

# Overview of Culvert Hydraulics

Mark Jensen

USACE, Institute for Water Resources, Hydrologic Engineering Center



US Army Corps  
of Engineers®

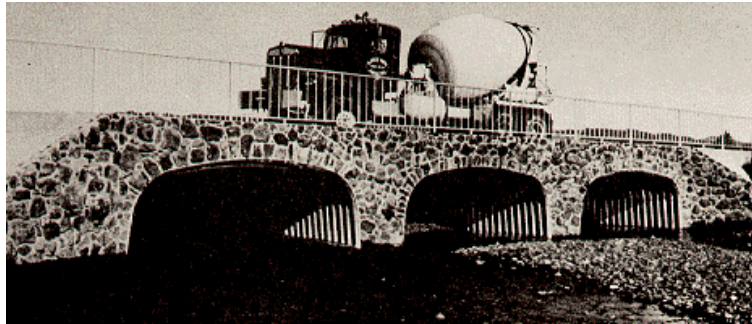


1



## Objectives

- Understand Culvert Hydraulics.
- Understand Basic Culvert Modeling Using HEC-RAS.
- Terminology, Basic Input Requirements and Program Solution Techniques will be Presented.



2



## Introduction

- HEC-RAS Computes Energy Losses:
  - Reach immediately downstream from culvert
  - Through culvert
  - Reach immediately upstream of culvert
- HEC-RAS Models:
  - Single culverts
  - Multiple identical culverts
  - Multiple non-identical culverts

3

### **Introduction:**

HEC-RAS computes energy losses, caused by structures such as culverts, in three parts:

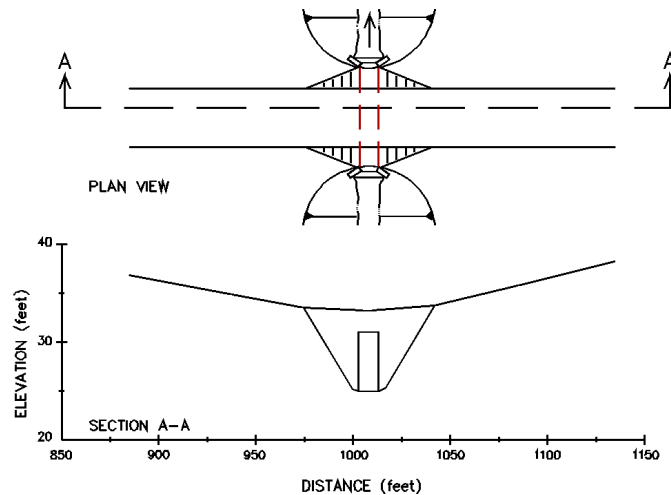
- First are the losses that occur in the reach immediately downstream from the structure, where an expansion of flow takes place.
- second are losses that occur as flow travels into, through, and out of the culvert.
- last are the losses that occur in the reach immediately upstream from the structure, where the flow is contracting towards the opening.

HEC-RAS has the ability to model single culverts; multiple identical culverts; and multiple non-identical culverts.

With the release of Version 3.0, due December 2000, HEC-RAS will be able to evaluate open bottom culverts by automatically calculating a composite Manning's n value. The user will be able to define the amount of flow blockage as well as the n values as it varies with material type.



# General Modeling Guidelines



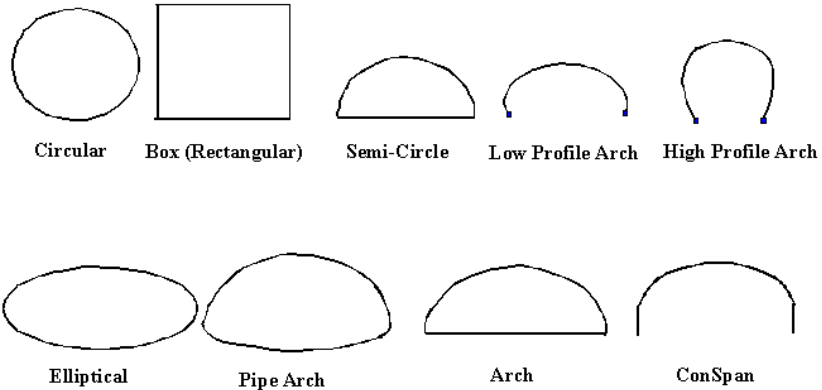
4

## General Modeling Guidelines:

The culvert routines in HEC-RAS are similar to the bridge routines, except that the Federal Highway Administration's (FHWA, 1985) standard equations for culvert hydraulics are used to compute inlet control losses at the structure. The Figure above illustrates a typical box culvert road crossing. As shown, the culvert is similar to a bridge in many ways. The walls and roof of the culvert correspond to the abutments and low chord of the bridge, respectively. The layout of cross sections, the use of the ineffective areas, the selection of loss coefficients, and most other aspects of bridge analysis apply to culverts as well.



