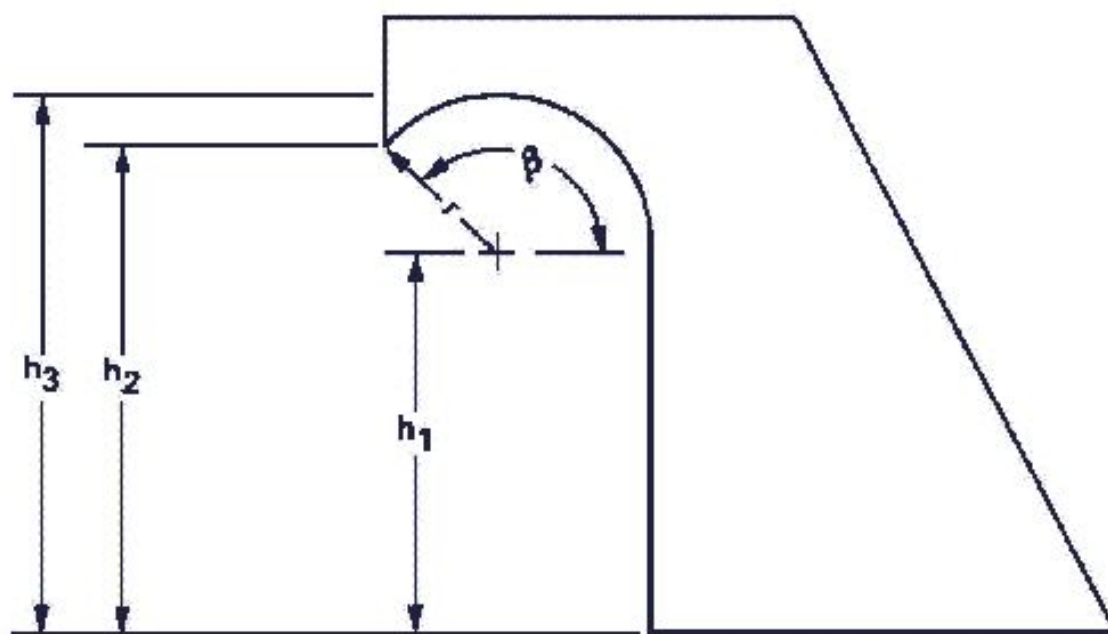
- β — Angle of radius
- r — radius
- h_1 — height to center of radius
- h_2 — Height to point
- h_3 — Height to top of radius
- y_e — Equivalent depth

The next two figures show a hook basin with a uniform uniform trapezoidal channel:



Variables from the figure

- W_0 — Outlet width
- W_1 — Width at first hooks
- W_2 — Distance between first hooks (row A)
- W_3 — lateral spacing between A and B hook
- W_4 — Width of hooks
- W_5 — Width of slot in end sill
- W_B — approximately channel width
- h_4 — Height of end sill
- h_5 — Height to top of end sill
- h_6 — Height to top of warped wingwall
- y_e — Equivalent depth
- L_1 — Distance to first hooks
- L_2 — Distance to second hooks (row B)
- L_B — Basin length



Variables from the figure

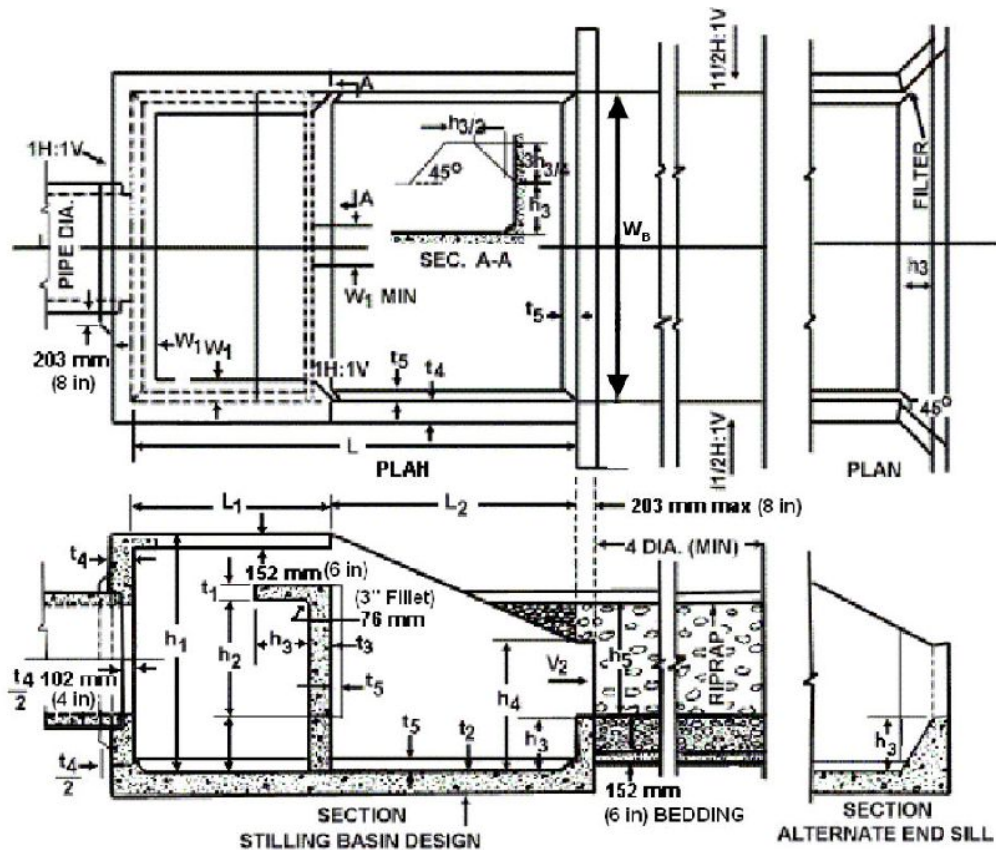
- β — Angle of radius
- r — radius
- h_1 — height to center of radius
- h_2 — Height to point
- h_3 — Height to top of radius

USBR Type VI Impact Basin

USBR Type VI Impact Basin

No input variables are required for this calculation.

The following figures show a USBR Type VI impact basin.



Variables from the figure

- W_B — Required basin width
- W_1 — Geometry design variable
- h_1 through h_5 — Geometry design variable
- t_1 through t_5 — Geometry design variable
- L_1 and L_2 — Geometry design variable
- L — Length of the Basin

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