HYDROCALC Hydraulics for Windows *by Dodson & Associates, Inc.*

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Program Description

The HYDROCALC Hydraulics for Windows program contains several main input screens/windows. Each window lets you perform analysis on a specific hydraulics structure.

These analysis include:

Trapezoidal Channel Analysis and **Circular Channel Analysis**: These procedures can compute the Normal Depth, Critical Depth, a Rating Curve, and a Standard Step Water Surface Profile for any Trapezoidal or Circular Channel.

Pipe Culvert Analysis and **Box Culvert Analysis**: These procedures can compute a Culvert Performance Curve using current Federal Highway Administration methods and equations.

Trapezoidal and Circular Channel Analysis

A **Trapezoidal Channel** has a flat bottom and sloping sides. Trapezoidal shapes are often used for man-made channels because they are relatively easy to construct and maintain, and provide good flow capacity. A **Circular Channel** is a segment of a round pipe or a semi-circular flume which is flowing part-full of water.

The Trapezoidal Channel Analysis can compute the **Normal Depth**, **Critical Depth**, **Rating Curve**, or **Standard Step Water Surface Profile** for flow in a trapezoidal channel. The Circular Channel Analysis provides the same information for circular channels.

Using the Trapezoidal Channel Analysis, you can quickly and easily analyze the hydraulic characteristics of almost any trapezoidal channel, including those with a different side slope for each bank. Triangular and rectangular channels can also be easily analyzed by the program because they are both special kinds of trapezoidal channels. A triangular channel is a trapezoidal channel with a channel bottom width of zero. A rectangular channel is a trapezoidal channel with side slopes of zero (vertical sides).

The Trapezoidal Channel Analysis and the Circular Channel Analysis are appropriate for open-channel flow only. Pressure flow in pipe and box culverts should be analyzed using the Pipe Culvert Analysis and Box Culvert Analysis which are also parts of the HYDROCALC ® Hydraulics for Windows program.

Normal Depth Computation

It's often useful to determine **Normal Depth** because it may represent a good approximation of the actual depth of flow within a channel segment. It is common practice to use Normal Depth computations to prepare a preliminary design for channel improvements, and then to check or refine the design by computing the water surface profile in the channel using the Standard Step or Direct Step Methods. The Standard Step procedure of the Trapezoidal and Circular Channel structures, for example, can be used for further analysis of a preliminary channel design identified using the Normal Depth procedure.

The following are input and output data for Normal Depth Computation:

Required Input Data:

Flow Rate

Channel Bottom Slope

Manning's Roughness Coefficient

Channel Side Slopes (Trapezoidal Channel)

Channel Bottom Width (Trapezoidal Channel)

Channel Diameter (Circular Channel)

Output Data:

Normal Depth in Circular Channel and Normal Depth in Trapezoidal Channel

Flow Velocity

Froude Number

Velocity Head

Energy Head

Cross-Sectional Area of Flow

Top Width of Flow

Critical Depth Computation

This program computes the **Critical Depth** by an iterative procedure, which arrives at a value that satisfies the following equations:

$$\frac{\mathbf{Q}^2}{g} = \frac{\mathbf{A}^3}{\mathbf{T}}$$

in which:

Q = Flow Rate in the channel (cfs or cu m/s)

g = Acceleration due to gravity (32.2 ft/s/s)

A = Cross-sectional area of flow (sq ft or sq m)

T = Top width of flow (ft or m)

For Trapezoidal Channels, the Newton-Raphson method of locating roots of a polynomial equation is used to solve the equation for the Critical Depth. This method gives a quick and efficient solution which is accurate to within 0.001 foot.

For Circular Channels, the Critical Depth is initially assumed to be at the midpoint of the pipe. A binary search algorithm is then used to converge to the actual Critical Depth. Successively smaller steps are used to adjust the estimated critical depth to the actual value to within 0.0001 foot. This method of solution is very stable and is highly accurate even for Critical Depths of 99% or more of the pipe depth.

The following are input and output data for Critical Depth Computation:

Required Input Data:

Flow Rate

Bottom Slope

Manning's Roughness Coefficient

Channel Side Slopes (Trapezoidal Channel)

Channel Bottom Width (Trapezoidal Channel)

Channel Diameter (Circular Channel**)**

Output Data:

Critical Depth

Critical Slope

Flow Velocity

Froude Number

Velocity Head

Energy Head

Cross-Sectional Area of Flow

Top Width of Flow

Rating Curve Computation

A Rating Curve is simply a table or curve which relates the flow rates to flow depths in a channel. Rating Curves are useful in estimating the capacity of a channel over a wide range of flood events or storm frequencies, or in quickly relating a known flood stage to a certain peak flow rate.

The following are input and output data for the Rating Curve Computation:

Required Input Data:

Channel Bottom Slope

Manning's Roughness Coefficient

Channel Side Slopes (Trapezoidal Channel)

Channel Bottom Width (Trapezoidal Channel)

Channel Diameter (Circular Channel)

Starting Flow Depth

Incremental Head

Number of Increments

Output Data:

Flow Rate

Flow Velocity

Froude Number

Velocity Head

Energy Head

Flow Area

Top Width

Standard Step Water Surface Profile Computation

"Gradually-varied flow" is used to describe a condition in which the depth of flow changes along the length of the channel. common examples of gradually varied flow include the "backwater" caused by an obstruction in a channel, or the "drawdown" of water surface in a channel upstream of a spillway. The Standard Step Water Surface Profile procedure can be used to analyze gradually-varied flow for trapezoidal or circular channels.

Limitation of Standard Step Procedure:
The Standard Step procedure can be used in place of such complex methods as the HEC-2 computer program, provided that the following conditions are met:

1) The flow rate in the channel must be uniform through the study reach.

2) The channel cross-section (the channel shape and roughness coefficient) must also be uniform throughout the study reach.

3) The channel bottom slope must be constant and positive.

4) The Channel slope must be sub-critical or "mild". This procedure is designed only for sub-critical water surface profiles.

The following are input and output data for the Standard Step Procedure:

Required Input Data:

Flow Rate

Channel Bottom Slope

Manning's Roughness coefficient

Channel Side Slopes (Trapezoidal Channel)

Channel Bottom Width (Trapezoidal Channel)

Channel Diameter (Circular Channel)

Channel Flow-Line Elevation at Starting Station

Water Surface Elevation at Starting Station

Starting Station

Channel Length between Stations

Number of Cross-Section (Stations)

Output Data:

Normal Depth

Critical Depth

Computed Flow-Line Elevation

Computed Water Surface Elevation

Depth of Flow

Flow Area

Flow Velocity

Velocity Head

Slope of the Energy Grade Line

Channel Flow Rate

For design of a new channel, the flow rate entered should be the desired capacity of the channel. For standard step procedure, the flow rate is assumed to be constant at all cross-sections.

You must supply the flow rate which the channel is to convey. Sometimes, the flow rate may vary through the length of a channel segment because of local inflow to the channel. In such cases, you must decide whether to base your analysis on the maximum flow rate or the average flow rate in the channel segment. Local drainage regulations or practice may provide guidance in this regard. When in doubt, perform the analysis with each flow rate and compare the results.

Data type: Input
Range of allowable values: 0.01 to 100,000.00

Units of measurement: cubic feet per second (cfs) or cubic meters per second (cu m/s)

Channel Bottom Slope

The slope of the channel bottom should be an average value in the area of the analysis. For the Standard Step procedure, the channel bottom slope is assumed to be constant for each reach.

The channel bottom slope is the average drop in elevation per foot of length along the channel. For example, if the channel bottom drops 1 foot in a length of 1000 feet, then the channel bottom slope is 0.001 feet per foot. Channel bottom slopes are sometimes expressed in percent. A slope of 0.001 feet per foot is the same as a 0.1% slope.

The slopes of the water surface and the energy grade line are assumed to be the same as the channel bottom slope for normal flow conditions. Therefore, it is important to provide the best possible estimate of the channel bottom slope.