## Culvert Shapes and Materials



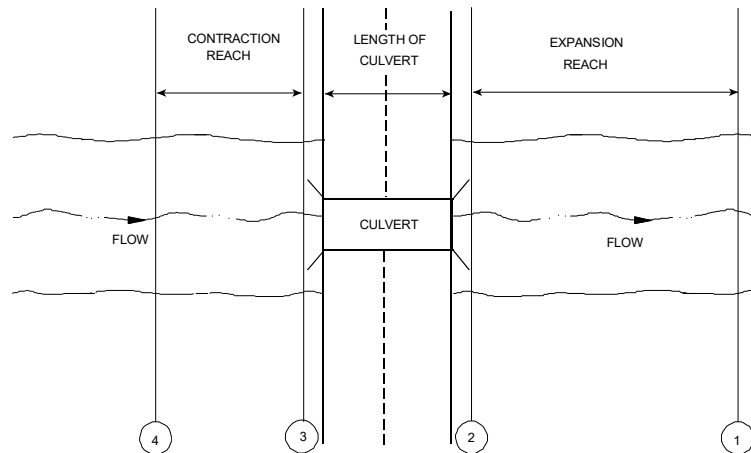
5

### **Culvert Shapes and Materials:**

HEC-RAS can model nine of the most commonly used culvert shapes and virtually any culvert material. These shapes include: circular; box (rectangular); arch; pipe arch; high profile arch; low profile arch; elliptical; ConSpans; and semi-circular culverts. The program can model up to ten different culvert types (any change in shape, slope, roughness, or chart and scale number requires the user to enter a new culvert type) at any given culvert crossing. For a given culvert type, the number of identical barrels is limited to 25.



## Cross Section Locations



6

### Cross Section Locations:

The HEC-RAS culvert routines require the same cross sections as the bridge routines. Four cross sections are required for a culvert model: (1) One cross section sufficiently downstream from the culvert that flow is not affected by the culvert, (2) one at the downstream end of the culvert, (3) one at the upstream end, and (4) one located upstream, beyond the effect of the culvert.

Cross Sections 2 and 3 represent the channel outside of the culvert. The separate culvert data will be used with a copy of these two cross sections to defined the inside of the culvert.

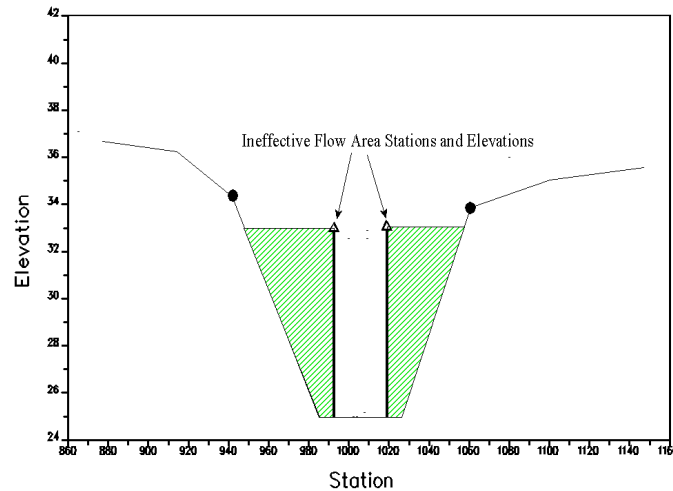


## Cross Section 1

- Downstream cross section is located where the flow has fully expanded from the restricted culvert flow.
- The entire cross section is considered effective in conveying flow.
- Guidelines for locating this cross section are the same as those used for bridge modeling.



## Cross Section 2



8

### Cross Section 2:

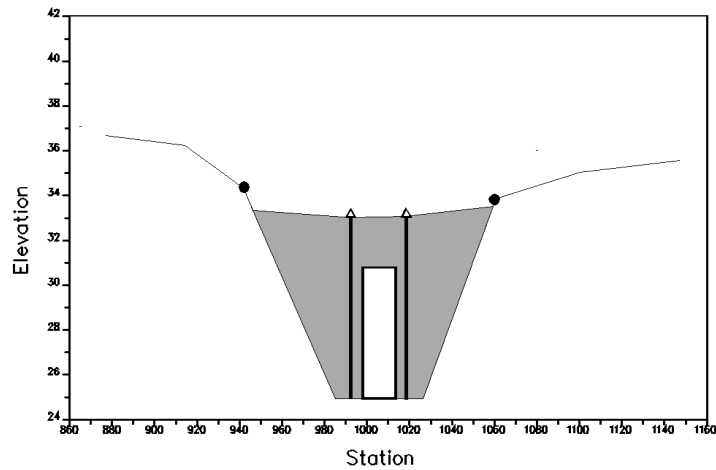
Cross section 2 is located a short distance downstream from the culvert exit. It does not include any of the culvert structure or embankments, but represents the physical shape of the channel just downstream of the culvert. The actual culvert is entered separately from the Bridge and Culvert editor.

The HEC-RAS ineffective area option is used to restrict the effective flow area of cross section 2 to the flow area around or near the edges of the culverts, until flow overtops the roadway. **Because the flow will begin to expand as it exits the culvert, the active flow area at section 2 is generally wider than the width of the culvert opening.** The width of the active flow area will depend upon how far downstream cross section 2 is from the culvert exit. In general, a reasonable assumption would be a 1:1 expansion rate over this short distance. The figure illustrates cross section 2 of a typical culvert model with a box culvert.





