

CHAPTER 5

CULVERTS

NOTE: All questions and comments should be directed to the Drainage Specialist, Design Support Area.

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5.1 INTRODUCTION/PURPOSE

This chapter provides design procedures for the hydraulic design of highway culverts, which are based on FHWA Hydraulic Design Series Number 5 (HDS5), *Hydraulic Design of Highway Culverts*. This chapter also:

- Presents results of culvert analysis using HY8 culvert analysis software, and
- Provides a summary of the design philosophy contained in the AASHTO Highway Drainage Guidelines, Chapter IV, Hydraulic Design of Culverts.

5.2 DEFINITIONS

Following are concepts important in culvert design. Several terms are shown in Figure 5-1, Culvert Terms.

Critical Depth - The depth at which the specific energy of a given flow rate is at a minimum. For a given discharge and cross-section geometry there is only one critical depth. Appendix 5-C at the end of this chapter contains critical depth charts for different shapes.

Crown - The highest interior elevation of a culvert, sewer, drain pipe, or tunnel. This may also be referred to as underclearance or low chord. See Figure 5-1.

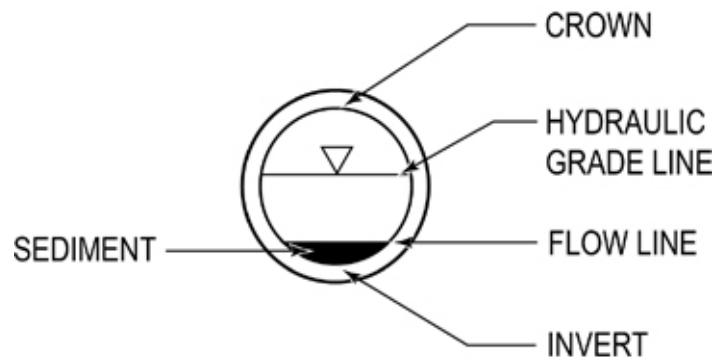


Figure 5-1 Culvert Terms

Culvert - A structure that is usually designed hydraulically to convey surface runoff through an embankment. The span is less than 20 feet.

Energy Grade Line (EGL) - A line joining the elevation of energy heads; a line drawn above the hydraulic grade line a distance equivalent to the velocity head of the flowing water at each section along a stream channel or conduit.

Flow Line - The lowest physical surface elevation in a drainage system. For storm sewers, the flow line is the same as the invert. This may not be true for culverts that are recessed. See Figure 5-1.

Flow Type - The USGS has established seven culvert flow types which assist in determining the flow conditions at a particular culvert site. Diagrams of these flow types are provided in the design methods, Section 5.4.

Free Outlet - An outlet that has a tailwater equal to or lower than critical depth. For culverts having free outlets, lowering of the tailwater has no effect on the discharge or the backwater profile upstream of the tailwater.

Harmful Interference - MDEQ defines harmful interference as cause of an unnaturally high stage or unnatural direction of flow on a river or stream that causes, or may cause, damage to property, a threat to life, a threat of personal injury, or a threat to water resources.

A working definition of harmful interference is any harm that may be caused to riparians including unnaturally low water stages.

Hydraulic Grade Line (HGL) - A profile of the piezometric level to which the water would rise in piezometric line tubes along a pipe run. In open channel flow, it is the water surface. See Figure 5-1.

Improved Inlet - An inlet that has an entrance geometry which decreases the flow contraction at the inlet and thus increases the capacity of culverts. These inlets are referred to as either side- or slope-tapered (walls or increased flow-line slope at the entrance) and sometimes are beveled edged.

Inlet Control - Occurs when the culvert barrel is capable of conveying more flow than the inlet will accept. The control section of a culvert operating under inlet control is located just inside the entrance. Critical depth occurs at or near this location, and the flow regime immediately downstream is supercritical. Hydraulic characteristics downstream of the inlet control section do not affect the culvert capacity. The upstream water surface elevation and the inlet geometry represent the major flow controls. The inlet geometry includes the barrel shape, cross-sectional area, and the inlet edge.

Invert - The lowest interior elevation of a culvert, sewer, or tunnel. See Figure 5-1.

Mild Slope - Occurs where critical depth is less than normal depth.

Normal Depth - The depth at normal flow.

Normal Flow - Occurs in a channel reach when the discharge, velocity, and depth of flow do not change throughout the reach. The water surface and channel bottom will be parallel. This type of flow will exist in a culvert operating on a constant slope, provided the culvert is sufficiently long and the tailwater is less than the normal depth.

Ordinary Mean High Water Mark - The line on the shore of a waterway that is:

- Established by the fluctuations of water.
- Indicated by physical characteristics such as a clear and natural line impressed on the bank, shelving, changes in the character of the soil, the destruction of terrestrial vegetation, or the presence of litter or debris.

Outlet Control - Occurs when the culvert barrel is not capable of conveying as much flow as the inlet opening will accept. The control section for outlet control flow in a culvert is located at the barrel exit or further downstream. Either subcritical or pressure flow exists in the culvert barrel under these conditions. All of the geometric and hydraulic characteristics of the culvert play a role in determining its capacity: water surface elevation at the outlet, slope, length, and hydraulic roughness of the culvert barrel.

Steep Slope - Hydraulically steep slopes occur where critical depth is greater than normal depth.

Submerged Inlet - Occurs when the headwater is greater than $1.2D$ where D is the culvert diameter or barrel height.

Submerged Outlet - Occurs when the tailwater elevation is higher than the crown of the culvert.

A list of symbols and acronyms used in this chapter is given in Appendix 5-A.

5.3 POLICY AND DESIGN CRITERIA

5.3.1 Introduction

The design of a culvert system for a highway crossing of a floodplain involves using information from the other chapters in this manual and should be referenced when necessary.

Culverts shall be selected which satisfy:

- topography, and
- design policies and criteria.

Culverts shall be analyzed for:

- environmental impact,
- harmful interference,
- hydraulic equivalency, and
- risk and cost.

Select a culvert which best integrates engineering, economic, and environmental considerations. The chosen culvert shall meet the selected structural and hydraulic criteria and shall be based on:

- construction and maintenance costs,
- risk of failure or property damage,
- traffic safety,
- environmental or aesthetic considerations,
- political or nuisance considerations, and
- land use requirements.

Structure Types to Consider

Culvert

- Is a covered structure with both ends open.
- Designed using procedures of HDS5.

Storm Drain (See Chapter 7, Road Storm Drainage Systems)

- Is a covered structure with either end in a manhole or other structure and is usually a part of a system of pipes.
- Explained in the Urban Drainage Design Manual, HEC-22, FHWA, 2001.

Methods of design discussed in this chapter include: hydrology methods, computational methods, and a computer software method.

Hydrologic Methods

Hydrologic methods are discussed in Chapter 3, Hydrology. Key elements of constant discharge are noted below, particularly use of peak discharge.

Constant Discharge

- Is assumed for most culvert designs.
- Is usually the peak discharge for the design storm hydrograph.
- Will yield a conservatively sized structure where temporary storage is available, but not accounted for in the determination of design discharge.

Computational Methods

An exact theoretical analysis of culvert flow can be complex because the following:

- Analyzing non-uniform flow with regions of both gradually varying and rapidly varying flow.
- Determining how the flow type changes as the flow rate and tailwater elevations change.
- Applying backwater and draw-down calculations, energy, and momentum balance.
- Applying the results of hydraulic model studies.
- Determining if hydraulic jumps occur and if they are inside or downstream of the culvert barrel.

This chapter outlines simplified hydrologic analysis by using nomographs and computer programs.

Nomographs

- Require a trial and error solution which is quite easy and provides reliable designs for many applications.
- Require additional computations for tailwater, outlet velocity, hydrographs, routing, and roadway overtopping.
- Circular and box shapes are included at the end of this chapter. Nomographs for other shapes and improved inlets are found in HDS5.
- Electronic version of nomographs are available on FHWA-SA-96-080, Hydraulic Design of Highway Culverts CDROM, 1996 and FHWA Hydraulics Library CDROM, 1999.

Computer Software Methods

HY8 (FHWA Culvert Analysis Software) and HEC-RAS have the capability to analyze culverts.

HY8:

- Is an interactive program written in Basic.
- Uses the theoretical basis for the nomographs.
- Computes tailwater, improved inlets, road overtopping, hydrographs, routing, and multiple independent barrels.
- Develops and plots tailwater rating curves.
- Develops and plots performance curves.
- Is documented in the HY8 Applications Guide.

HEC-RAS (Hydraulic Engineering Center - River Analysis Systems):

- Allows users to perform steady and unsteady flow calculations.
- Is an integrated system of software designed for interactive use in a multi-tasking, multi-user network environment.
- Will contain three hydraulic analysis components:
 - Steady flow water surface profile calculations,
 - Unsteady flow simulation,
 - Moveable boundary sediment transport computations.

5.3.2 Culvert Policy

FHWA's Federal Aid Policy Guide (FAPG), Part 650 for Federal aid projects and State law, requires that at each location where the highway will encroach on the floodplain, the plans will show the following: magnitude, frequency, and water surface elevations for the design, 2 percent chance (50-year), flood and base, 1 percent chance (100-year), flood. Floodplain data, based on the culvert analysis, shall be included in the Hydraulic Analysis Form included in Chapter 6, Bridges, Appendix 6-B. In addition, MDOT must comply with the Governor's State Executive Order 1977-4, "*State Flood Hazard Management Plan*," since it establishes flood standards and design requirements (see Chapter 2, Legal Policy and Procedure, Appendix 2-F).

All highways that encroach on the floodplain, either transversely or longitudinally, shall require a hydraulic analysis and be designed to permit conveyance of up to the 1 percent chance (100-year) flood without causing an adverse impact on natural and beneficial floodplain levels, damage to property, or a significant increase in potential for interruption or termination of emergency service or emergency evacuation routes.

Where the size of the waterway opening is controlled by factors other than hydraulics, FHWA requests that they be advised of these considerations when the plans are submitted for their review. FHWA and MDOT review requires early submittal of this data. Data must be included prior to the Plan Review Meeting.