Data type: Input
Range of allowable values: 0.0001 to 1.0
Units of measurement: dimensionless - feet/foot (ft/ft) or meters/meter (m/m)

Manning's Roughness Coefficient

This program uses **Manning's Equation** to analyze open-channel flow. The roughness of the channel is represented by Manning's Roughness Coefficient, commonly called the "n-value".

There are two ways to enter the n-value. You can either enter the value manually, or you can select it from the **Manning's Roughness Coefficients Window** by pressing the button to the right of the Manning's N-Value input field.

Roughness coefficients should be adjusted according to experience in your geographic area.

Data type: Input
Range of allowable values: 0.001 to 1.0
Units of measurement: Dimensionless

Manning's Roughness Coefficients Table

The Manning's Roughness Coefficients Table contains suggested n-values for various types of channels and culverts. (These tables were extracted from Table 5-6 of the book **Open Channel Hydraulics** by Ven Te Chow, McGraw-Hill, Inc., 1959).

To select an n-value, use the following steps:

1) From the first picklist, **Structure Type**, select the type which best describes the structure that you're working with.
2) From the second picklist, **Structure Composition/Dimension**, select the material that the structure is composed of. If you selected pipe as the structure type, this list will contain the dimensions of the pipe.
3) From the third field, **Structure Description/Condition**, pick a physical condition (or description) that most describes the current structure.
4) In the **Coeffcients** box, there are 3 n-values which relate to the surface roughness of the structure perimeter. Select the value that is most appropriate for the current structure. Structures with smooth surface has low n-value.

Channel Side Slopes (Trapezoidal Channel)

The slope of each side of the **Trapezoidal Channel** is expressed as the run divided by the rise. This is called the "Z-Ratio". A channel with 3:1 side slopes would have a Z-Ratio of 3: The side of the channel rises 1 foot in each 3 feet of (horizontal) distance away from the channel bottom. For a rectangular channel, both side slopes are equal to zero. Z-Ratio of 3 or 4 are common for earthen channels. Concrete-lined channels may have steeper banks, with Z-Ratio of 1.5 or 2.

The Trapezoidal Channel Analysis has the capability of analyzing channels with a different side slope for each channel bank. For example, flow in a street gutter can be analyzed using this program. The vertical curb would cause the side slope to be 0 on one side. On the other side, a 6-inch difference between the pavement crown elevation and the gutter elevation, divided by a 12-foot lane width, would yield a side slope of 24.

Data type: Input
Range of allowable values: 0.0 to 100.0
Units of measurement: Dimensionless - horizontal/vertical (ft/ft) or (m/m)

Channel Bottom Width

The bottom width of a **Trapezoidal Channel** is measured between the toes of each channel bank. A bottom width of 0 implies a triangular channel.

Data type: Input
Range of allowable values: 0.01 to 1,000,000.0
Units of measurement: feet (ft) or meters (m)

Channel Diameter (Circular Channel)

The channel diameter is the inside diameter of the pipe. If the channel is a semicircular flume, then the channel diameter is the diameter of the circle circumscribing the flume.

Data type: Input
Range of allowable values: 0.01 to 1,000,000.0
Units of measurement: feet (ft) or meters (m)

Normal Depth in Trapezoidal Channel

This program computes **Normal Depth** using an iterative approach to arrive at a value which satisfies **Manning's Equation**.

For a trapezoidal channel, the equation is rearranged in terms of the depth of flow. An initial flow depth estimate of 1 foot is substituted into the equation, and a new approximation is computed for the flow depth. The new value is compared with the previous approximation, and if the difference is less than 0.0001 feet, the depth is assumed to be the Normal Depth. If not, a new approximation for Normal Depth is computed as the geometric mean of the previous two approximations. This method quickly gives a very precise and reliable value for the Normal Depth of flow in a trapezoidal channel.

Data type: Output
Units of measurement: feet (ft) or meters (m)

Manning's Equation

$$\mathbf{Q} = \frac{\mathbf{1.486}}{n}\,\mathbf{AR}^{(2/3)}\sqrt{\mathbf{S}}$$

in which:
Q = Flow Rate in the channel (cfs or cu m/s)
n = Manning's Roughness Coefficient
A = Area of Flow (sq ft or sq m)
R = Hydraulic Radius (ft or m) = (Flow Area) / Wetted Perimeter)
S = Slope of Energy Grade Line (ft/ft or m/m)

Flow Velocity

The flow velocity in the channel is computed as simply the flow rate divided by the cross-sectional area of the flow. The velocity is assumed to be constant throughout the cross-section.

The flow velocity is an important consideration in many channel design situations. The allowable flow velocity may be limited by local drainage criteria.

Data type: Output
Units of measurement: feet per second (fps) or meters per second (m/s)

Froude Number

The Froude Number is the ratio of the inertial forces to the gravitational forces in a flowing fluid. It is computed using this formula:

$$\textit{Froude Number} = \frac{\mathbf{V}}{\sqrt{g\frac{\mathbf{A}}{\mathbf{T}}}}$$

in which:

V = Flow Velocity (fps or m/s)

g = Acceleration due to gravity = 32.2 ft/s/s

A = Cross-sectional Area of Flow (sq ft or sq m)

T = Top Width of Flow (ft or m)

At **Normal Depth**, if the Froude Number is greater than one (1.00), then flow in the channel is "super-critical". A Froude Number less than one is more common, indicating "sub-critical" flow.

At **Critical Depth**, the Froude Number equals 1. Therefore, the computed Froude Number provides a quick check on the accuracy of the computed Critical Depth. The Froude Number should always be very close to 1.000 for the Critical Depth procedure, except where Critical Depth exceeds the diameter of a circular channel.

Data Type: Output
Units of measurement: Dimensionless

Velocity Head

Water flowing in an open channel contains two major types of energy: potential energy and kinetic energy. Potential energy is expressed as the elevation of the water surface. Kinetic Energy is expressed as the "velocity head". The term "head" can also be stated as "energy level".

The velocity head is computed using the following formula:

$$\textit{Velocity Head} = \frac{\mathbf{V}^2}{\mathbf{2}g}$$

in which:

V = Flow Velocity in the channel (fps or m/s)

g = Acceleration due to gravity = 32.2 ft/s/s

Data Type: Output
Units of Measurement: feet (ft) or meters (m)

Energy Head

The "Energy Head" of the flow is the total energy of the flow, including both potential energy and kinetic energy. In other words, the energy head is simply the sum of the **water surface elevation** and the **velocity head**.

Data type: Output
Units of measurement: feet (ft) or meters (m)

Cross-Sectional Area of Flow

The cross-sectional area of flow is computed in order to provide a quick check on the other computed quantities, and also to aid in computing excavation requirements for a trapezoidal channel. The flow area of a **Trapezoidal Channel** is computed using the following formula:

$$\mathbf{A} = (\mathbf{B} + \mathbf{T})\,(\mathbf{D} / \mathbf{2})$$

in which:

A = Cross-sectional Area of Flow (sq ft or sq m)

B = Channel Bottom Width (ft or m)

T = Top Width of Flow (ft or m)

D = Depth of Flow (ft or m)

The flow area for a Circular Channel is computed by the following formula:

$$\mathbf{A} = (\mathbf{F} - r)r^2 - (\mathbf{F} - r)^2 + r^2 \mathrm{ArcCos}\left(\frac{r - \mathbf{F}}{r}\right)$$

in which:

A = Cross-sectional Area of Flow (sq ft or sq m)

F = Depth of Flow (ft or m)

r = Radius of Channel (ft or m)

Data type: Output
Units of measurement: square feet (sq ft) or square meters (sq m)

Top Width of Flow

The top width of flow is computed in order to make it easier to quickly estimate the required right-of-way width for a trapezoidal channel. The top width of the channel will probably be greater than the top width of the flow because most channels are required to have some freeboard.