## Bridge/Roadway with Culvert

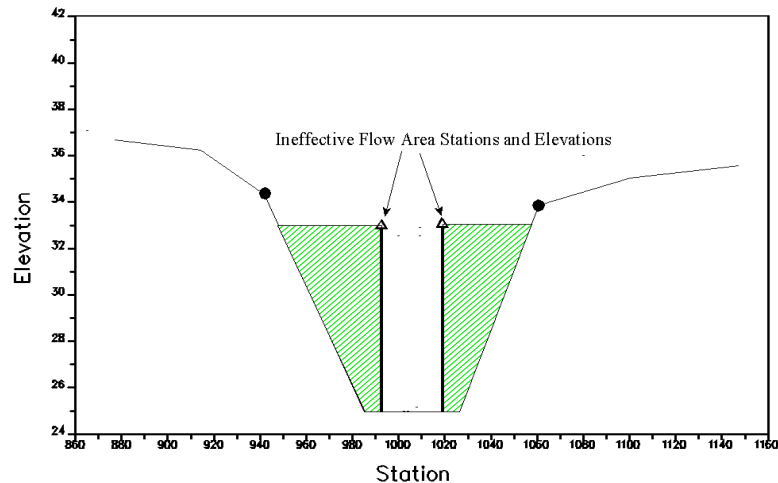


9

The actual culvert is entered separately using the Bridge and Culvert editor. The culvert method uses a combination of a bridge deck, cross sections 2 and 3, and culvert data, to describe the culvert or culverts and the roadway embankment. The culvert data is located at a river station between cross section 2 and cross section 3.



## Cross Section 3



10

### Cross Section 3:

Cross section 3 is located a short distance upstream from the culvert entrance, and represents the physical configuration of the upstream channel. It does not include any of the culvert structure or embankments, but represents the physical shape of the channel just upstream of the culvert.

The HEC-RAS ineffective area option is used to represent the of active flow area just upstream of the culvert. **Because the flow is contracting rapidly as it enters the culvert, the active flow area at section 3 is generally wider than the width of the culvert opening.** The width of the active flow area will depend upon how far upstream cross section 3 is placed from the culvert entrance. Again, an assumption of a 1:1 contraction rate would be reasonable. On the figure, the channel bank locations are indicated by small circles and the ineffective area stations and elevations are indicated by triangles.



## Cross Section 4

- Upstream cross section in the culvert model is located at a point where the flow has not begun to contract to its constricted flow area near the culvert.
- This distance is normally determined assuming a 1:1 contraction of the flow.
- The entire cross section is considered effective in conveying flow.
- The bridge modeling guidelines can be used to help locate this cross section.



## Expansion and Contraction Coefficients

	Contraction	Expansion
No transition loss computed	0.0	0.0
Gradual transitions	0.1	0.3
Typical bridge sections	0.3	0.5
Abrupt transitions	0.6	0.8

\*Set these on XS 2, 3 and 4

12

### Expansion and Contraction Coefficients:

User-defined coefficients are required to compute head losses due to the contraction and expansion of flows upstream and downstream from a culvert. These losses are computed by multiplying an expansion or contraction coefficient by the absolute difference in velocity head between two cross sections.

If the velocity head increases in the downstream direction, a contraction coefficient is applied (between cross sections 4 and 3). When the velocity head decreases in the downstream direction, an expansion coefficient is used (between cross sections 2 and 1). Recommended values for the expansion and contraction coefficients are given in Chapter 3 of the hydraulics manual (table 3.2).

Energy losses increase with the abruptness of the transition; therefore, for culverts with abrupt flow transitions, the contraction and expansion loss coefficients may need to be increased to account for additional energy losses.



## Limitations

- For Each Culvert, constant
  - Cross Sectional Area
  - Bottom Slope
  - Roughness
  - Flow
- Manning's n Values for Top
- Manning's n Value for the Bottom
  - Good for natural bottom culverts  
(or ones that are partially filled with sediment)

13

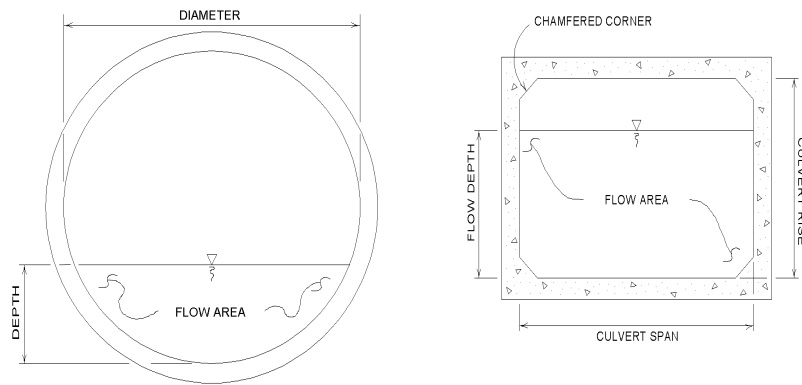
### **Limitations:**

While different culverts can have varying slopes, cross sectional areas and roughness, any given culvert must have constant slope, cross sectional area and roughness.