5.3.2.1 Culvert Pipe Class Designation

Culvert pipe classes are used to designate the pipe's strength and its load-carrying properties. Culvert pipes are designated by class. The height of fill over the top of culvert pipe determines the class pipe to be used. See the current MDOT Standard Specifications for Construction.

5.3.2.2 Culvert Usage Guidelines

All pipe culverts will be specified by class and diameter, e.g., Culv, Cl A, 24-inch. The design life for culverts will be 50 years, except driveway culverts will be 25 years.

For pipe culverts equal to or greater than 30 inches, the material type (i.e., the Manning's roughness coefficient) must be accounted for in the hydraulic analysis. The designer must perform a hydraulic analysis for all available pipe materials in the class. Alternative pay items must be called for on the plans and in the proposal.

In some applications a specific material for a culvert pipe may be required exclusively, or a specific material may be determined inappropriate for a particular location. The required material should be specified in the pay item. The pipe culvert class, material, and diameter (e.g., Culv, Cl A, Conc, 42 inch) should be specified. The prohibited material should be identified by note on the plans. When a specific material is prohibited and its exclusion is not covered in the Standard Specifications, a note to the file must be written to describe the basis for exclusion. This information should also be forwarded to the field. The exception is when extending an existing system with like material.

The following guidelines are specific to culverts:

- All culverts should have a hydraulic analysis.
- Survey information shall include topographic features, channel characteristics, high water information, existing structures, and other related site-specific information.
- Multiple culverts (parallel) should be avoided.

- Culverts shall be designed to accommodate debris, or proper provisions shall be made for debris control.
- Design data and calculations shall be assembled in the project design files.
- Where practical, some means shall be provided for personnel and equipment access to facilitate maintenance.
- Culverts should be regularly inspected and maintained.

5.3.3 Culvert Environmental Permit Requirements

All Michigan Department of Environmental Quality (MDEQ) and USACE permit applications are to be reviewed and coordinated by MDOT's Regional Environmental Permit Coordinators. In addition, MDOT must comply with the Governor's State Executive Order 1977-4, "State Flood Hazard Management Plan," since it establishes flood standards and design requirements (See Chapter 2, Legal Policy and Procedures, Appendix 2-F). The MDEQ coordinates under joint permit application the U.S. Army Corps of Engineers 404 Permit. The Water Pollution Control Act's 404 Permit is required for watercourses adjacent to wetlands, as currently listed in the USACE jurisdiction maps.

More details and information on applicable State laws can be found in Chapter 2, Legal Policy and Procedures. The following laws are applicable to culverts:

- Part 301, Inland Lakes and Streams, of the Natural Resources and Environmental Protection Act, Act 451 of Public Acts of 1994, as amended, requires an Inland Lakes and Streams Permit from the MDEQ for construction over or adjacent to inland lakes or streams.
- Part 31, Water Resources Protection, of the Natural Resources and Environmental Protection Act, Act 451 of Public Acts of 1994, as amended, requires a Floodplain Permit from the MDEQ for construction over or adjacent to streams that have drainage areas greater than or equal to 2 square miles.
- Part 303, Wetland Protection, of the Natural Resources and Environmental Protection Act, Act 451 of the Public Acts of 1994, requires a State Wetland Permit from the MDEQ for construction in wetland areas. Wetland mitigation plans are to be coordinated with the Environmental Section, Project Planning Division.

5.3.4 Culvert Design Considerations (updated January 2004)

Structure Type Selection (Culvert or Bridge)

Culverts are used where:

- bridges are not hydraulically required,

- debris and ice are tolerable, and
- more economical than a bridge.

Where practical, culvert design should provide for personnel and equipment access to facilitate maintenance. Culverts should be regularly inspected and maintained.

Length and Slope

The culvert length and slope shall be chosen to approximate existing topography, and to the degree practical:

- the culvert invert shall be aligned with the channel bottom and the skew angle of the stream, and
- the culvert entrance shall match the geometry of the roadway embankment.

Steep Slopes

The use of culverts on steep slopes should be avoided unless maintaining the existing slope of a natural channel. When culverts on steep slopes flow full, reduced or negative pressures prevail along the boundaries of the culvert. These low pressures can cause failure of the joints and collapse the culvert pipe.

Allowable Headwater

Allowable headwater is the depth of water that can be ponded at the upstream end of the culvert during the design flood and should:

- not cause harmful interference to adjacent property.
- be at least 1.5 feet below the edge of the shoulder during the 2 percent chance (50-year) storm.
- be no greater than the elevation where flow diverts around the culvert.

The hydraulic capacity and headwater depth are normally controlled by the conditions at either the inlet or the outlet of the culvert. Inlet control, as described in the HDS-5, means that the discharge capacity of a culvert is controlled by the entrance geometry. Outlet control is dependent on downstream conditions. Losses for a culvert flowing under outlet control would include expansion (at outlet), friction (culvert length and material type), and contraction (at entrance).

Tailwater

Tailwater relationships may or may not be impacted by downstream conditions. If no downstream water bodies are present, consider the following:

- Evaluate the hydraulic conditions of the downstream channel to determine a tailwater depth for a range of discharges, which includes the review discharge (see Chapter 4, Natural Channels and Roadside Ditches, Section 4.4.1).

- Calculate tailwater using standard step method at sensitive locations or use a single cross-section analysis. (Standard step analysis yields the most accurate tailwater.)
- if the culvert outlet is operating with a free outfall, use the critical depth (d_c) plus pipe diameter (D) divided by two, expressed in formula as: $(d_c + D/2)$.
- Use the headwater elevation of downstream culvert if it is greater than the channel depth.

If downstream water bodies are present, consider the following:

- Use the high water mark that has the same discharge as the design flood if events are known to occur concurrently (statistically dependent).
- At the confluence, if statistically independent, evaluate the joint probability of flood magnitudes and use a likely combination resulting in the greater tailwater depth. Guidelines are provided in Chapter 7, Road Storm Drainage Systems, Table 7-7, Joint Probability Analysis.

Outlet Velocity

The outlet velocity at the culvert exit at the design storm shall be consistent with the velocity in the natural channel (and less than 6.0 fps) or shall be mitigated with:

- Channel erosion control (see Chapter 4, Channels, Section 4.4).
- Energy dissipation (see FHWA, HEC-14).

Outlet velocities less than 6.0 fps will generally not require special treatment if a headwall or end section is used.

Hydraulic Analysis Requirements

The drainage area to a culvert determines the level of hydraulic analysis needed, which must be documented in projects and/or submitted for environmental permit applications. (See Appendix D.)

When a culvert drains an area less than 2 square miles, determine the existing and proposed hydraulic conditions for the 2 percent chance (50-year) and 1 percent chance (100-year) flood events. The proposed design shall be based on passing the 2 percent chance (50-year) storm through the culvert while maintaining 1.5 feet of freeboard below the edge of shoulder, and based on passing the 1 percent chance (100-year) flood event while producing no harmful interference to the highway or adjacent property.

New culverts, culvert extensions, and replacements with a drainage area less than 2 square miles require an analysis. Culvert extensions and replacements must be evaluated for both existing and proposed conditions. The results of the analyses must show no "harmful interference" to adjacent properties. Assistance is available from the MDOT Hydraulics Unit.

If the drainage area is greater than 2 square miles, an environmental permit under Part 31 of NREPA from MDEQ and a detailed hydraulic analysis are required. A request for hydrologic and hydraulic analyses **must be submitted** to the Design Engineer - Hydraulics. The Hydraulics Unit will prepare the hydraulic analysis and submit a report to MDEQ. (See Chapter 2, Legal Policy and Procedures.)

Culvert Invert Placement

The invert of a circular or box culvert will be buried below the stream or ditch flow line a minimum of 0.1 x diameter, or 6 inches, whichever is less. The elevation is to be referred to as the invert elevation on the details to avoid confusion with the flow line of the waterway. However, the hydraulic analysis should assume that the full waterway area (including the 6 inches of buried area) is available for design discharge.

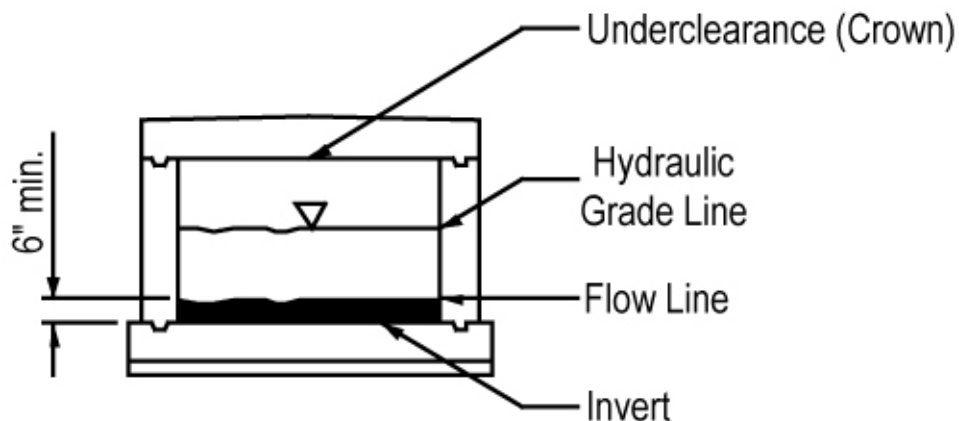


Figure 5-2 Box Culvert Invert Placement

The culvert size and shape selected shall be based on engineering and economic criteria related to site conditions.

The following sizes shall be considered as a minimum (unless supported by calculations and the backwater is within the MDOT right of way):

- 24 inches for Interstate system.
- 18 inches for trunklines other than Interstate systems.
- 12 inches for driveway culverts.
- Use arch or oval shapes only if required by hydraulic limitations, site characteristics, structural criteria, or environmental criteria.

Corrugated Structural Plate Pipe and Pipe Arches

Structural plate pipe and structural plate pipe arches are field-assembled pipes from curved sections with 6-inch by 2-inch corrugations.

Whenever corrugated structural plate pipe or corrugated structural plate pipe arches are used, the following information is required on the plans:

- span and rise (or diameter),
- pay length (bottom length),
- nominal thickness of metal,
- angle with centerline, and
- cutoff height.

The following is an example of how the first three items mentioned above should be shown on plans:

("Corrugated Steel Structural Plate Pipe Arch 9'-4" by 6'-3", (0.138-inch thick) 58 LFT.")