The top width of flow for a Circular Channel is computed for comparison purposes only. It is computed by the following formula:

$$T = 2r^2 - (F - r)^2$$

in which:

T = Top width of flow (ft or m)

r = Radius of Channel (ft or m)

F = Depth of flow (ft or m)

Data type: Output
Units of measurement: feet (ft) or meters (m)

Pipe and Box Culvert Analysis

A culvert is a relatively short segment of closed conduit which connects two channels or bodies of water. Two types of culverts are most commonly used: **Pipe Culverts**, which are circular in cross-section, and **Box Culverts**, which are rectangular in cross-section.

The Pipe Culvert Analysis and the Box Culvert Analysis analyze culverts using the methods and equations described in the Federal Highway Administration report "Hydraulic Design of Highway Culverts" (FHWA, 1985) **"SEE APPENDIX A".** The HYDROCALC Hydraulics program can be used to analyze an existing culvert for a specific flow rate, or to design a new culvert for proposed conditions. This program can compute and plot a **Culvert Performance Curve** for almost any pipe culvert or box culvert.

The Pipe Culvert Analysis and Box Culvert Analysis are subject to the following limitations:

1) The culvert cross-section, flow rate, and bottom slope are assumed to be constant throughout the length of the culvert.
2) The culvert bottom slope is required to be positive.
3) Because of the method used to estimate friction losses for culverts flowing partially full, the length of such culverts, which may be accurately analyzed, is limited.

The Pipe and Box Culvert Analysis windows contain the following data:

Required Input Data:

Pipe Culvert Diameter

Box Culvert Span (Width of Opening)

Box Culvert Rise (Height of Opening)

FHWA Chart Number and Scale Number

Manning's Roughness Coefficient

Entrance Loss Coefficient

Culvert Length

Invert Elevation at Downstream side of Culvert

Invert Elevation at Upstream side of Culvert

Starting Flow Rate

Incremental Flow Rate

Number of Flow Rate Increments

Starting Tailwater

Incremental Tailwater

Output Table:

Inlet Control Headwater

Outlet Control Headwater

Normal Depth of Flow in the Culvert

Critical Depth of Flow in the Culvert

Depth of Flow at Culvert Outlet

Culvert Outlet Velocity

Performance Curve Procedure

A "Culvert Performance Curve" is a graph or table which shows several different flow rates and the headwater required to produce each in the culvert. The "headwater" of a culvert is the difference between the upstream culvert flow-line elevation and the elevation of the water surface in the channel immediately upstream of the culvert. Similarly, the "tailwater" of a culvert is the difference between the downstream culvert flow-line elevation and the elevation of the water surface in the channel immediately downstream of the culvert.

How the Performance Curve Procedure Works:
The Analysis of flow in culverts is complicated. It is common to use the concepts of ***Inlet Control*** and ***Outlet Control*** to simplify the analysis. Inlet Control flow occurs when the flow capacity of the culvert entrance is less than the flow capacity of the culvert barrel. Outlet Control flow occurs in other cases. The Performance curve procedure computes the headwater required to produce the flow rate through the culvert for Inlet Control conditions and for Outlet Control conditions. The higher headwater "controls" the design and determines the type of flow in the culvert, at that flow rate.

For Inlet Control, the required headwater is computed by taking the depth of flow at the culvert outlet plus all head losses, minus the change in flow-line elevation of the culvert from the upstream to downstream end. This program considers the entrance losses, the friction loss in the the culvert barrel, and the loss of velocity head at the outlet in computing the outlet control headwater of the culvert.

The following are input and output data for Performance Curve Procedure:

Inlet Control Headwater

Outlet Control Headwater

Normal Depth of Flow in the Culvert

Critical Depth of Flow in the Culvert

Depth of Flow at Culvert Outlet

Culvert Outlet Velocity

Pipe Culvert Diameter

The inside diameter of the circular pipe culvert opening is important not only in determining the total flow area of the culvert, but also in determining whether the headwater and tailwater elevations are adequate to submerge the inlet or outlet of the culvert.

Data type: Input
Range of allowable values: 0.01 to 1,000,000.0
Units of measurement: feet (ft) or meters (m)

Box Culvert Span (Width of Opening)

Box culverts are essentially rectangular in cross-section. They are described by the Span and Rise, which are the horizontal and vertical dimension of the culvert opening, respectively. For example, a "4 by 3 box culvert" has a span of 4 feet and a rise of 3 feet.

Data type: Input
Range of allowable values: 0.01 to 1,000,000.0
Units of measurement: feet (ft) or meters (m)

Box Culvert Rise (Height of Opening)

The height or rise of the culvert opening is important not only in determining the total flow area of the culvert, but also in determining whether the headwater or tailwater elevations are adequate to submerge the inlet or outlet of the culvert

Most box culverts have chamfered corners on the inside. The chamfers are ignored by this program in computing the cross-sectional area of the culvert opening. Some manufacturer's literature contains the true cross-sectional area of each size of box culvert, considering the reduction in area caused by the chamfered corners. If you wish to consider the loss in area due to the chamfers, then you should reduce the span of the culvert. You should not reduce the rise of the culvert because the program uses the culvert rise to determine the submergence of the culvert entrance and outlet.

Data type: Input
Range of allowable values: 0.01 to 1,000,000.0
Units of measurement: feet (ft) or meters (m).

FHWA Chart Number and Scale Number

The Bureau of Public Roads (now called the Federal Highway Administration) published a series of nomographs in 1965 (BPR, 1965), which allowed the inlet control headwater to be computed for different types of culverts operating under a wide range of flow conditions. These nomographs and others constructed using the original methods were published in 1985 (FHWA, 1985).

The FHWA Chart Number determines which of the inlet control nomographs to use. Each Scale Number represents a different type of culvert inlet or entrance.

If you know the chart number and scale number for the current culvert structure, you can enter them in the Chart Number and Scale Number data fields. To select chart and scale numbers from a table, select the button to the right of these fields.

The following table contains all the Chart and Scale numbers for Pipe culverts and Box culverts. Chart numbers 1, 2, and 3 are used by Pipe culverts, and Chart numbers 8 through 13 are used by Box culverts.

Chart No.	Scale No.	Description
1		***Concrete Pipe Culvert***
	1	Square edge Entrance with headwall
	2	Groove end Entrance with headwall
	3	Groove end Entrance, pipe projecting from fill
2		***Corrugated Metal Pipe Culvert***
	1	Headwall
	2	Mitered to conform to slope

	3	Pipe projecting from fill
3		***Concrete Pipe Culvert; Beveled Ring Entrance***
	1(A)	Small bevel
	2(B)	Large bevel
8		***Box Culvert w/ Flared Ringwalls***
	1	Wingwalls flared 30 to 75 degrees
	2	Wingwalls flared 90 to 15 degrees
	3	Wingwalls flared 0 degrees (sides extended straight)
9		***Box Culvert w/ Flared Wingwalls & Inlet Top Edge Bevel***
	1	Wingwall flared 45 degrees; Inlet top edge bevel=0.043D
	2	Wingwall flared 18 to 33.7 degrees; Inlet top edge bevel=0.083D
10		***Box Culvert;90-Degree Headwall;Chamfered or Beveled Inlet Edges***
	1	Inlet edges chamfered 3/4-inch
	2	Inlet edges beveled 1/2-in/ft at 45 degrees (1:1)
	3	Inlet edges beveled 1-in/ft at 33.7 degrees (1:1.5)
11		***Box Culvert;Skewed Headwall;Chamfered or Beveled Inlet Edges***
	1	Headwall skewed 45 degrees; Inlet edges chamfered 3/4-inch
	2	Headwall skewed 30 degrees; Inlet edges chamfered 3/4-inch
	3	Headwall skewed 15 degrees; Inlet edges chamfered 3/4-inch
	4	Headwall skewed 10 to 45 degrees; Inlet edges beveled
12		***Box Culvert;Non-Offset Flared Wingwalls;3/4-inch Chamfer at Top of Inlet***
	1	Wingwalls flared 45 degrees (1:1); Inlet not skewed
	2	Wingwalls flared 18.4 degrees (3:1); Inlet not skewed
	3	Wingwalls flared 18.4 degrees (3:1); Inlet skewed 30 degrees
13		***Box Culvert;Offset Flared Wingwalls;Beveled Edge at Top of Inlet***
	1	Wingwalls flared 45 degrees (1:1); Inlet top edge bevel=0.042D
	2	Wingwalls flared 33.7 degrees (1.5:1); Inlet top edge bevel=0.083D
	3	Wingwalls flared 18.4 degrees (3:1); Inlet top edge bevel=0.083D

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Data type: Input
Units of measurement: Dimensionless

Downstream and Upstream Elevations

The Downstream and Upstream Elevations are the invert elevations at the downstream and upstream ends of the culvert, respectively. These two elevations are used by this program to compute the **Outlet Control Headwater**.