With Version 3.0, the use of a single Manning's n value is no longer a limitation. The user can now define the bottom roughness for an open bottom or partially filled culvert and define the culvert material n value as well. HEC-RAS uses the user supplied information such as the blocked or filled in area to compute a composite Manning's n value for the hydraulic calculations.



# Culvert Terminology



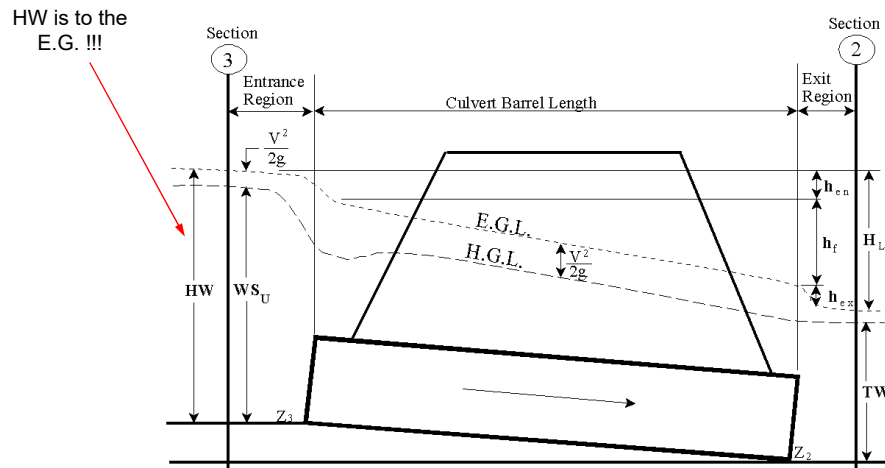
14

## Introduction to Culvert Terminology:

A **culvert** is a relatively short length of closed conduit which connects two open channel segments or bodies of water. Two of the most common types of culverts are: **circular pipe culverts**, which are circular in cross section, and **box culverts**, which are rectangular in cross section. In addition to box and pipe culverts, HEC-RAS has the ability to model arch; pipe arch; high profile arch; low profile arch; elliptical; semi-circular culvert shapes; and ConSpans.



# Culvert Terminology



15

## Culvert Terminology:

Culverts are made up of an **entrance** where water flows into the culvert, a **barrel**, which is the closed conduit portion of the culvert, and an **exit**, where the water flows out of the culvert. The total flow capacity of a culvert depends upon the characteristics of the entrance as well as the culvert barrel and exit.

The **Tailwater** is the depth of water on the exit or downstream side of the culvert, as measured from the downstream invert (shown as **TW**). The **invert** is the lowest point on the inside of the culvert, at a particular cross section.

**Headwater** (HW) is the depth from the culvert inlet invert to the energy grade line, for the cross section just upstream of the culvert (section 3). The Headwater represents the amount of energy head required to pass a given flow through the culvert.

The **Upstream Water Surface** ( $WS_U$ ) is the depth of water on the entrance or upstream side of the culvert (section 3), as measured from the upstream invert of cross section 3.

The **Total Energy** at any location is equal to the elevation of the invert plus the specific energy (depth of water + velocity head) at that location. All of the culvert computations within HEC-RAS compute the total energy for the upstream end of the culvert. The upstream water surface ( $WS_U$ ) is obtained by placing that energy into the upstream cross section and computing the water surface that corresponds to that energy for the given flow rate.



## Flow Analysis for Culverts

Factor	Inlet Control	Outlet Control
Headwater Elevation	X	X
Inlet Area	X	X
Inlet Edge Configuration	X	X
Barrel Shape	X	X
Barrel Roughness		X
Barrel Area		X
Barrel Length		X
Barrel Slope	X	X
Tailwater Elevation		X

16

### Flow Analysis for Culverts:

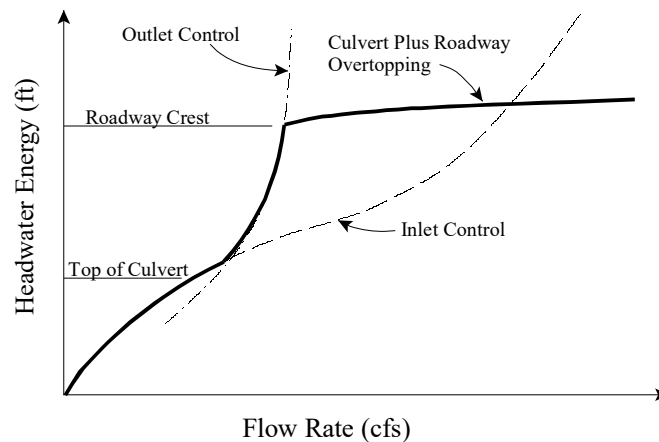
The analysis of flow in culverts is quite complicated. It is common to use the concepts of "inlet control" and "outlet control" to simplify the analysis.

The HEC-RAS culvert routines compute the upstream energy required to produce a given flow rate through the culvert for inlet control conditions and for outlet control conditions. The higher upstream energy "controls" and determines the type of flow in the culvert for a given flow rate and tailwater condition.