The angle with centerline and cutoff height shall be detailed on plans.

5.3.5 End Treatment (Inlet or Outlet)

The culvert inlet type shall be selected from the following list based on the considerations given and the inlet coefficient, K_e . (A table of recommended values of K_E is included in Appendix 5-B.) Consideration shall also be given to safety since some end treatments can be hazardous to errant vehicles. All culverts 48-inch diameter or larger should have headwalls or slope paving on the inlet end. Table 5-1 outlines the guidelines for culvert end treatments within the clear zone.

Table 5-1 Guidelines for Culvert End Treatments within the Clear Zone

Guidelines for Culvert End Treatments within the Clear Zone			
Transverse Culverts	Circular 18-inch and smaller	Existing End Section	Leave in place, no grate required.
		Existing Headwall	Remove headwall, extend if needed to meet slope, fit with standard end section
		New culvert, or current end section needs adjustment.	Design/extend to meet slope, fit with standard end section.
	Circular 21-in. to 60-in. Arch 21-in. x 15-in. to 83-in. x 57-in. Elliptical 14-in. x 23-in. to 48-in. x 76-in.	Existing End Section	Leave in place, but grate required. Alternative: Fit with culvert sloped end section
		Existing Headwall	Remove headwall, extend if needed to meet slope, fit with culvert sloped end section.
		New culvert, or current end section needs adjustment	Design/extend to meet slope, fit with culvert sloped end section
	Slab and Box culverts and all pipes larger than listed above	Shield with guardrail or extend beyond clear zone.	

Table 5-1 Guidelines for Culvert End Treatments (continued)

Guidelines for Culvert End Treatments within the Clear Zone - continued				
Longitudinal Culverts (approach end)	Freeway		Circular 12-in.	Standard end section. Alternative: Use 375 mm pipe, culvert sloped end section
			Circular 15-in. and larger	Culvert sloped end section.
	Non-Freeway	Posted speed 40 mph or greater	Circular 12-in. and 15-in.	Standard end section. Alternative: Use 15-in. pipe, culvert sloped end section
			Circular 18-in. and larger	Culvert sloped end section.
		Posted speed 35 mph or less	Generally, no grates or sloped end sections required. Crash analysis and recommendations from Traffic and Safety Division may indicate a need to shield culvert ends in unique locations.	
Culverts Outside the Clear Zone	Engineering judgment should be used to provide improved roadside safety when a small increase in cost is involved. Examples might include extending small culverts beyond the clear zone or placing a culvert sloped end section outside the clear zone in a gore area.			
	1:3 slopes should be free of fixed objects or discontinuities that might interfere with an otherwise clear run out distance. See Road Design Manual Sections 7.01.11 A and 7.01.30 for more information on clear zone criteria and guardrail at embankments.			

5.3.5.1 Pipe End Treatments

Pipe end treatments can be used to terminate culverts at embankments. The following discussions cover some common types of end treatments.

Projecting Inlets or Outlets:

- Extend beyond the roadway embankment and are susceptible to damage during roadway maintenance and from errant vehicles.
- Have low construction cost.
- Have poor hydraulic efficiency for thin materials.
- Shall include anchoring the inlet to strengthen the weak leading edge for culverts 48-inch diameter or larger.

Mitered Inlets:

- Are hydraulically more efficient than thin edge projecting.
- Shall be mitered to match the fill slope.
- Shall include anchoring the inlet to strengthen the weak leading edge for culverts 48-inch diameter or larger.

Headwalls (shown on Standard Plan R-85-Series):

- Should not be used where they will be exposed to traffic in the clear zone, regardless of which way they face, unless they are in an area protected by guardrail.
- Must be considered with a baffle for the lower ends of steep culverts with large areas of runoff, with ditches longer than 400 feet, and/or with large cut slopes.

Headwalls with Bevel Edges:

- Increase the efficiency of metal pipe.
- Provide embankment stability and embankment erosion protection.
- Provide protection from buoyancy (see Section 5.3.9 for related designs on buoyancy protection).
- Shorten the required structure length.

Downspout Headers (Shown on Standard Plan R-32-Series):

- Accepted design procedure for placement of downspout headers can be found in the *Urban Drainage Design Manual*, HEC-22, prepared by FHWA.
- Are designed to fit between the 6-foot, 3-inch guardrail post spacing; therefore, the spacing between downspout headers must be in 6 foot, 3-inch intervals, but not necessarily every 6 feet, 3 inches.

- Should be located to prevent erosion of the approach shoulders as well as to intercept the highest concentration of runoff as is possible.

Culvert Sloped End Sections:

Culvert sloped end sections can be installed on the ends of culverts and fitted into 1:4 or 1:6 slopes. They are designed to be used for cross or parallel drainage. Standard Plan R-95-Series details the various cross and longitudinal tubes needed for each situation along with the connection details of the culvert sloped end section to the various culvert pipe materials and sizes.

The culvert sizes that can be fitted with the culvert sloped end sections are as follows:

- Circular pipe culverts sizes 15-inch to 60-inch
- Arch pipes 21-inch x 15-inch through 83-inch x 57-inch
- Elliptical pipes 14-inch x 23-inch through 48-inch x 76-inch

Commercial End Sections:

- Are available for both corrugated metal and concrete pipe.
- Retard embankment erosion and incur less damage from maintenance.
- May improve projecting metal pipe entrances by increasing hydraulic efficiency, reducing the accident hazard, and improving their appearance.
- Are equal to a headwall hydraulically, but can be equal to a beveled or side-tapered entrance if a flared, enclosed transition takes place before the barrel.

5.3.5.2 Boxes/Slab End Treatments (updated January 2004)

Concrete Slab (3-sided) Culverts:

- Are not commonly used and are specified by a special provision. Contact the Hydraulics Unit for assistance with hydraulics.
- Cast-in-place reinforced concrete slab culvert details are available from the Quality Assurance/Standards and Manuals unit. These details are for constructing new or extending existing slab culverts and were designed for HS20 loading.
- Extension of existing slab culvert shall use adhesive anchored bolts to tie the new construction to the existing.
- Locate top of footing a minimum of 18 inches below the average stream flow line within the culvert.

Precast Concrete Box Culverts

- Precast box culverts are available in numerous sizes State-wide. The designer should contact a local supplier to verify that a particular size is available. The supplier, in some instances, may be willing to furnish a larger size if available forms do not match the required size. Precast box culverts offer the advantage of rapid installation and are competitively priced with cast-in-place box culverts for new construction or culvert extensions.
- Design of precast concrete box culverts shall conform to 401.03 of the current Standard Specifications for Construction. However, for modified and special designs for sizes and live loads which differ from 401.03, the manufacturer shall be allowed to request approval from the Design Engineer- Municipal Utilities.
- If the culvert is located under a railroad crossing, modified and special designs for sizes and live (Cooper) loading shall apply. Consult the Design Engineer - Municipal Utilities. When the culvert requires headwalls, details must be obtained from the Design Engineer - Municipal Utilities.
- When extending box culverts, adhesive anchored bolts shall be used to tie the new construction to the existing.
- The invert of a box culvert is to be set 6 inches below the normal flow line. This elevation is to be referred to as the invert elevation on the details to avoid confusion with the flow line of the waterway that appears on the profile.

Headwalls and Wingwalls:

- Are used to retain the roadway embankment to avoid a projecting culvert barrel.
- Are used where the side slopes of the channel are unstable.
- Are used where the culvert is skewed to the normal channel flow.
- Provide the best hydraulic efficiency if the flare angle is between 30 and 60 degrees.

Aprons:

- Are used to reduce scour from high headwater depths or from approach velocity in the channel at the inlet.
- Shall extend at least one pipe diameter upstream/downstream.
- Shall not protrude above the normal streambed elevation.

Cut-off Walls:

- Prevent piping along the culvert barrel and undermining at the culvert end treatments (headwalls and wingwalls).
- Shall be used on all culverts with headwalls

- Shall be a minimum of 1.5 to 2 feet deep depending on size of culvert.

5.3.5.3 Weep Holes

If weep holes are used to relieve uplift pressure, they shall be designed in a manner similar to underdrain systems.

5.3.6 Culvert Extensions and Replacements

For MDEQ permit applications and hydraulic analysis, the length of a culvert extension is defined as the length of the extension on both ends of the pipe, not including the length of the end sections. Note: The hydraulic analysis requirements are given in Section 5.3.4.

Reinforced Circular Concrete Pipe Extensions

It is often necessary to extend circular culverts on upgrading projects. The concrete industry has changed its joint design over the years, and when old culverts are extended with new pipe, which is presently designed to be adaptable to gasketed joints, this may result in poorly fitted joints. In order to ensure tight joints and to forewarn contractors of possible extra work required on applicable projects, the following General Plan Note should be placed on the note sheet:

General Note: Circular Culvert Extensions

The extension of existing circular concrete culverts on this project may require extra work to obtain a tight seal at the joint connecting new culvert pipe to existing culvert pipe. The joint between the existing and new pipes shall be completely filled with mortar to form a tight seal. Any extra work required to obtain tight joints will not be paid for separately but will be included in compensation for extending culverts.

Extending Existing Box and Slab Culverts

The extension of existing box or slab culverts less than 4-foot by 4-foot may be with a concrete circular pipe, with a reinforced concrete connecting collar, of sufficient size to have a hydraulic capacity equal to or greater than the existing culvert. The following table is provided as a guide for the scope preparation and initial cost estimating by the designer until a hydraulic analysis is completed.

Table 5-2 Equivalent Circular and Box Culvert Sizes

Existing Size	Concrete Circular Pipe Size
2 feet by 2 feet	30 inches
2.5 feet by 2.5 feet	36 inches
3 feet by 3 feet	48 inches
4 feet by 3 feet	60 inches
4 feet by 4 feet	Use pre-cast concrete box

For box culverts equal to or greater than 4-foot by 4-foot, the extension must be a pre-cast concrete box with the appropriate connecting collar. Design of the extension can be obtained from the Design Engineer - Municipal Utilities.

Extension of an existing slab culvert is not recommended. If a slab culvert is extended with a reinforced concrete box culvert or circular pipe, it must have the area between the footings poured with concrete and sufficient steel reinforcement doweled into the footings.