The Downstream and Upstream elevations and the Culvert Length are also used to compute the culvert flow-line slope which is the average drop in elevation per foot of length along the culvert. The flow-line of a culvert is the lowest point on the inside of the culvert opening. The following equation is used to compute the flow-line slope of a culvert:

$$Slope = \frac{(\mathbf{U} - \mathbf{D})}{\mathbf{L}}$$

in which:

U = Invert Elevation at Upstream end of Culvert (ft or m)

D = Invert Elevation at Downstream end of Culvert (ft or m)

L = Culvert Length (ft or m)

The Pipe and Box Culvert Analysis require that the culvert slope be positive which means ***the upstream invert elevation must always be higher than the downstream invert elevation***.

Data type: Input
Range of allowable values: -1,000,000.0 to 1,000,000.0

Units of measurement: feet (ft) or meters (m)

Entrance Loss Coefficient of Culvert Opening

The Entrance Loss Coefficient is used to determine the amount of head (energy) loss as flow enters the culvert from upstream. A higher value for the coefficient gives a higher head loss.

Appropriate values for the entrance loss coefficient range from 0.2 to about 0.8 for pipe culverts, or about 0.2 to about 0.5 for box culverts. For a sharp-edged culvert entrance with no rounding, 0.5 is recommended. For a well-rounded entrance, 0.2 is appropriate. An example of a fairly well-rounded entrance is the socket end of a concrete pipe section.

To select a coefficient from an existing Table, click on the button next to the Entrance Loss Coefficient data field.

The following tables lists the suggested Entrance Loss Coefficients for various Pipe and Box culverts. The source of the information in this table is "Street and Highway Drainage", Institute of Transportation and Traffic Engineering, University of California at Berkeley, 1969.

Entrance Loss Coefficient for Pipe Culvert

Type of Structure and Design of Entrance	Coefficient
Concrete Pipe Projecting from Fill (no headwall)	
Socket end of pipe	0.20
Square cut end of pipe	0.50
Concrete Pipe w/ Headwall or headwall and wingwalls	
Socket end of pipe	0.10
square cut end of pipe	0.50
Rounded entrance, w/ rounding radius = 1/12 of diameter	0.10
Corrugated Metal Pipe	
Projecting from fill (no headwall)	0.80
With Headwall or headwall and wingwalls, square edge	0.50

Entrance Loss Coefficient for Box Culvert

Type of Structure and Design of Entrance	Coefficient
Headwall Parallel to embankment (no wingwalls)	
Square edge of three edges	0.50
3 edges rounded to radius of 1/12 barrel dimension	0.20
Wingwalls at 15 to 45 degrees to barrel	
Square-edge top corner	0.40
Top corner rounded to radius of 1/12 barrel dimension	0.20

Data type: Input
Range of allowable values: 0.0 to 1.0
Units of measurement: Dimensionless

Entrance Loss Coefficient Table

The Entrance Loss Coefficient Table contains the standard coefficients for various structures and designs of entrance. The source of the information in this table is "Street and Highway Drainage", Institute of Transportation and Traffic Engineering, University of California at Berkeley, 1969.

To select an Entrance Loss Coefficient:

1) From the **Structure Type** picklist, select the type of structure that describes the current culvert.
2) From the **Design of Entrance** picklist, select a description of the culvert entrance. After you've selected a culvert entrance, a value is displayed in the **Coefficient** box. This is the recommended Entrance Loss Coefficient for the current culvert.
3) Click on the **OK** button to exit.

Culvert Length

The Culvert Length should be measured along the center-line of the culvert. The Culvert Length is used to determine the friction loss in the culvert barrel and the total drop in flow-line elevation between the upstream and downstream ends of the culvert.

Data type: Input
Range of allowable values: 0.0 to 1,000,000.0
Units of measurement: feet (ft) or meters (m)

Outlet Control Headwater

For outlet control flow, the required headwater must be computed considering several conditions within the culvert and downstream. The headwater required for outlet control conditions is computed using the method recommended by the Federal Highway Administration (FHWA, 1985) (see manual).

Data type: Output
Units of Measurement: feet (ft) or meters (m)

Culvert Flow Rates

The HYDROCALC Hydraulics for Windows program can analyze a maximum of 100 flow rates at constant interval. The program automatically compute the flow rate values base on the following input data:

Starting Flow Rate: The first value at which the program will begin the analysis.

Incremental Flow Rate: The constant interval between one flow data and the next.

Number of Increments: The number of data to analyze.

The flow rate should reflect the desired capacity of the culvert. For example, if the culvert is to be designed to pass the 10-year storm event without overtopping the road embankment, then the 10-year peakflow rate is the required flow rate, and the minimum elevation of the road embankment represents the maximum allowable headwater elevation.

If you are analyzing multiple culverts (all of which are identical), you may divide the flow rate among the culverts equally and analyze each culvert separately. If the culverts are not identical, use the following procedure:

1) Estimate the flow rate through each culvert (on the basis of cross-sectional area, for example).
2) Compute the required headwater for each culvert using this program.
3) Adjust the assumed flow rates and repeat the analysis until the computed headwater elevations roughly match for all culverts.
4) Be sure that the total flow rate equals the sum of the individual flow rates for the various culverts.

Data type: Input
Range of allowable values: 0.01 to 1,000,000.0
Units of measurement: cubic feet per second (cfs) or cubic meters per second (cu m/s)

Critical Depth of Flow in the Culvert

The Critical Depth of flow in the culvert is used to determine the culvert outlet head. Critical Depth may also influence the inlet control headwater for unsubmerged conditions. In addition, the depth of flow at the culvert outlet is assumed to equal critical depth for culverts operating under outlet control with low tailwater. This program computes the critical depth using the procedures described in the help topic **Critical Depth Computation**, except that for box culverts, a non-iterative equation is used:

$$\mathbf{D} = \left(\frac{\mathbf{Q}^2}{g\mathbf{W}^2} \right)^{\frac{1}{3}}$$

in which:

D = Critical Depth (ft or m)

Q = Flow Rate (cfs or cu m/s)

g = Acceleration due to gravity (32.2 ft/s/s)

W = Culvert Span (ft or m)

Data type: Output
Units of measurement: feet (ft) or meters (m)

Tailwater Elevations in the Culvert

The HYDROCALC Hydraulics for Windows program can analyze a maximum of 100 tailwater elevations at constant interval. The program automatically compute the tailwater elevations base on the following input data:

Starting Tailwater: The first value at which the program will begin the analysis.

Incremental Tailwater: The constant interval between one tailwater elevation and the next.

Number of Increments: The number of tailwater elevations to analyze..

The tailwater of a culvert is the difference between the downstream culvert flow-line elevation and the elevation of the water surface in the channel immediately downstream of the culvert.

It is important to remember that the headwater and tailwater depths are each measured from the culvert flow-line elevation on different ends of the culvert. Therefore, just because the headwater and the tailwater are equal for a particular culvert, it is not necessarily true that the water surface elevations on the upstream and downstream side of the culvert are equal.

Data type: Input
Range of allowable values: 0.0 to 1,000,000.0
Units of measurement: feet (ft) or meters (m)

Inlet Control Headwater

For inlet control conditions, the capacity of the culvert is limited by the capacity of the culvert opening rather than by conditions farther downstream. For inlet control flow, the culvert inlet acts either as a weir or as an orifice. Extensive laboratory tests by the National Bureau of Standards, the Bureau of Public Roads, and other entities resulted in a series of equations which describe the inlet control headwater under various conditions. These equations form the basis of the FHWA Inlet Control nomographs (see manual).