## Flow Analysis for Culverts



17

### Flow Analysis for Culverts:

The HEC-RAS culvert routines compute the upstream energy required to produce a given flow rate through the culvert for inlet control conditions and for outlet control conditions. The higher upstream energy "controls" and determines the type of flow in the culvert for a given flow rate and tailwater condition.

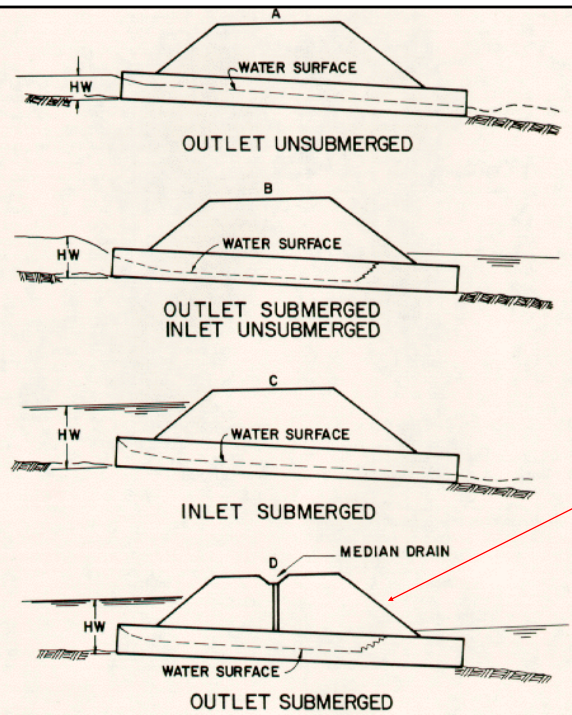
During the computations, if the inlet control answer comes out higher than the outlet control answer, the program will perform some additional computations to evaluate if the inlet control answer can actually persist through the culvert without pressurizing the culvert barrel. The assumption of inlet control is that the flow passes through critical depth near the culvert inlet and transitions into supercritical flow. If the flow persists as low flow through the length of the culvert barrel, then inlet control is assumed to be valid. If the flow goes through a hydraulic jump inside the barrel, and fully develops the entire area of the culvert, it is assumed that this condition will cause the pipe to pressurize over the entire length of the culvert barrel and thus act more like an orifice type of flow. If this occurs, then the outlet control answer (under the assumption of a full flowing barrel) is used instead of the inlet control answer.



## Inlet Control

- Occurs when the flow capacity of the entrance is less than the flow capacity of the barrel.
- The control section is located just inside the culvert entrance.
- The water surface passes through critical depth.
- Flow downstream is supercritical.
- Energy is computed assuming culvert acts as a sluice gate or weir.
- Therefore, inlet capacity depends on the entrance geometry.

18



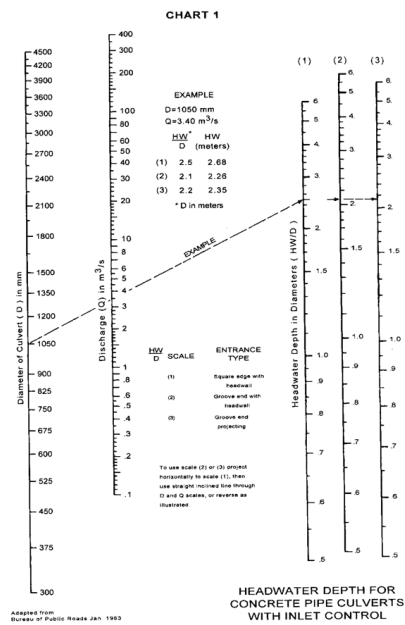
RAS assumes this scenario goes to full pressure

19

### Inlet Control:

In inlet control, the flow is always free surface downstream of the inlet, and the entrance and outlet may be submerged or unsubmerged. Even though the outlet is submerged with high tailwater, the culvert should be checked for inlet control.

For inlet control conditions, the capacity of the culvert is limited by the capacity of the culvert opening.



20

### Inlet Control Nomographs:

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 shown in the "Hydraulic Design of Highway Culverts" publication [FHWA, 1985].



## Computing Inlet Control Headwater

• Unsubmerged Inlet 
$$\frac{HW_i}{D} = \frac{H_c}{D} + K \left[ \frac{Q}{AD^{0.5}} \right]^M - 0.5S$$

• Submerged Inlet 
$$\frac{HW_i}{D} = K \left[ \frac{Q}{AD^{0.5}} \right]^M$$

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

21

### Inlet Control:

$HW_i$  = Headwater energy depth above the invert of the culvert inlet, ft.

$D$  = Interior height of the culvert barrel, ft.

$H_c$  = Specific head at critical depth ( $d_c + V_c^2/2g$ ), ft.

$Q$  = Discharge through the culvert, cfs.

$A$  = Full cross sectional area of the culvert barrel, ft<sup>2</sup>.

$S$  = Culvert barrel slope, ft/ft.

$K, M, c, Y$  = Equation constants, based on shape & entrance

The FHWA inlet control equations are used by the HEC-RAS culvert routines in computing the upstream energy. The inlet control equations were developed for submerged and unsubmerged inlet conditions.

Note that there are two forms of the unsubmerged inlet equation. The first form is more correct from a theoretical standpoint, but form two is easier to apply and is the only documented form of equation for some of the culvert types. Both forms of the equations are used in the HEC-RAS software, depending on the type of culvert.