The designer is cautioned that total culvert extensions greater than 24 feet will require hydraulic certification for the MDEQ permit application. The hydraulic certification must be submitted and approved by the Design Engineer - Hydraulics and then provided to the Region Environmental Permit Coordinator.

5.3.7 Bedding and Filling Around Pipe Culverts

The bedding and filling around pipe culverts shall be done according to Standard Plan R-82-Series upon which the Culvert Class-Depth-Usage Table is based. For further discussion on bedding and filling, see RDM, Chapter 4, Section 4.05.12.

5.3.8 Related Designs

Buoyancy Protection

Headwalls, endwalls, slope paving, or other means of anchoring to provide buoyancy protection shall be considered for all flexible culverts (i.e., corrugated metal or plastic). Buoyancy is more serious with steepness of the culvert slope, depth of the potential headwater (debris blockage may increase), flatness of the upstream fill slope, height of the fill, large culvert skews, or mitered ends.

Relief Opening

Where multiple use culverts or culverts serving as relief openings have their outlet set above the normal stream flow line, special precautions shall be required to prevent headcuts or erosion from undermining the culvert outlet.

Sag Culverts

Sag culverts (sometimes called inverted siphons or sag lines) are used to convey water by gravity under roads, railroads, various types of drainage channels, and depressions. A sag culvert is a closed conduit designed to run full and under pressure.

MDOT generally discourages use of sag culverts because of safety and maintenance issues. For information on sag culverts, see AASHTO's Model Drainage Manual, 1999.

Tapered Inlets

Tapered inlets are flared culvert inlets with an enlarged face section and a hydraulically efficient throat section. MDOT generally discourages the use of tapered inlets. For information on tapered inlets, see AASHTO's Model Drainage Manual, 1999.

Sedimentation in Culverts

A concern with culverts, particularly improved inlet or high velocity culverts, is problems associated with sedimentation. Excessive sedimentation may block a portion of the culvert inlet, barrel, or outlet. It is sometimes necessary to make an assessment of potential sediment problems at a culvert. For procedures and guidance on this, see AASHTO's Model Drainage Manual, 1999.

5.4 DESIGN GUIDANCE AND PROCEDURE

The section discusses design approach and gives guidance in culvert design.

5.4.1 Approach

Control Section: The location where there is a unique relationship between the flow rate and the upstream water surface elevation. Inlet control is governed by the inlet geometry. Outlet control is governed by a combination of the culvert inlet geometry, the barrel characteristics, and the tailwater.

Minimum Performance: Assumed by analyzing both inlet and outlet control and using the highest headwater. The culvert may operate more efficiently at times (more flow for a given headwater level), but it will not operate at a lower level of performance than calculated.

5.4.2 Inlet Control

For inlet control, the control section is at the upstream end of the barrel (the inlet). The flow passes through critical depth near the inlet and becomes shallow, high velocity (supercritical) flow in the culvert barrel. Depending on the tailwater, a hydraulic jump may occur downstream of the inlet.

Headwater Factors

- Headwater depth is measured from inlet invert of the inlet control section to the surface of the upstream pool.
- Inlet area is the cross-sectional area of the face of the culvert. Generally, the inlet face area is the same as the barrel area.
- Inlet edge configuration describes the entrance type. Some typical inlet edge configurations are thin edge projecting, mitered, square edges in a headwall, and beveled edge.
- Inlet shape is usually the same as the shape of the culvert barrel. Typical shapes are rectangular, circular, elliptical, and arch. Check for an additional control section if different than the barrel.

Hydraulics

Three regions of flow are shown in the Figure 5-3, Unsubmerged, Transition, and Submerged.

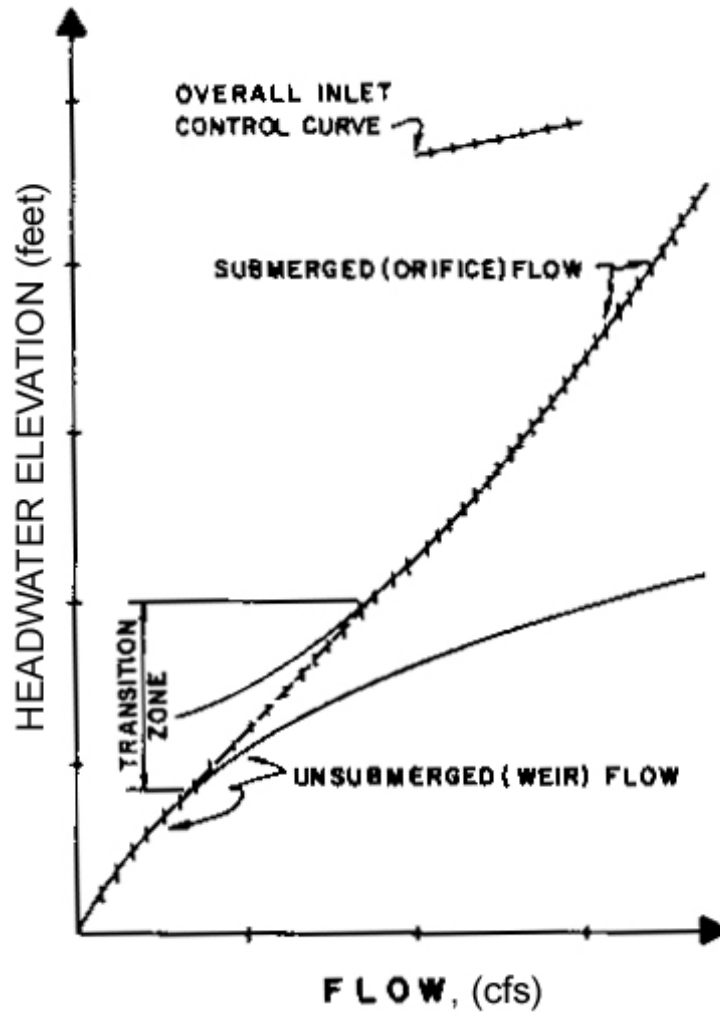


Figure 5-3 Unsubmerged, Transition, and Submerged

Unsubmerged

For headwater below the inlet crown, the entrance operates as a weir.

- A weir is a flow control section where the upstream water surface elevation can be predicted for a given flow rate.
- The relationship between flow and water surface elevation must be determined by model tests of the weir geometry or by measuring prototype discharges.
- These tests are then used to develop equations. Appendix A of HDS5 contains the equations which were developed from model test data, see Figure 5-4, Unsubmerged Flow.

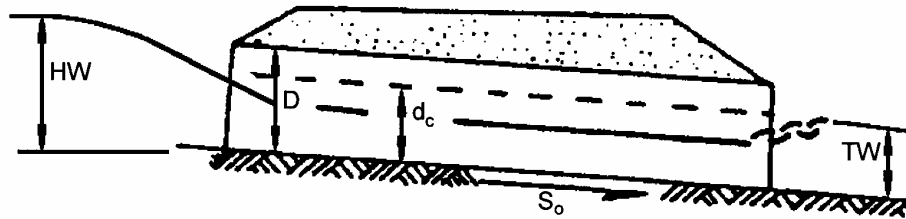


Figure 5-4 Unsubmerged Flow

Submerged

For headwaters above the inlet, the culvert operates as an orifice.

- An orifice is an opening, submerged on the upstream side and flowing freely on the downstream side, which functions as a control section.
- The relationship between flow and headwater can be defined based on results from model tests. Appendix A of HDS 5 contains flow equations which were developed from model test data. See Figure 5-5, Submerged Flow.

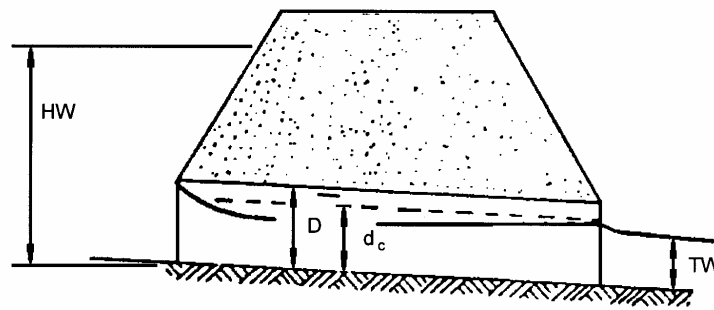


Figure 5-5 Submerged Flow

Transition Zone

The transition zone is located between the unsubmerged and the submerged flow conditions where the flow is poorly defined. This zone is approximated by plotting the unsubmerged and submerged flow equations and connecting them with a line tangent to both curves.

For culverts on hydraulically steep slopes (slope greater than the slope that would produce critical depth), the Bureau of Reclamation describes a situation where the control alternated between inlet control and some downstream point (Design of Small Dams, 1987). At a ratio of $HW/D = 1.2$, control is normal at the inlet. As the discharge increases, channel friction or local disturbances may force the level to flow full near the outlet, sealing the downstream end. This condition will vacate trapped air causing the flow to be at sub-atmospheric pressure. This will increase the discharge. The increased discharge will cause a deeper draw-down that may bring more air into the pipe. This air will lower the discharge and increase the negative pressure on the pipe. This cycle will repeat. The fluctuating pressures will cause a pulsating action on the pipe and vibrate the embankment. This pulsating may become so strong that damage to the pipe section and/or joints could lead to structural failure of the pipe.

When the headwater condition is such that HW/D is greater than 1.5, the entrance draw-down may be insufficient to interface with the fill-flow action, and a steady state of full pipe flow will likely occur thereby eliminating the pulsation.

Nomographs

The inlet control flow versus headwater curves which are established using the above procedure are the basis for constructing the inlet control design nomographs. Note that in the inlet control nomographs, headwater is measured to the total upstream energy grade line including the approach velocity head. Nomographs taken from FHWA, HDS 5 are given in Appendix 5-C.

5.4.3 Outlet Control

Outlet control involves depths and velocities which are subcritical. The control of the flow is at the downstream end of the culvert (the outlet). The tailwater depth is either assumed to be critical depth near the culvert outlet or the downstream channel depth, whichever is higher. In a given culvert, the type of flow is dependent on all of the barrel factors. All of the inlet control factors also influence culverts in outlet control.