Data type: Output
Units of measurement: feet (ft) or meters (m)

Normal Depth of Flow in the Culvert

For Inlet Control conditions, the depth of flow within the culvert is assumed to be **Normal Depth**. This assumption is only valid if the culvert pipe is sufficiently long to allow the flow depth to stabilize at Normal Depth. The culvert length should be at least 6 times the culvert height before normal depth is attained. The Pipe Culvert Analysis and Box Culvert Analysis compute Normal Depth in the culvert using the methods described in **Normal Depth in Circular Channel** and **Normal Depth in Trapezoidal Channel**, respectively.

Data type: Output
Units of measurement: feet (ft) or meters (m)

Normal Depth in Circular Channel

This program computes **Normal Depth** using an iterative approach to arrive at a value which satisfies **Manning's Equation.**

The first step in determining the Normal Depth in a Circular Channel is to compute the maximum flow capacity of the channel. This capacity occurs at a flow depth of 0.9382 times the channel diameter. If this capacity is less than the required flow rate, then it is not possible to compute a Normal Depth of flow, and the program will add a message to that effect to the project Report.

Assuming that the channel has sufficient capacity to convey the required flow rate, this program computes Normal Depth using the same method as the **Trapezoidal Channel Normal Depth** procedure except that the initial flow depth is assumed to be one-half of the channel diameter.

This method quickly gives very precise and reliable values for the Normal Depth of flow in a circular channel, except in cases in which the Normal Depth is above about 88% of the channel diameter. In such cases, the program may complete the maximum 30 iterations without reaching the required accuracy.

Data type: Output
Units of measurement: feet (ft) or meters (m)

Normal Depth is the depth at which uniform flow will occur in an open channel. In other words, if you had a uniform channel of infinite length. Carrying a constant flow rate, then flow in the channel would be at a constant depth at all points along the channel, and this depth would be normal depth.

Depth of Flow at Culvert Outlet

The depth of flow at the culvert outlet is used to compute the outlet flow velocity. For inlet control conditions, the depth of flow at the culvert outlet is assumed to equal the normal depth of flow in the culvert. For outlet control conditions, the depth of flow at the culvert outlet is assumed to equal the critical depth of flow in the culvert or the tailwater depth, whichever is greater.

Data type: Output
Units of measurement: feet (ft) or meters (m)

Culvert Outlet Velocity

The outlet flow velocity of the culvert is computed as simply the flow rate divided by the cross-sectional area of the flow at the outlet. The allowable flow velocity of a culvert may be restricted to a certain value, such as 10 feet per second. In some cases, high flow velocities at the downstream end of a culvert may create the need for erosion protection.

Data type: Output
Units of measurement: feet per second (fps) or meters per second (m/s)

Critical Depth occurs when the flow in a channel has minimum specific energy. Specific energy refers to the sum of the depth of flow and the velocity head. At Critical Depth, the velocity head is equal to one-half the average depth of flow. Critical Depth depends only on the channel shape and flow rate.

It is sometimes useful to compute Critical Depth in order to analyze the type of flow profile which will occur in a particular channel.

Data Type: Output
Units of measurement: feet (ft) or meters (m)

Critical Slope

Critical Slope is the channel slope at which Normal Depth equals Critical Depth. Critical Slope is computed by inserting the Critical Depth equation into Manning's Equation, which is rearranged as follows:

$$\mathbf{S} = \left(\frac{\mathbf{Q}n}{1.486\mathbf{A}\mathbf{R}^{\left(\frac{2}{3}\right)}} \right)^2$$

in which:

S = Slope of Energy Grade Line (ft/ft or m/m)

Q = Flow Rate in the channel (cfs or cu m/s)

n = Manning's Roughness Coefficient

A = Area of Flow (sq ft or sq m)

R = Hydraulic Radius (ft or m) = (Flow Area) / (Wetted Perimeter)

Data type: Output
Units of measurement: Dimensionless - feet per foot (ft/ft) or meters per meter (m/m)

Flow Depth for Rating Curve

The HYDROCALC Hydraulics for Windows program can analyze a Rating Curve with a maximum of 100 flow depths at constant interval. The program automatically compute the flow depths values base on the following input data:

Starting Flow Depth: The first value at which the program will begin the analysis.

Incremental Head: The constant interval between one flow depth and the next.

Number of Increments: The number of data to analyze.

For Circular Channel Analysis, the flow depths that equal or exceed the channel diameter are ignored.

Data type: Input
Range of allowable values: 0.01 to 1,000,000.00
Units of measurement: feet (ft) or meters (m)

Channel Flow-Line Elevation at Starting Station

This value represents the elevation of the lowest point in the channel cross-section. It is used along with the input value of the Channel Bottom Slope to compute the flow-line elevation at each subsequent channel cross-section. The channel flow-line elevation at the starting station can be any reasonable value, including negative values.

Data type: Input
Range of allowable values: -1,000,000.0 to 1,000,000.0
Units of measurement: feet (ft) or meters (m)

Water Surface Elevation at Starting Station

The starting water surface elevation at the starting station represents the initial condition of the water surface profile. The value given for the starting water surface elevation must be greater than the channel flow-line elevation at the starting station. For a circular channel, the starting water surface elevation must also be less than the sum of the channel diameter and the starting flow-line elevation.

The starting water surface elevation determines the type of water surface profile which will be computed. If the starting water surface elevation is greater than Normal Depth, then the computed water surface profile will be a "backwater profile", or M1. For example, the water surface profile in a channel upstream of a flow obstruction would be an M1 profile.

If the starting water surface elevation is less than Normal Depth, then the computed water surface profile will be a "drawdown" profile, or M2. An M2 profile would be produced upstream of a free outfall.

Channel Stations

The HYDROCALC Hydraulics for Windows program can analyze a maximum of 100 channel stations. The program automatically compute channel stations base on the following input data:

Starting Station: The first station number at which the program will begin the analysis.

Channel Length: The distant between cross-section stations. This value must be positive, ranging from 0.01 to 1,000,000.0 feet.

Number of Cross-Sections: The number of stations to analyze. A maximum of 100 stations can be analyzed.

Data type: Input
Range of allowable values: -1,000,000.0 to 1,000,000.0
Units of measurement: feet (ft) or meters (m)

Computed Flow-Line Elevation

This program computes the flow-line elevation at each station using the following formula:

$$\mathbf{E} = \mathbf{F} + \mathbf{S} \times \mathbf{D}$$

in which:

E = the flow-line elevation at the current station (ft or m)

F = the flow-line elevation at the starting station (ft or m)

S = the channel bottom slope (ft/ft or m/m)

D = the distance between the current station and the starting station (ft or m)

Data type: Output
Units of measurement: feet (ft) or meters (m)

Computed Water Surface Elevation

The water surface elevation at each channel station is computed using the Standard Step Method. For the Standard Step Method, an iterative (trial and error) procedure is used to balance the total energy at each cross-section to the total energy at the previous cross-section. **Manning's Equation** is used to estimate the energy loss due to friction between the cross-section.

Data type: Output
Units of Measurement: feet (ft) or meters (m)

Depth of Flow (Standard Step Procedure)

The depth of flow is simply the difference between the computed water surface elevation and the computed flow-line elevation. The depth of flow should approach **Normal Depth** as the stations increase.