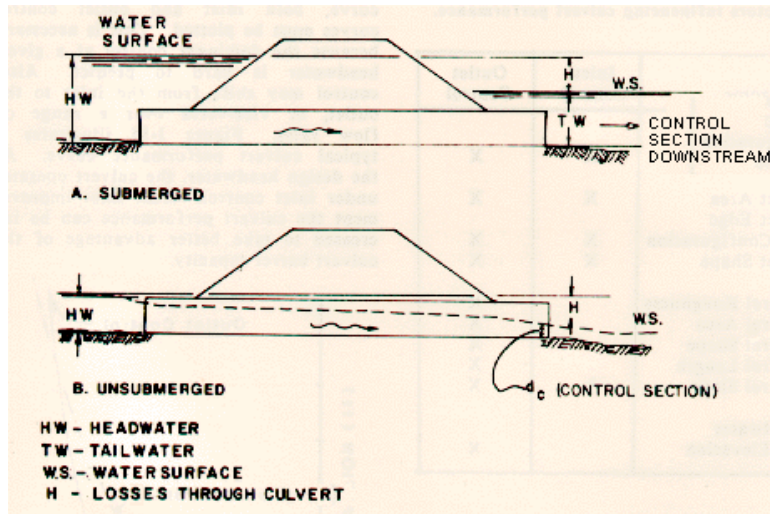
## Outlet Control

- Occurs when the flow capacity is limited by downstream conditions (high tailwater) or by the capacity of the barrel.
- Flow is subcritical.
- Energy is computed by performing an energy balance from the downstream section (section 2) to the upstream section (section 3).
- Entrance, friction, and exit losses are computed.

22



## Computing Outlet Control Headwater



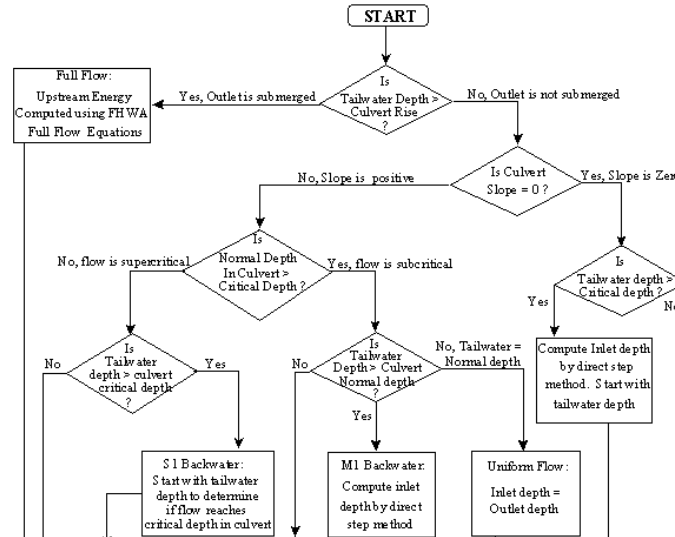
23

### Outlet Control:

In outlet control, the culvert can have free surface flow throughout the length of the culvert or have low or high tailwater conditions. All the factors listed in the inlet control and outlet control table have some influence on the energy to move the flow through the culvert.



# Computing Outlet Control Headwater



24

## Outlet Control Flow Diagram:

This figure illustrates the logic of the outlet control computations. The full flow diagram can be found in Chapter 6 of the HEC-RAS Hydraulic Reference Manual.





## Computing Outlet Control Headwater

$$Z_3 + Y_3 + \frac{\alpha_3 V_3^2}{2g} = Z_2 + Y_2 + \frac{\alpha_2 V_2^2}{2g} + H_L$$

Where:  $Z_3$  = Upstream invert elevation of the culvert

$Y_3$  = The depth of water above the upstream culvert inlet

$V_3$  = The average velocity upstream of the culvert

$\alpha_3$  = The velocity weighting coefficient upstream of the culvert

$g$  = The acceleration of gravity

$Z_2$  = Downstream invert elevation of the culvert

$Y_2$  = The depth of water above the downstream culvert inlet

$V_2$  = The average velocity downstream of the culvert

$\alpha_2$  = The velocity weighting coefficient downstream of the culvert

$H_L$  = Total energy loss through the culvert (from section 2 to 3)

25

### Outlet Control:

For outlet control flow, the required upstream energy to pass the given flow must be computed considering several conditions within the culvert and downstream of the culvert. HEC-RAS uses Bernoulli's equation to compute the change in energy through the culvert under outlet control conditions.



## Outlet Control Computations

- $HL = h_{en} + h_f + h_{ex}$

- Entrance loss     $h_{en} = k_{en} (VH_{Culv \text{ inlet}})$
- Friction loss          $h_f \rightarrow$  from direct step
- Exit loss             $h_{ex} = k_{ex} (VH_{Culv \text{ outlet}} - VH_{xs2})$

- Where  $VH$  is velocity head

26

### Full Flow Equations:

For culverts flowing full, the total **head loss**, or energy loss ( $H_L$ ), through the culvert is measured in feet (or meters).

The friction loss in the culvert is computed using Manning's formula.