Barrel Roughness

Barrel roughness is a function of the material used to fabricate the barrel. Typical materials include concrete and corrugated metal. The roughness is represented by a hydraulic resistance coefficient such as the Manning n value. Typical Manning n values are presented in Appendix 5-B.

Barrel Area

Barrel area is measured perpendicular to the flow.

Barrel Length

Barrel length is the total culvert length from the entrance crown to the exit crown of the culvert. Because the design height of the barrel and the slope influence the actual length, an approximation of barrel length is usually necessary to begin the design process.

Barrel Slope

Barrel slope is the actual slope of the culvert barrel.

Tailwater Elevation

Tailwater is based on the downstream water surface elevation. Backwater calculations should start from a downstream control, a normal depth approximation in the channel, or critical depth just inside the culvert. The largest of the conditions is considered to be the tailwater.

Hydraulics

Full flow in the culvert barrel is assumed for the analysis of outlet control hydraulics. Outlet control flow conditions can be calculated based on an energy balance from the tailwater pool to the headwater pool. Figure 5-6, Full Flow Energy and Hydraulic Grade Lines, shows the energy and hydraulic grade lines during full flow. Example problem is provided in Section 5.4.8.

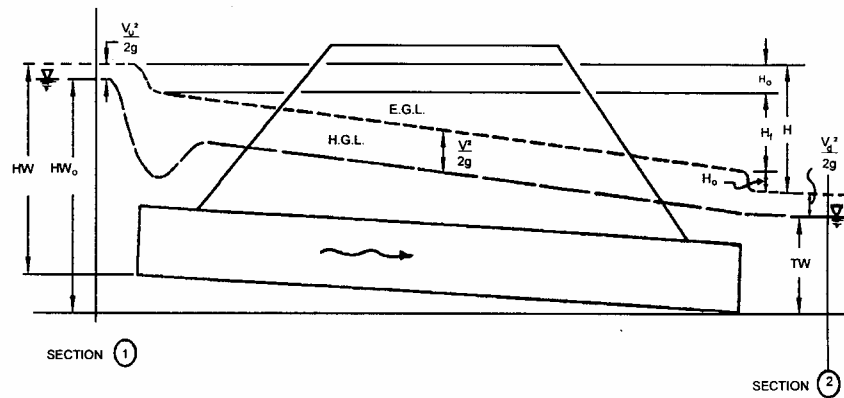


Figure 5-6 Full Flow Energy and Hydraulic Grade Lines

$$\text{Losses} \quad H_L = H_E + H_f + H_o + H_b + H_j + H_g \quad (5.1)$$

Where:

- H_L = total energy loss, feet
- H_E = entrance loss, feet
- H_f = friction losses, feet
- H_o = exit loss (velocity head), feet
- H_b = bend losses, feet (see HDS 5)
- H_j = losses at junctions, feet (see HDS 5)
- H_g = losses at grates, feet (see HDS 5)

$$\text{Velocity} \quad V = Q/A \quad (5.2)$$

Where:

- V = average barrel velocity, fps
- Q = flow rate, cfs
- A = cross sectional area of flow with the barrel full, sf

$$\text{Velocity head} \quad H_v = V^2/2g \quad (5.3)$$

Where: g = acceleration due to gravity, 32.2 feet/s²

$$\text{Entrance loss} \quad H_e = K_e (V^2/2g) \quad (5.4a)$$

Where: K_e = entrance loss coefficient (See Table 2 in Appendix 5-B.)

$$\text{Friction loss} \quad H_f = [(29n^2L)/R^{1.33}] [V^2/2g] \quad (5.4b)$$

Where:

- n = Manning's roughness coefficient (See Table 1 in Appendix 5-B.)
- L = length of the culvert barrel, feet
- R = hydraulic radius of the full culvert barrel = A/WP , feet
- WP = wetted perimeter of the barrel, feet

$$\text{Exit loss} \quad H_o = 1.0 [(V^2/2g) - (V_d^2/2g)] \quad (5.4c)$$

Where: V_d = channel velocity downstream of the culvert, fps (Usually neglected, see Equation 5.4d.)

$$H_o = V^2/2g \quad (5.4d)$$

Bend loss, junction loss, and grate loss are usually neglected because they are not common in culverts, but their loss takes the form of $H = K(V^2/2g)$. Each has its own table of K values listed in HDS 5, Chapter VI.

Neglecting the change in velocity from inlet to outlet, and the losses from bends, junctions, or grates, Equation 5.1 reduces to Equation 5.5.

$$\text{Losses} \quad H_L = H_E + H_o + H_f$$

$$H_L = [1 + K_e + (29n^2L/R^{1.33})] [V^2/2g] \quad (5.5)$$

Energy Grade Line

The energy grade line represents the total energy at any point along the culvert barrel. Equating the total energy at Sections 1 and 2, upstream and downstream of the culvert barrel in Figure 5-6, the following relationship results:

$$HW_o + (V_u^2/2g) = TW + (V_d^2/2g) + H_L \quad (5.6)$$

Where:

- HW_o = headwater depth above the outlet invert, feet
- V_u = approach velocity, fps
- TW = tailwater depth above the outlet invert, feet
- V_d = downstream velocity, fps
- H_L = sum of all losses (Equation 5.1 or 5.5)

Hydraulic Grade Line

The hydraulic grade line is the depth to which water would rise in vertical tubes connected to the sides of the culvert barrel. In full flow, the energy grade line and the hydraulic grade line are parallel lines separated by the velocity head, except at the inlet and the outlet.

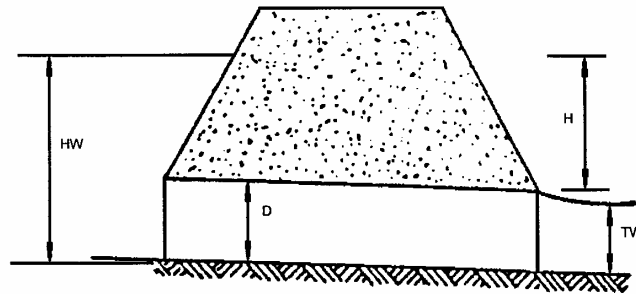


Figure 5-7 Full Flow in the Culvert

Nomographs (Full Flow)

The nomographs were developed assuming that the culvert barrel is flowing full and:

- $TW \geq D$, full flow (see Figure 5-6) or
- $d_c \geq D$, full flow (see Figure 5-7)
- V_u is small and its velocity head can be considered to be a part of the available headwater (HW) used to convey the flow through the culvert.
- V_d is small and its velocity head can be neglected.
- Equation (5.6) becomes:

$$HW = TW + H - S_oL \quad (5.7)$$

Where: HW = depth from the inlet invert to the energy grade line, feet.
 H = is the value read from the nomographs (Equation 5.5), feet.
 S_oL = drop from inlet to outlet invert, feet.

Nomographs (Partly Full Flow)

Equations 5.1 through 5.7 were developed for full barrel flow. The equations also apply to the flow situations which are effectively full flow conditions, if $TW < d_c$, (see Figure 5-8).

- Backwater calculations may be required which begin at the downstream water surface and proceed upstream. If the depth intersects the top of the barrel, a full flow extends from that point upstream to the culvert entrance.

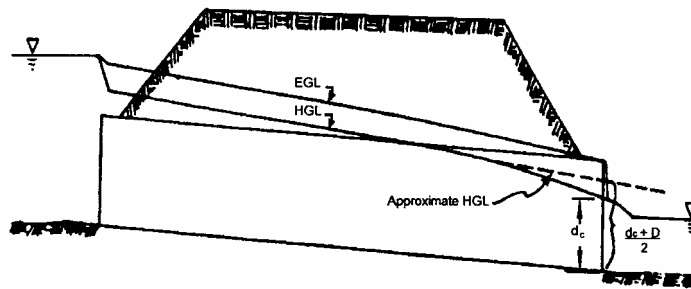


Figure 5-8 Partly Full Flow

Nomographs (Partly Full Flow) - Approximate Method

Based on numerous backwater calculations performed by the FHWA staff, it was found that the hydraulic grade line pierces the plane of the culvert outlet at a point approximately one-half way between critical depth and the top of the barrel or $(d_c + D)/2$ above the outlet invert. TW should be used if higher than $(d_c + D)/2$. The following equation should be used:

$$HW = h_o + H - S_o L \quad (5.8)$$

Where: h_o = the larger of TW or $(d_c + D)/2$, feet

Adequate results are obtained down to a $HW = 0.75D$. For lower headwater, backwater calculations are required.

(See Figure 5-9 if $TW < d_c$ and Figure 5-10 if $TW > d_c$)

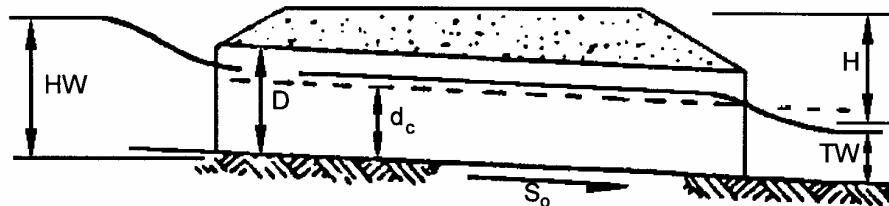


Figure 5-9 Partly Full Flow when $TW < d_c$

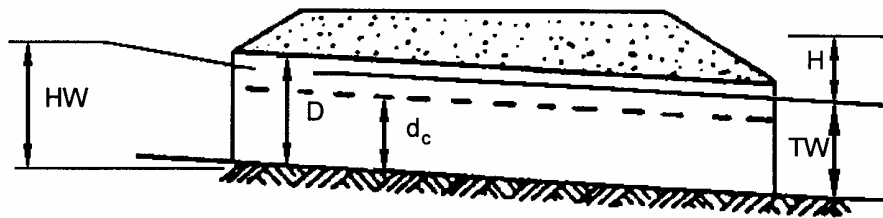


Figure 5-10 Partly Full Flow when $TW > d_c$

5.4.4 Outlet Velocity

Culvert outlet velocities shall be calculated to determine need for erosion protection at the culvert exit. Culverts usually result in outlet velocities which are higher than the natural stream velocities. These outlet velocities may require flow readjustment or energy dissipation to prevent downstream erosion. If outlet erosion protection is necessary, the flow depths and Froude number may also be needed (see FHWA HEC-14 and HEC-11 for more information on erosion protection of stream banks).