Data type: Output
Units of measurement: feet (ft) or meters (m)

Slope of the Energy Grade Line

The slope of the energy grade line will eventually approach the channel bottom slope. The slope of the energy grade line is computed by inserting the computed flow depth in **Manning's Equation**, which is rearranged as follows:

$$\mathbf{S} = \left(\frac{\mathbf{Q}n}{1.486\mathbf{A}\mathbf{R}^{\left(\frac{2}{3}\right)}} \right)^2$$

in which:

S = Slope of Energy Grade Line (ft/ft or m/m)

Q = Flow Rate in the channel (cfs or cu m/s)

n = Manning's Roughness Coefficient

A = Area of Flow (sq ft or sq m)

R = Hydraulic Radius (ft or m) = (Flow Area) / (Wetted Perimeter)

Data type: Output
Units of measurement: Dimensionless - feet per foot (ft/ft) or meters per meter (m/m)

APPENDIX A
DESIGN METHODS AND EQUATIONS

A. Introduction

This appendix contains explanations of the equations and methods used to develop the design charts of this publication, where those equations and methods are not fully described in the main text. The following topics are discussed: the design equations for the unsubmerged and submerged inlet control nomographs, the dimensionless design curves for culvert shapes and sizes without nomographs, and the dimensionless critical depth charts for long span culverts and corrugated metal box culverts.

B. Inlet Control Nomograph Equations

The design equations used to develop the inlet control nomographs are based on the research conducted by the National Bureau of Standards (NBS) under the sponsorship of the Bureau of Public Roads (now the Federal Highway Administration). Seven progress reports were produced as a result of this research. Of these, the first and fourth through seventh reports dealt with the hydraulics of pipe and box culvert entrances, with and without tapered inlets (4, 7, to 10). These reports were one source of the equation coefficients and exponents, along with other references and unpublished FHWA notes on the development of the nomographs (56 and 57).

The two basic conditions of inlet control depend upon whether the inlet end of the culvert is or is not submerged by the upstream headwater. If the inlet is not submerged, the inlet performs as a weir. If the inlet is submerged, the inlet performs as an orifice. Equations are available for each of the above conditions.

Between the unsubmerged and the submerged conditions, there is a transition zone for which the NBS research provided only limited information. The transition zone is defined empirically by drawing a curve between and tangent to the curves defined by the unsubmerged and submerged equations. In most cases, the transition zone is short and the curve is easily constructed.

Table 8 contains the unsubmerged and submerged inlet control design equations. Note that there are two forms of the unsubmerged equation. Form (1) is based on the specific head at critical depth, adjusted with two correction factors. Form (2) is an exponential equation similar to a weir equation. Form (1) is preferable from a theoretical standpoint, but Form (2) is easier to apply and is the only documented form of equation for some of the inlet control nomographs.

The constants and the corresponding equation form are given in Table 9. Table 9 is arranged in the same order as the design nomographs in Appendix D, and provides the unsubmerged and submerged equation coefficients for each shape, material, and edge configuration. For the unsubmerged equations, the form of the equation is also noted.

*** Please Note: HydroCALC Hydraulics uses the "Inlet Control Nomograph Equations" published by the FHWA in this document.**

Table 8. Inlet Control Design Equations.

UNSUBMERGED[1]

$$\text{Form}(1)\ \frac{HW_i}{D} = \frac{H_c}{D} + K\left[\frac{K_u Q}{AD^{0.5}}\right]^M - 0.5S^2 \qquad (26)$$

$$\text{Form}(2)\ \frac{HW_i}{D} = K\left[\frac{K_u Q}{AD^{0.5}}\right]^M \qquad (27)$$

SUBMERGED[3]

$$\frac{HW_i}{D} = c\left[\frac{K_u Q}{AD^{0.5}}\right]^2 + Y - 0.5S^2 \qquad (28)$$

Definitions

HW_i	Headwater depth above inlet control section invert, m (ft)
D	Interior height of culvert barrel, m (ft)
H_c	Specific head at critical depth ($d_c + V_c^2/2g$), m (ft)
Q	Discharge, m^3/s (ft^3/s)
A	Full cross sectional area of culvert barrel, m^2 (ft^2)
S	Culvert barrel slope, m/m (ft/ft)
K,,M,c,Y	Constants from Table 9
K_u	1.811 SI (1.0 English)

NOTES: [1]Equations (26) and (27) (unsubmerged) apply up to about $Q/AD^{0.5}$ = 1.93 (3.5 English)
[2]For mitered inlets use +0.7S instead of -0.5S as the slope correction factor
[3]Equation (28) (submerged) applies above about $Q/AD^{0.5}$ = 2.21 (4.0. English)

The equations may be used to develop design curves for any conduit shape or size. Careful examination of the equation constants for a given form of equation reveals that there is very little difference between the constants for a given inlet configuration. Therefore, given the necessary conduit geometry for a new shape from the manufacturer, a similar shape is chosen from Table 9, and the constants are used to develop new design curves. The curves may be quasi-dimensionless, in terms of $Q/AD^{0.5}$ and HW_i /D, or dimensional, in terms of Q and HW_i for a particular conduit size. To make the curves truly dimensionless, $Q/AD^{0.5}$ must be divided by $g^{0.5}$, but this results in small decimal numbers. Note that coefficients for rectangular (box) shapes should not be used for nonrectangular (circular, arch, pipe-arch, etc.) shapes and vice-versa. A constant slope value of 2 percent (0.02) is usually selected for the development of design curves. This is because the slope effect is small and the resultant headwater is conservatively high for sites with slopes exceeding 2 percent (except for mitered inlets).

Table 9 Constants for Inlet Control Design Equations.

Chart No.	Shape and Material	Nomograph Scale	Inlet Edge Description	Equation Form	Unsubmerged		Submerged		References
					K	M	c	Y	
1	Circular Concrete	1	Square edge w/headwall	1	.0098	2.0	.0398	.67	56/57
		2	Groove end w/headwall		.0018	2.0	.0292	.74	
		3	Groove end projecting		.0045	2.0	.0317	.69	
2	Circular CMP	1	Headwall	1	.0078	2.0	.0379	.69	56/57
		2	Mitered to slope		.0210	1.33	.0463	.75	
		3	Projecting		.0340	1.50	.0553	.54	
3	Circular	A	Beveled ring, 45° bevels	1	.0018	2.50	.0300	.74	57
		B	Beveled ring, 33.7° bevels*		.0018	2.50	.0243	.83	
8	Rectangular Box	1	30° to 75° wingwall flares	1	.026	1.0	.0347	.81	56
		2	90° and 15° wingwall flares		.061	.75	.0400	.80	56
		3	0° wingwall flares		.061	.75	.0423	.82	8
9	Rectangular Box	1	45° wingwall flare d = .043D	2	.510	.667	.0309	.80	8
		2	18° to 33.7° wingwall flare d = .083D		.486	.667	.0249	.83	
10	Rectangular Box	1	90° headwall w/3/4" chamfers	2	.515	.667	.0375	.79	8
		2	90° headwall w/45° bevels		.495	.667	.0314	.82	
		3	90° headwall w/33.7° bevels		.486	.667	.0252	.865	
11	Rectangular Box	1	3/4" chamfers; 45° skewed headwall	2	.545	.667	.04505	.73	8
		2	3/4" chamfers; 30° skewed headwall		.533	.667	.0425	.705	
		3	3/4" chamfers; 15° skewed headwall		.522	.667	.0402	.68	
		4	45° bevels; 10°-45° skewed headwall		.498	.667	.0327	.75	
12	Rectangular Box 3/4" chamfers	1	45° non-offset wingwall flares	2	.497	.667	.0339	.803	8
		2	18.4° non-offset wingwall flares		.493	.667	.0361	.806	
		3	18.4° non-offset wingwall flares 30° skewed barrel		.495	.667	.0386	.71	
13	Rectangular Box Top Bevels	1	45° wingwall flares - offset	2	.497	.667	.0302	.835	8
		2	33.7° wingwall flares - offset		.495	.667	.0252	.881	
		3	18.4° wingwall flares - offset		.493	.667	.0227	.887	
16-19	C M Boxes	2	90° headwall	1	.0083	2.0	.0379	.69	57
		3	Thick wall projecting		.0145	1.75	.0419	.64	
		5	Thin wall projecting		.0340	1.5	.0496	.57	