The entrance energy loss is computed as a coefficient times the velocity head inside the culvert at the upstream end.

The exit energy loss is computed as a coefficient times the change in velocity head from just inside the culvert, at the downstream end, to outside of the culvert, at the downstream end.



## Outlet Computations (Standard Step from XS2 into Outlet)

$$Z_C + Y_C + \frac{\alpha_C V_C^2}{2g} = Z_2 + Y_2 + \frac{\alpha_2 V_2^2}{2g} + h_{ex}$$

Where: ZC = Elevation of the culvert invert at the downstream end  
YC = Depth of flow inside culvert at downstream end  
VC = Velocity inside culvert at downstream end  
Z2 = Invert elevation of the cross section downstream of culvert (Cross Section 2)  
Y2 = Depth of water at Cross Section 2  
V2 = Average velocity of flow at Section 2

27

### Direct Step Water Surface Profile Computations:

For culverts flowing partially full, the water surface profile in the culvert is computed using the direct step method. This method is very efficient, because no iterations are required. The water surface profile is computed for small increments of depth (usually between 0.01 and 0.05 feet). If the flow depth equals the height of the culvert before the profile reaches the upstream end, the friction loss through the remainder of the culvert is computed assuming full flow.

The first step in the direct step method is to compute the exit loss and establish a starting water surface inside the culvert. If the tailwater depth is below critical depth inside the culvert, then the starting condition inside the culvert is assumed to be critical depth. If the tailwater depth is greater than critical depth in the culvert, then a mini energy balance is performed from the downstream cross section to inside of the culvert.

Once a downstream water surface is established inside the culvert, the direct step backwater is computed through the culvert. The calculations will continue until a water surface and energy are obtained inside the upstream end of the culvert. The final step is to add an entrance loss to the computed energy to obtain the upstream energy outside of the culvert at section 3.

The water surface outside the culvert is then obtained by computing the water surface at section 3 that corresponds to the calculated energy for the given flow rate.



## hex → Exit Loss

- Exit Loss is computed as the exit loss coefficient ( $k_{ex}$ ) times the difference in velocity head from culvert exit and the XS downstream (XS2)
- Exit loss coefficient ( $k_{ex}$ ) default is 1 – This assumes the culvert is exiting into a calm pool of water. If not  $k_{ex} < 1.0$
- (this computation is a normal Standard Step)

28

The default value for  $K_{ex} = 1.0$ , This is conservative and is set this way for design purposes. If you are performing an analysis and trying to develop the most accurate model you can, then this value should be evaluated and set to an appropriate magnitude based on the degree of expansion that will occur downstream of the culvert.



## H<sub>f</sub> → Friction loss in barrel

- Check if its flowing full
- If full then:

$$h_f = L \left( \frac{Qn}{1.486 AR^{2/3}} \right)^2$$

- Otherwise:
  - Uses direct step methodology

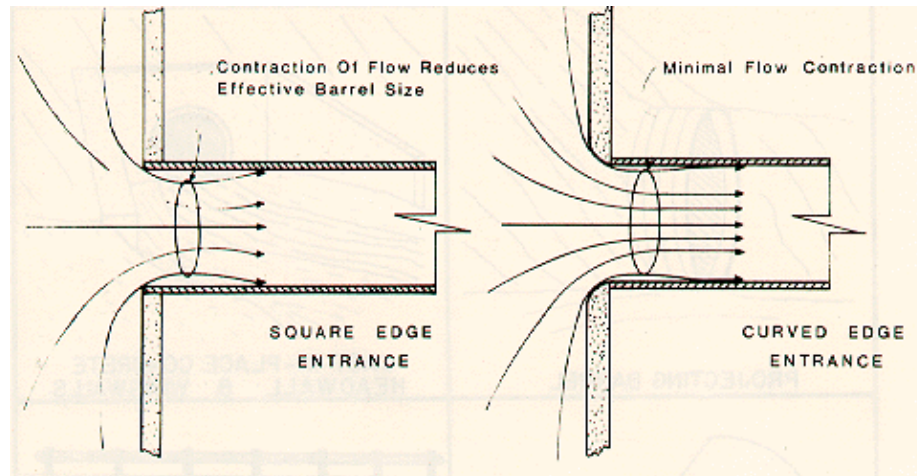


## $h_{en} \rightarrow$ Entrance Loss

- Entrance Loss is computed as the entrance loss coefficient ( $k_{en}$ ) times the absolute velocity head in the culvert entrance
- This computation is not a normal Standard Step approach, and therefore  $k_{en}$  is not the same as a contraction loss coefficient. Values for  $k_{en}$  are listed in the hydraulic reference manual



## Entrance Efficiency



31

### Inlet Edge Configuration:

As flow accelerates to enter the culvert, it separates to some extent from the edges, causing a flow contraction. Note the reduction in flow area caused by the contraction. This reduces the effective area of flow, and the barrel area is thus not fully used.

If the inlet conditions were more favorable, this contraction, and the associated energy losses, could be reduced. As a result, the culvert would convey more flow.