Inlet Control

The velocity is calculated from Equation 5.2 after determining the outlet depth. Either of the following methods may be used to determine the outlet depth.

- Calculate the water surface profile through the culvert. Begin the computation at d_c at the entrance and proceed downstream to the exit. Determine the depth and flow area at the exit.
- Assume normal depth and velocity. This approximation may be used since the water surface profile converges towards normal depth if the culvert is of adequate length. This outlet velocity may be slightly higher than the actual velocity at the outlet. Normal depths, in feet, may be obtained from design aids in publications such as *Design Charts for Open Channel Flow*, HDS 3 (FHWA).

Outlet Control

The cross-sectional area of the flow is defined by the geometry of the outlet and either critical depth, tailwater depth, or the height of the conduit.

- Critical depth is used when the tailwater is less than critical depth.
- Tailwater depth is used when tailwater is greater than critical depth, but below the top of the barrel.
- The total barrel area is used when the tailwater exceeds the top of the barrel.

5.4.5 Roadway Overtopping

Roadway overtopping will normally not be considered as part of a MDOT design. However, overtopping is presented in this manual to help in analysis of historical flooding observations.

Roadway overtopping will begin when the headwater rises to the elevation of the roadway. The overtopping will usually occur at the low point of a sag vertical curve on the roadway. Roadway overtopping is usually not designed for, but is analyzed during a flood event to ensure properly sized crossings. Overtopping should not occur during the 2 percent chance (50-year) storm event and should not cause harmful interference during the 1 percent chance (100-year) storm event. See Chapter 8, Stormwater Storage Facilities, Section 8.4.6 for a discussion on sloped weirs. The flow will be similar to flow over a broad crested weir. See Section 5.3.5 on culvert design limitations and policy on harmful interference. Flow coefficients for flow overtopping roadway embankments are found in HDS No. 1, Hydraulics of Bridge Waterways (FHWA), as well as in the documentation of HY8, the Bridge Waterways Analysis Model (FHWA). Curves from the latter are included in Appendix 5-D.

$$Q_r = C_d L HW_r^{1.5} \quad (5.9)$$

Where: Q_r = overtopping flow rate, cfs

C_d = overtopping discharge coefficient (weir coefficient) = $k_t C_r$

k_t = submergence coefficient

C_r = discharge coefficient

L = length of the roadway crest, feet

HW_r = the upstream depth, measured above the roadway crest, feet.

Length

The length is difficult to determine when the crest is defined by a roadway sag vertical curve.

- Recommend subdividing into a series of segments. The flow over each segment is calculated for a given headwater. The flows for each segment are added together to determine the total flow.
- The length can be represented by a single horizontal line (one segment). The length of the weir is the horizontal length of this segment. The depth is the average depth (area/length) of the upstream pool above the roadway.

Total Flow

Total flow is calculated for a given upstream water surface elevation using Equation 5.9. An alternate approach is given in Chapter 4, Channels, Section 4.4.6.

- Roadway overflow plus culvert flow must equal total design flow.

- A trial and error process is necessary to determine the flow passing through the culvert and the amount flowing across the roadway.
- Performance curves for the culvert and the road overflow may be summed to yield an overall performance curve.

5.4.6 Performance Curves

Performance curves are plots of flow rate versus headwater depth or elevation, velocity, or outlet scour. The culvert performance curve is made up of the controlling portions of the individual performance curves for each of the following control sections (see Figure 5-11).

Inlet Performance Curve: Developed using the inlet control nomographs (see Appendix 5-C).

Outlet Performance Curve: Developed using Equations 5.1 through 5.7, the outlet control nomographs (see Appendix 5-C), or backwater calculations.

Roadway Performance Curve: Developed using Equation 5.9.

Overall Performance Curve: The sum of the flow through the culvert and the flow across the roadway and can be determined by performing the following steps.

- Select a range of flow rates and determine the corresponding headwater elevations for the culvert flow alone. These flow rates should fall above and below the design discharge and cover the entire flow range of interest. Both inlet and outlet control headwaters shall be calculated.
- Combine the inlet and outlet control performance curves to define a single performance curve for the culvert.
- When the culvert headwater elevations exceed the roadway crest elevation, overtopping will begin. Calculate the upstream water surface depth above the roadway for each selected flow rate. Use these water surface depths and Equation 5.9 to calculate flow rates across the roadway.
- Add the culvert flow and the roadway overtopping flow at the corresponding headwater elevations to obtain the overall culvert performance curve as shown in Figure 5-11.

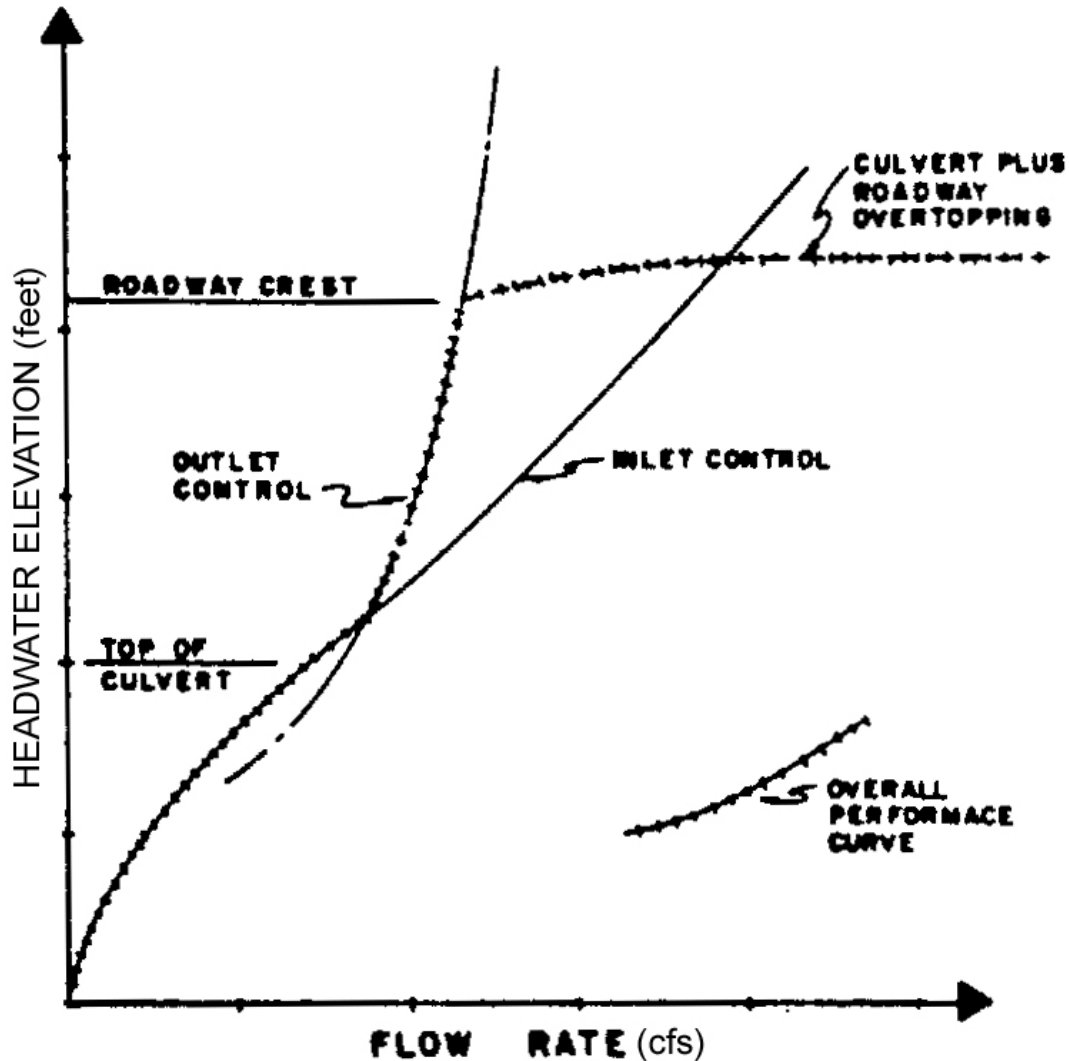


Figure 5-11 Overall Performance Curve

5.4.7 Culvert Design Procedure

The following design procedure provides a method for designing culverts for a constant discharge, considering inlet and outlet control.

- The designer should be familiar with all the equations given earlier in Section 5.4 before using these procedures.
- Following the design method without an understanding of culvert hydraulics, can result in an inadequate, unsafe, or costly structure.
- The computation form has been provided in Appendix 5-B to guide the user. It contains blocks for the project description, designer's identification, hydrologic data, culvert dimensions and elevations, trial culvert description, inlet and outlet control headwater, culvert barrel selected, and comments.

Step 1 Assemble Site Data and Project File

- a. The minimum data are:
 - USGS, site, and location maps
 - Embankment cross section
 - Roadway profile
 - Photographs
 - Field visit estimate (sediment, debris potential)
 - Design data at nearby structures
- b. Studies by other agencies including:
 - Small dams - NRCS, USACE, TVA, BLM
 - Canals - NRCS, USACE, TVA, USBR
 - Floodplain - NRCS, USACE, TVA, FEMA, USGS, NOAA
 - Storm drain - local or private
- c. Environmental constraints including:
 - Commitments contained in review documents
 - Fish migration
 - Wildlife passage
- d. Design criteria:
 - Review Section 5.3 for applicable criteria
 - Prepare risk assessment or analysis

Step 2 Determine Hydrology

- a. See Hydrology, Chapter 3.
- b. Determine extent of drainage area. If more than 2 square miles, request design flows from the Design Engineer-Hydraulics Unit. If less than 2 square miles, calculate peak flow (greater than 20 acres, use SCS method or TR-55; less than 20 acres, use Rational Method).
- c. See Section 5.3.4, Culvert Design Considerations.
- d. Determine flood frequency from criteria.
- e. Determine Q from discharge-frequency plot (Step 2).