Table 9 (continued) Constants for Inlet Control Design Equations

Chart No.	Shape and Material	Nomograph Scale	Inlet Edge Description	Equation Form	Unsubmerged		Submerged		References
					K	M	c	Y	
29	Horizontal	1	Square edge w/headwall	1	.0100	2.0	.0398	.67	57
	Ellipse	2	Groove end w/headwall		.0018	2.5	.0292	.74	
	Concrete	3	Groove end projecting		.0045	2.0	.0317	.69	
30	Vertical	1	Square edge w/headwall	1	.0100	2.0	.0398	.67	57
	Ellipse	2	Groove end w/headwall		.0018	2.5	.0292	.74	
	Concrete	3	Groove end projecting		.0095	2.0	.0317	.69	
34	Pipe Arch	1	90° headwall	1	.0083	2.0	.0379	.69	57
	18" Corner	2	Mitered to slope		.0300	1.0	.0463	.75	
	Radius CM	3	Projecting		.0340	1.5	.0496	.57	
35	Pipe Arch	1	Projecting	1	.0300	1.5	.0496	.57	56
	18" Corner	2	No Bevels		.0088	2.0	.0368	.68	
	Radius CM	3	33.7° Bevels		.0030	2.0	.0269	.77	
36	Pipe Arch	1	Projecting	1	.0300	1.5	.0496	.57	56
	31" Corner		No Bevels		.0088	2.0	.0368	.68	
	Radius CM		33.7° Bevels		.0030	2.0	.0269	.77	
41-43	Arch CM	1	90° headwall	1	.0083	2.0	.0379	.69	57
		2	Mitered to slope		.0300	1.0	.0463	.75	
		3	Thin wall projecting		.0340	1.5	.0496	.57	
55	Circular	1	Smooth tapered inlet throat	2	.534	.555	.0196	.90	3
		2	Rough tapered inlet throat		.519	.64	.0210	.90	
56	Elliptical	1	Tapered inlet-beveled edges	2	.536	.622	.0368	.83	3
	Inlet Face	2	Tapered inlet-square edges		.5035	.719	.0478	.80	
		3	Tapered inlet-thin edge projecting		.547	.80	.0598	.75	
57	Rectangular	1	Tapered inlet throat	2	.475	.667	.0179	.97	3
58	Rectangular	1	Side tapered-less favorable edges	2	.56	.667	.0446	.85	3
	Concrete	2	Side tapered-more favorable edges		.56	.667	.0378	.87	
59	Rectangular	1	Slope tapered-less favorable edges	2	.50	.667	.0446	.65	3
	Concrete		Slope tapered-more favorable edges		.50	.667	.0378	.71	

NOTE: The rest of this Appendix A is only given in English units since it only describes the procedures used to develop a dimensionless design curve.

Example: Develop a dimensionless design curve for elliptical structural plate corrugated metal culverts, with the long axis horizontal. Assume a thin wall projecting inlet. Use the coefficients and exponents for a corrugated metal pipe-arch, a shape similar to an ellipse.

From Table 9, Chart 34, Scale 3:

Unsubmerged: equation Form (1)

K = .0340
M = 1.5

Submerged: c = .0496
Y = 0.53

From Table 8:

Unsubmerged, equation Form 1 (Equation 49):

$$\frac{HW_i}{D} = \frac{H_c}{D} + .0340\left(\frac{Q}{AD^{0.5}}\right)^{1.5} - (0.5)(0.02)$$

Submerged (Equation 28):

$$\frac{HW_i}{D} = 0.0496\left(\frac{Q}{AD^{0.5}}\right)^{2} + 0.53 - (.5)(0.02)$$

A direct relationship between HW_i/D and $Q/AD^{0.5}$ may be obtained for the submerged condition. For the unsubmerged condition, it is necessary to obtain the flow rate and equivalent specific head at critical depth. At critical depth, the critical velocity head is equal to one-half the hydraulic depth.

$$\frac{V_c^2}{2g} = \frac{y_h}{2} = \frac{A_p}{2T_p}$$

Therefore:

$$\frac{H_c}{D} = \frac{d_c}{D} + \frac{y_h}{2D} \tag{29}$$

Also, at critical depth, the Froude number equals 1.0.

$$F_r = \frac{V_c}{(gy_h)^{0.5}} = 1$$

Setting: $V_c = Q_c / A_p$

$$Q_c = A_p (gy_h)^{0.5} \text{, or}$$

$$\frac{Q_c}{AD^{0.5}} = \frac{A_p}{A}\left(g \bullet \frac{y_h}{D}\right)^{0.5} \qquad (30)$$

From geometric data supplied by the manufacturer for a horizontal ellipse (58), the necessary geometry is obtained to calculate H_c/D and $Q_c/AD^{5.0}$.

d_c/D	y_h/D	(From Equation 29) H_c/D	A_p/A	(From Equation 30) $Q_c/AD^{0.5}$
0.1	0.04	0.12	0.04	0.05
0.2	0.14	0.27	0.14	0.30
0.4	0.30	0.55	0.38	1.18
0.6	0.49	0.84	0.64	2.54
0.8	0.85	1.22	0.88	4.60
0.9	1.27	1.53	0.97	6.20
1.0	--	--	1.00	--

From unsubmerged Equation (26) with the appropriate constants for unsubmerged flow:

$Q_c/AD^{0.5}$	.0340 x $(Q_c/AD^{0.5})^{1.5}$	$+H_c/D$	-0.5S=	HW_i/D
0.05	0.0004	0.12	0.01	0.11
0.30	0.0054	0.27	0.01	0.27
1.18	0.044	0.55	0.01	0.58
2.54	0.138	0.84	0.01	0.55
4.60	0.336	1.22	0.01	1.54
6.20	0.525	1.53	0.01	2.05
--	--			

For the submerged equation, any value of $Q/AD^{0.5}$ may be selected, since critical depth is not involved. From Equation (28), with the appropriate constants:

$Q_c/AD^{0.5}$	.0496 x $(Q_c/AD^{0.5})^2$	+Y	-0.5S=	HW_i/D
1.0	0.05	0.53	0.01	*0.57
2.0	0.20	0.53	0.01	*0.72
4.0	0.79	0.53	0.01	1.31
6.0	1.79	0.53	0.01	2.31
8.0	3.17	0.53	0.01	3.69

*Obviously Unsubmerged

Note that overlapping values of HW_i/D were calculated in order to define the transition zone between the unsubmerged and the submerged states of flow.

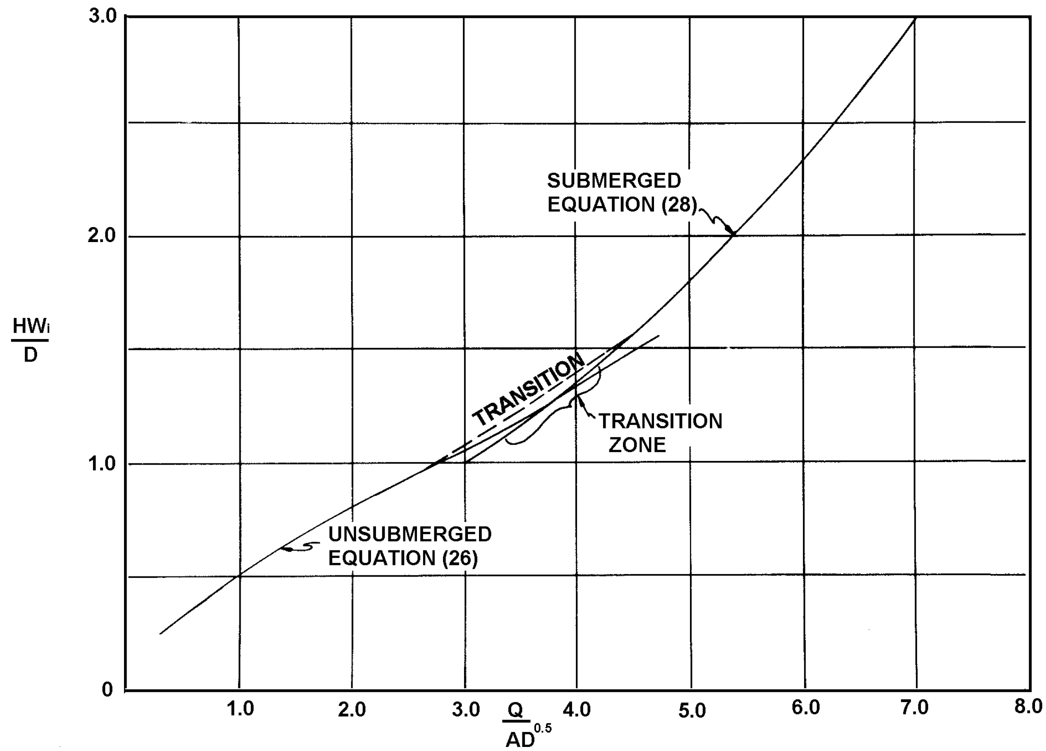

Figure A-1--Dimensionless Performance Curve for Structural Plate Elliptical Conduit, Long Axis Horizontal, Thin Wall Projecting Entrance