## Entrance Loss Coefficients (For Outlet Control Only)

Type of Structure and Design of Entrance	Coefficient, $k_{en}$
<b>Concrete Pipe Projecting from Fill (no headwall):</b>	
Socket end of pipe	0.2
Square cut end of pipe	0.5
<b>Concrete Pipe with Headwall or Headwall and Wingwalls:</b>	
Socket end of pipe (grooved end)	0.2
Square cut end of pipe	0.5
Rounded entrance, with rounding radius = 1/12 of diameter	0.2
<b>Concrete Pipe:</b>	
Mitered to conform to fill slope	0.7
End section conformed to fill slope	0.5
Beveled edges, 33.7 or 45 degree bevels	0.2
Side slope tapered inlet	0.2
<b>Corrugated Metal Pipe or Pipe-Arch:</b>	
Projected from fill (no headwall)	0.9
Headwall or headwall and wingwalls square edge	0.5
Mitered to conform to fill slope	0.7
End section conformed to fill slope	0.5
Beveled edges, 33.7 or 45 degree bevels	0.2
Side slope tapered inlet	0.2

32

### Typical Values of $k_{en}$ :

Listed are some typical values of  $k_{en}$  for pipe culverts. A more complete list is provided in Chapter 6 of the HEC-RAS Hydraulic Reference Manual.

**Note:** These values are only to be used for outlet control conditions. While the inlet edge configuration is extremely important under inlet control as well, different factors to model the inlet are used during the inlet control calculations.





## Critical Depth in Culvert

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

Where:  $Q$  = flow rate in the channel (cfs)  
 $g$  = acceleration due to gravity (32.2 ft/sec<sup>2</sup>)  
 $A$  = cross-sectional area of flow (square feet)  
 $T$  = top width of flow (feet)

$$y_c = \sqrt[3]{\frac{q^2}{g}}$$

Where:  $y_c$  = critical depth (feet)  
 $q$  = unit discharge per linear foot of width (cfs/ft)

33

### Critical Depth of Flow in the Culvert:

**Critical depth** occurs when the flow in a channel has a minimum specific energy. **Specific energy** refers to the sum of the depth of flow and the velocity head. Critical depth depends only on the channel shape and flow rate.

The depth of flow at the culvert outlet is assumed to be equal to critical depth for culverts operating under outlet control with low tailwater. Critical depth may also influence the inlet control headwater for unsubmerged conditions.

The culvert routines compute critical depth in the culvert by an iterative procedure, which arrives at a value satisfying the first equation. Critical depth for box culverts can be solved directly with the second or lower equation [AISI, 1980].



## Horizontal and Adverse Culvert Slopes

- The culvert routines also allow for horizontal and adverse culvert slopes. The primary difference is that normal depth is not computed for a horizontal or adverse sloping culvert. Outlet control is either computed by the direct step method for an unsubmerged outlet or the full flow equation for a submerged outlet.



## Weir Flow

- HEC-RAS first assumes all flow is going through the culvert.
- Checks energy elevation against minimum elevation for weir flow to occur.
- If energy elevation is less than weir elevation, solution is final.
- If energy elevation is greater than elevation that would cause weir flow, HEC-RAS performs an iterative procedure balancing weir and culvert flow.
- Solution is final when the weir flow and culvert flow produces the same energy elevations.

35

### **Weir Flow:**

The first solution through the culvert is under the assumption that all of the flow is going through the culvert barrels. Once a final upstream energy is obtained, the program checks to see if the energy elevation is greater than the minimum elevation for weir flow to occur.

If the computed energy is less than the minimum elevation for weir flow, then the solution is final.

If the computed energy is greater than the minimum elevation for weir flow, the program performs an iterative procedure to determine the amount of flow over the weir and flow through the culverts. During this procedure, the program recalculates both inlet and outlet control culvert solutions for each estimate of the culvert flow. In general, the higher of the two is used for the culvert portion of the solution, unless the program calculates that inlet control cannot be maintained through the culvert barrel. The program will iterate until the flow divide produces the same upstream energy (within the error tolerance) for both weir and culvert flow.



## Subcritical and Mixed Flow Regime Inside Culvert

- Performs a backwater (subcritical flow) calculation first.
- If critical depth is reached, usually with a steep slope, supercritical or forewater calculation is performed.
- Specific force is calculated for both.
- If subcritical specific force is greater than supercritical, a hydraulic jump occurs.
- If not, a supercritical flow profile exists for the entire length of the culvert.

36

### **Supercritical and Mixed Flow Regime Inside Culvert:**

The culvert routines allow for supercritical and mixed flow regimes inside the culvert barrel. During outlet control computations, the program first makes a subcritical flow pass through the culvert, from downstream to upstream. If the culvert barrel is on a steep slope, the program may default to critical depth inside of the culvert barrel. If this occurs, a supercritical forewater calculation is made from upstream to downstream, starting with the assumption of critical depth at the culvert inlet. During the forewater calculations, the program is continually checking the specific force of the flow, and comparing it to the specific force of the flow from the subcritical flow pass. If the specific force of the subcritical flow is larger than the supercritical answer, the program assumes that a hydraulic jump will occur at that location. Otherwise, a supercritical flow profile is calculated all the way through and out of the culvert barrel.

Questions?



US Army Corps  
of Engineers®

IWR



37