Step 3 Design Downstream Channel

- a. See, Chapter 4, Natural Channels and Roadside Ditches.
- b. Minimum data are cross section of channel and the rating curve for channel.

Step 4 Summarize Data on Design Form

- a. See chart in Appendix 5-B.
- b. Data from Steps 1 - 3.

Step 5 Select Design Alternative

- a. See Section 5.3 for some culvert design features.
- b. Choose trial culvert material, shape, size, and entrance type.

Step 6 Select Design Discharge, Q_d

- a. Determine flood frequency from criteria.
- b. Determine Q from discharge - frequency plot (Step 2).
- c. Divide Q by the number of barrels.

Step 7 Determine Inlet Control Headwater Depth (HW_i)

Use the inlet control nomograph (Appendix 5-C).

- a. Locate the size or height on the scale.
- b. Locate the discharge.
 - For a circular shape use discharge.
 - For a box shape use Q per foot of width.
- c. Locate headwater to diameter ratio.
 - Use a straightedge.
 - Extend a straight line from the culvert size through the flow rate.
 - Mark the first HW/D scale. Extend a horizontal line to the desired scale and read HW/D and note on Design Form in Appendix 5-B.
- d. Calculate headwater depth (HW_i).
 - Multiply HW/D by D to obtain HW to energy grade line.
 - Neglecting the approach velocity $HW_i = HW$.
 - Including the approach velocity $HW_i = HW - \text{approach velocity head}$.

Step 8 Determine Outlet Control Headwater Depth at Inlet (HW_{oi})

- a. Calculate the tailwater depth (TW) using the design flow rate and normal depth (single section) or using a water surface profile.
- b. Calculate critical depth (d_c) using appropriate chart in Appendix 5-C.
 - Locate flow rate and read d_c .
 - d_c cannot exceed D.
 - If $d_c > 0.9D$, consult Handbook of Hydraulics (King and Brater) for a more accurate d_c , if needed, since curves are truncated where they converge.
- c. Calculate $(d_c + D)/2$.

- d. Determine (h_o).
 - h_o = the larger of TW or $(d_c + D/2)$.
- e. Determine (K_e).
 - Entrance loss coefficient from Table 2 in Appendix 5-B.
- f. Determine losses through the culvert barrel (H).
 - Use nomograph (Appendix 5-C) or Equation 5.5 or 5.6 if outside range.
 - Locate appropriate K_e scale.
 - Locate culvert length (L) or (L_1):
 - use (L) if Manning's n matches the n value of the culvert and
 - use (L_1) to adjust for a different culvert n value.

$$L_1 = L(n_1/n)^2 \quad (5.10)$$

Where: L_1 = adjusted culvert length, feet
 L = actual culvert length, feet
 n_1 = desired Manning n value
 n = Manning n value on chart

Mark point on turning line:

- use a straightedge, and
- connect size with the length.

Read H:

- use a straightedge,
- connect Q and turning point, and
- read H on Head Loss scale.

- g. Calculate outlet control headwater HW_{oi} .
 Use Equation 5.11, if V_u and V_d are neglected:

$$HW_{oi} = H + h_o - S_oL \quad (5.11)$$

- Use Equations 5.1, 5.4c, and 5.6 to include V_u and V_d .
- If HW_{oi} is less than $1.2D$ and control is outlet control:
 - The barrel may flow partly full.
 - The approximate method of using the greater of tailwater or $(d_c + D)/2$ may not be applicable.
 - Backwater calculations should be used to check the result.
 - If the headwater depth falls below $0.75D$, the approximate nomograph method shall not be used.

Step 9 Determine Controlling Headwater (HW_c)

- a. Compare HW_i and HW_{oi} , use the higher.
- b. $HW_c = HW_i$, if $HW_i >$ retained for future reference as provided for in documentation.

Step 10 Compute Discharge over the Roadway (Q_r), (if applicable)

- a. Calculate depth above the roadway (HW_r).
 $HW_r = HW_c - HW_{ov}$
 HW_{ov} = height of road above inlet invert
- b. If $HW_r = 0$, $Q_r = 0$
 If $HW_r > 0$, determine C_d from Appendix 5-C
- c. Determine length of roadway crest (L).
- d. Calculate Q_r using Equation 5.12.

$$Q_r = C_d L HW_r^{1.5} \quad (5.12)$$

Step 11 Compute Total Discharge (Q_t)

$$Q_t = Q_d + Q_r \quad (5.13)$$

Step 12 Calculate Outlet Velocity (V_o) and Depth (d_n)

If inlet control is the controlling headwater:

- a. Calculate flow depth at culvert exit:
 - use normal depth (d_n) or
 - use water surface profile
- b. Calculate flow area (A).
- c. Calculate exit velocity (V_o) = Q/A .

If outlet control is the controlling headwater:

- a. Calculate flow depth at culvert exit:
 - use (d_c) if $d_c > TW$
 - use (TW) if $d_c < TW < D$
 - use (D) if $D < TW$
- b. Calculate flow area (A).
- c. Calculate exit velocity (V_o) = Q/A .

Step 13 Review Results

- a. Barrel must have adequate cover.
- b. The length shall be close to the approximate length.
- c. Wingwalls and headwalls must fit site constraints.

- d. Allowable headwater shall not be exceeded.
- e. Allowable overtopping shall not be exceeded.
- f. Verify no harmful interference is created.

Step 14 Documentation

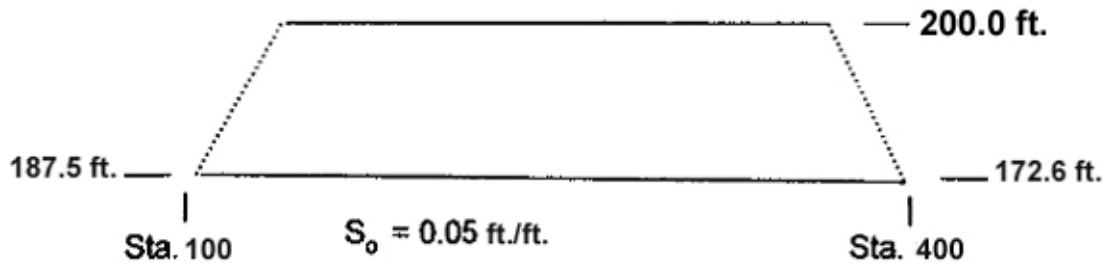
- a. Document results on standard HDS-5 forms found in Appendix 5-C.

5.4.8 Nomograph Design and Analysis

The following example problem follows the Design Procedure Steps described in Section 5.4.7.

Step 1 Assemble Site Data and Project File

- a. Site survey project file contains:
 - USGS, site and location maps,
 - Roadway profile, and
 - Check drainage area.



Site notes indicate:

- No sediment or debris problems, and
 - No nearby structures.
- b. Studies by other agencies – none.
- c. Environmental risk assessment shows:
 - No building near floodplain,
 - No sensitive floodplain values,
 - No FEMA involvement, and
 - Convenient detours exist.
- d. Design criteria:
 - 2 percent chance (50-year) frequency for design, and
 - 1 percent chance (100-year) frequency for check.

Step 2 Determine Hydrology

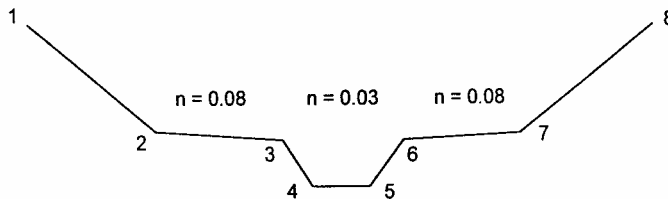
Peak flows provided by MDEQ (drainage area greater than 2 square miles):

- $Q_{50} = 400$ cfs
- $Q_{100} = 500$ cfs

Step 3 Design Downstream Channel

Cross section of channel (Slope = 0.05 feet/foot)

<u>Point</u>	<u>Station, feet</u>	<u>Elevation, feet</u>
1	12	178.0
2	22	175.0
3	32	174.5
4	34	172.5
5	39	172.5
6	41	174.5
7	51	175.0
8	61	180.0

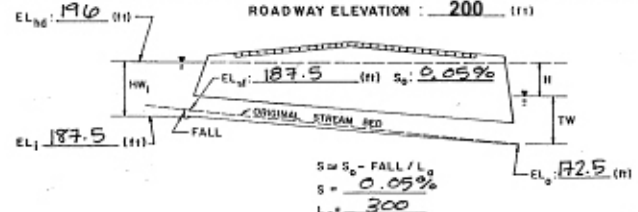


The rating curve for the channel calculated by normal depth yields:

<u>Flow (cfs)</u>	<u>Tailwater (feet)</u>	<u>Velocity (fps)</u>
100	1.4	11.1
200	2.1	13.7
300	2.5	16.0
400	2.8	17.5
500	3.1	18.8

Step 4 Summarize Data on Design Form (Chart 17 in Appendix 5-C)