The results of the above calculations are plotted in Figure A-1. A transition line is drawn between the unsubmerged and the submerged curves. The scales are dimensionless in Figure A-1, but the figures could be used to develop dimensional curves for any selected size of elliptical conduit by multiplying: $Q/AD^{0.5}$ by $AD^{0.5}$ HW_i/D by D.

Similar calculations were used to develop the dimensionless inlet control design curves for the long span arches and elliptical pipe in Chapter III.

To derive overall inlet control equations for use on a computer, it is necessary to plot the unsubmerged and submerged curves from these equations and draw the connecting transition line. Then, the coordinates of selected points can be read from the curve and a best fit statistical analysis performed. A polynomical curve of the following form has been found to provide an adequate fit.

$$\frac{HW_i}{D} = A + B\left[\frac{Q}{BD^{1.5}}\right] + C\left[\frac{Q}{BD^{1.5}}\right]^2 + \ldots + X\left[\frac{Q}{BD^{1.5}}\right]^n - 0.5S$$

The flow factor could be based on $AD^{0.5}$ rather than $BD.^{1.5}$ The constants for the best fit equations are found in the user's manuals for various computer programs (20, 53, 54, 55, 59).

C. <u>Development of Dimensionless Inlet Control Design Charts</u>.

The dimensionless inlet control design charts provided for long span arches, circular and elliptical pipes were derived using the equations presented in Table 8, selected constants from Table 9, conduit geometry obtained from various tables, and manufacturer's information (58, 60, 61). There are several inlet edge configurations for which no hydraulic tests have been performed. In lieu of such tests, the selected edge conditions should approximate the untested configurations and lead to a good estimate of culvert performance. In some cases, it will be necessary to evaluate the inlet edge configuration at a specific flow depth. For example, some inlets may behave as mitered inlets at low headwaters and as thin wall projecting inlets at high headwaters. The designer must apply engineering judgment in selection of the proper relationships for these major structures.

1. **Unsubmerged Conditions**. Equation (26) was used to calculate HW_i/D for selected inlet edge configurations. The following constants were taken from Table 9, Chart 34 for pipe-arches, except for the 45 degree beveled edge inlet. These constants were taken from Chart 3, Scale A, for circular pipe. No constants were available from tests on pipe-arch models with beveled edges.

Inlet Edge	K	M	Slope Correction
Thin Wall Projecting	0.0340	1.5	-0.01
Mitered to Embankment	.0300	1.0	+0.01
Square Edge in Headwall	.0083	2.0	-0.01
Beveled Edge (45^o Bevels)	.0018	2.5	-0.01

Geometric relationships for the circular and elliptical (long axis horizontal) conduits were obtained from reference (60), Tables 4 and 7, respectively. Geometric relationships for the high and low profile long span arches were obtained from reference (58) and the results were checked against tables in reference (61).

2. **Submerged Conditions**. Equation (28) was used to calculate HW_i/D for the same inlet configurations using the following constants:

Inlet Edge	c	Y	Slope Correction
Thin Wall Projecting	0.0496	0.53	-0.01
Mitered to Embankment	.0463	.75	+ .01
Square Edge in Headwall	.0496	.57	- .01
Beveled Edge (45^o Bevels)	.0300	.74	- .01

In terms of $Q/AD^{0.5}$, all non-rectangular shapes have practically the same dimensionless curves for submerged, inlet control flow.

This is not true if $Q/BD^{1.5}$ is used as the dimensionless flow parameter.

To convert $Q/BD^{1.5}$ to $Q/AD^{0.5}$, divide by A/BD for the particular shape of interest as shown in Equation (31). This assumes that the shape is geometrically similar, so that A/BD is nearly constant for a range of sizes.

$$\frac{Q/BD^{1.5}}{(A/BD)} = \left(\frac{Q}{BD^{1.5}}\right)\left(\frac{BD}{A}\right) = \frac{Q}{AD^{0.5}} \qquad (31)$$

3. **Dimensionless Curves**. By plotting the results of the unsubmerged and submerged calculations and connecting the resultant curves with transition lines, the dimensionless design

curves shown in Charts 51 and 52 were developed. All high and low profile arches can be represented by a single curve for each inlet edge configuration. A similar set of curves was developed for circular and elliptical shapes. It is recommended that the high and low profile arch curves in Chart 52 be used for all true arch shapes (those with a flat bottom) and that the curves in Chart 51 be used for curved shapes including circles, ellipses, pipe-arches, and pear shapes.

D. Dimensionless Critical Depth Charts

Some of the long span culverts and special culvert shapes had no critical depth charts. These special shapes are available in numerous sizes, making it impractical to produce individual critical depth curves for each culvert size and shape. Therefore, dimensionless critical depth curves were developed for the shapes which have adequate geometric relationships in the manufacturer's literature. (58) It should be noted that these special shapes are not truly geometrically similar, and any generalized set of geometric relationships will involve some degree of error. The amount of error is unknown since the geometric relationships were developed by the manufacturers.

The manufacturers' literature contains geometric relationships which include the hydraulic depth divided by the rise (inside height) of the conduit (y_h/D) and area of the flow prism divided by the barrel area (A_p/A) for various partial depth ratios, y/D. From Equation (30):

$$\frac{Q}{AD^{0.5}} = \frac{A_p}{A}\left(g \bullet \frac{y_h}{D}\right)^{0.5} \tag{32}$$

Setting y/D equal to d_c/D, it is possible to determine A_p/A and y_h/D at a given relative depth and then to calculate $Q_c/AD^{0.5}$.

Dimensionless plots of d_c/D versus $Q_c/AD^{0.5}$ have been developed for the following culvert materials and shapes:

1. Structural plate corrugated metal box culverts with the following span to rise (B/D) ratios:

$B/D < 0.3$

$0.3 \leq B/D < 0.4$

$0.4 \leq B/D < 0.5$

$B/D \geq 0.5$

2. Structural plate corrugated metal arches with the following B/D ratios:

$0.3 \leq B/D < 0.4$

$0.4 \leq B/D \leq 0.5$

$B/D \geq 0.5$

3. Structural plate corrugated metal ellipses, long axis horizontal.

4. Low profile, long span, structural plate corrugated metal arches.

5. High profile, long span, structural plate corrugated metal arches with the following B/D ratios:

$B/D \leq 0.56$

$B/D > 0.56$

E. Precision of Nomographs

In formulating inlet and outlet control design nomographs, a certain degree of error is introduced into the design process. This error is due to the fact that the nomograph construction involves graphical fitting techniques resulting in scales which do not exactly match the equations. Checks by the authors and others indicate that all of the nomographs from HEC No. 5 have precisions of ± 10 percent of the equation values in terms of headwater (inlet control) or head loss (outlet control).

Extensive checking of the corrugated aluminum structural plate conduit nomographs provided by Kaiser aluminum indicates that most are within ± 5 percent, except for the outlet control nomograph for structural plate corrugated metal box culverts. This nomograph is within the ± 10 percent range of precision.

The new nomographs constructed for tapered inlets have errors of less than 5%, again in terms of headwater or head loss.