See Figure 5-10, Chart 17, and Performance Curve for Design Example

PROJECT: <u>Example Problem</u> <u>MDOT Drainage Manual</u>		STATION: <u>Test+ 9+00</u>		CULVERT DESIGN FORM														
		SHEET <u>1</u> OF <u>1</u>		DESIGNER/DATE: <u>MJH / 8/02</u>														
				REVIEWER/DATE: _____ / _____														
HYDROLOGICAL DATA METHOD: <input checked="" type="checkbox"/> USGS DRAINAGE AREA: _____ STREAM SLOPE: _____ CHANNEL SHAPE: _____ ROUTING: _____ OTHER: _____			ROADWAY ELEVATION: <u>200</u> (ft)  <p> $S = S_0 - \text{FALL} / L_0$ $S = 0.059\%$ $L_0 = 300$ </p>															
DESIGN FLOWS/TAIWATER <table border="1" style="width:100%; text-align: center;"> <tr> <th>R.I. (YEARS)</th> <th>FLOW (cfs)</th> <th>TW (ft)</th> </tr> <tr> <td><u>50</u></td> <td><u>400</u></td> <td><u>2.8</u></td> </tr> <tr> <td><u>100</u></td> <td><u>500</u></td> <td><u>3.1</u></td> </tr> </table>			R.I. (YEARS)	FLOW (cfs)	TW (ft)	<u>50</u>	<u>400</u>	<u>2.8</u>	<u>100</u>	<u>500</u>	<u>3.1</u>							
R.I. (YEARS)	FLOW (cfs)	TW (ft)																
<u>50</u>	<u>400</u>	<u>2.8</u>																
<u>100</u>	<u>500</u>	<u>3.1</u>																
CULVERT DESCRIPTION:		TOTAL FLOW		HEADWATER CALCULATIONS														
MATERIAL - SHAPE - SIZE - ENTRANCE		Q (cfs)	Q/N	INLET CONTROL		OUTLET CONTROL		CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS								
<u>RCB - 7 x 6 - Bevel</u>		400	57	HW ₁ /D	HW ₁	FALL	EL ₁ (ft)	TW	d _c	d _c +D/2	h ₀	h _a	H	EL ₉₀ (ft)	CONTROL HEADWATER ELEVATION	OUTLET VELOCITY	COMMENTS	
		500	72	1.77	7.6	0	195.1	2.8	4.7	5.4	5.4	0.2	2.8	180.7	195.1	32	195.1 < 196 OK	
<u>Performance Curve</u>		100	14	1.56	9.4	0	196.9	3.1	5.4	5.7	5.7	0.2	4.3	182.5	196.9	34	> 196 Calc Q _r	
		200	29	0.46	2.8	0	190.3											
		300	43	0.78	4.7	0	192.2											
				1.01	6.1	0	193.6											
TECHNICAL FOOTNOTES: (1) USE Q/NB FOR BOX CULVERTS (2) HW ₁ /D + HW ₁ /D OR HW ₁ /D FROM DESIGN CHARTS (3) FALL = HW ₁ - (EL ₁ - EL ₂), FALL IS ZERO FOR CULVERTS ON GRADE				(4) EL ₁ = HW ₁ + EL ₁ (INVERT OF INLET CONTROL SECTION) (5) TW BASED ON DOWN STREAM CONTROL OR FLOW DEPTH IN CHANNEL.				(6) h ₀ = TW or (d _c + D/2) (WHICHEVER IS GREATER) (7) H = [1 + h _a (29n ² L) / R ^{1.48}] v ² / 2g (8) EL ₉₀ = EL ₀ + H + h ₀										
SUBSCRIPT DEFINITIONS:		COMMENTS / DISCUSSION: Use 500 cfs in Culvert:				CULVERT BARREL SELECTED:												
1. APPROXIMATE 2. CULVERT FACE 3. DESIGN HEADWATER 4. HEADWATER IN INLET CONTROL 5. HEADWATER IN OUTLET CONTROL 6. INLET CONTROL SECTION 7. OUTLET 8. STREAMBED AT CULVERT FACE 9. TAILWATER		$Q_r = C_d L HW_r^{1.5} = 3.03 (200') (0.9)^{1.5} = 520 \text{ cfs}$ $Q_r = 500 + 520 = 1020 \text{ cfs}$				SIZE: <u>7 x 6</u> SHAPE: <u>RCB</u> MATERIAL: _____ ENTRANCE: <u>Bevel</u>												

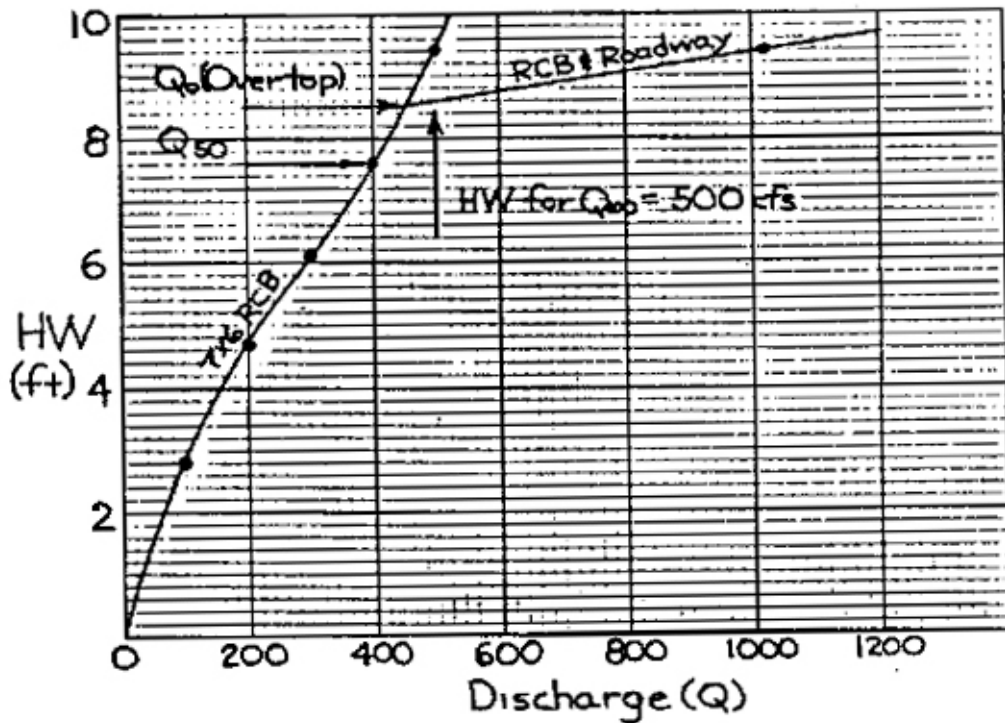


Figure 5-12 Chart 17 and Performance Curve for Design Example

Step 5 Select Design Alternative

Shape - box Size - 7 feet by 6 feet
 Material - concrete Entrance - beveled

Step 6 Select Design Discharge ($Q_d = Q_{50} = 400$ cfs)

Step 7 Determine Inlet Control Headwater Depth (HW_i)

Use inlet control nomograph (Chart 10)

- a. $D = 6$ feet
- b. $Q/B = 400/7 = 57.1$
- c. $HW/D = 1.33$ for 3/4-inch
 $HW/D = 1.27$ for 45-degree bevel
- d. $HW_i = (HW/D)D = (1.27) 6 = 7.62$ feet (neglect the approach velocity)

Step 8 Determine Outlet Control Headwater Depth at Inlet (HW_{oi})

- a. $TW = 2.8$ feet for $Q_{50} = 400$ cfs
- b. $d_c = 4.7$ feet (Chart 14)
- c. $(d_c + D)/2 = (4.7 + 6)/2 = 5.35$ feet
- d. $h_o =$ the larger of TW or $(d_c + D)/2$
 $h_o = (d_c + D)/2 = 5.35$ feet
- e. $K_E = 0.2$ from Table 12
- f. Determine (H) – use Chart 15
 - K_E scale = 0.2
 - culvert length (L) = 300 feet
 $n = 0.012$ same as chart
 - area = 42 sf
 - $H = 3.2$ feet
- g. $HW_{oi} = H + h_o - S_oL = 3.2 + 5.35 - (0.05) 245 = 6.63$ feet

Step 9 Determine Controlling Headwater (HW_c)

- a. $HW_c = HW_i = 7.62$ feet greater than $HW_{oi} = 6.63$ feet; therefore, the culvert is in inlet control.

Step 10 Compute Discharge Over the Roadway (Q_r)

- a. Calculate depth above the roadway:
 $HW_r = HW_c - HW_{ov} = 7.62 - 8.40 = -0.78$ foot
- b. If $HW_r = 0$, $Q_r = 0$

Step 11 Compute Total Discharge (Q_t)

$$Q_t = Q_d + Q_r = 400 \text{ cfs} + 0 = 400 \text{ cfs}$$

Step 12 Calculate Outlet Velocity (V_o) and Depth (d_n)

Inlet Control

a. Calculate normal depth (d_n):

$$\begin{aligned} Q &= (1.49/n)AR^{2/3} S^{1/2} = 400 \text{ cfs} \\ &= (1.49/0.012)(7xd_n)[7xd_n/(7+2d_n)]^{2/3}(0.05)^{0.5} \\ &= (7xd_n)[7xd_n/(7+2d_n)]^{2/3} = 14.4 \end{aligned}$$

Try $d_n = 2$ feet, $16.4 > 14.4$

Use $d_n = 1.8$ feet, $14.1 \approx 14.4$

b. $A = 7(1.8) = 12.6$ sf

c. $V_o = Q/A = 400/12.6 = 31.7$ fps

Step 13 Review Results

Compare alternative design with constraints and assumptions. If any of the following are exceeded, repeat Steps 5 through 12:

- barrel has $(8.5-6) = 2.5$ feet
- $L = 300$ feet is OK, since inlet control
- headwalls and wingwalls fit site
- allowable headwater (8.5 feet) greater than 7.62 feet is OK
- overtopping flood frequency greater than 2 percent chance (50-year) flood

Step 14 Documentation

Report prepared and background filed.

5.4.9 HY8 Computer Program

5.4.9.1 Overview

Culvert hydraulic analysis can also be accomplished with the aid of computer software. The following example has been produced using the HY8 Culvert Analysis Microcomputer Program and is the computer solution of the data provided in Section 5.4. HY8 screens were modified so they would fit into the text of this chapter; they may not match exactly what is seen on the computer screen.

5.4.9.2 Data Input

After creating a file, the user will be prompted for the discharge range, site data, and culvert shape, size, material, and inlet type. The discharge range for this example will be from 0 to 500 cfs. The site data are entered by providing culvert invert data. If embankment data points are input, the program will fit the culvert in the fill and subtract the appropriate length.

Culvert Data

As an initial size estimate, try a 60-inch by 60-inch concrete box culvert. For the culvert assume that a conventional inlet with 1:1 bevels and 45-degree wingwalls will be used. As each group of data is entered, the user is allowed to edit any incorrect entries. The following is how the screen that summarizes the culvert information will look.

```

CULVERT FILE: EXAMPLE      FHWA CULVERT ANALYSIS      DATE:05-30-2002
TAILWATER FILE: EXAMPLE    HY8, VERSION 6.1           CULVERT NO. 1 OF 1

NO ITEM          CULVERT DATA

<1> BARREL SHAPE:      BOX
<2> BARREL SIZE:       5.00 feet x 5.00 feet
<3> BARREL MATERIAL:   CONCRETE
<4> MANNING'S N:       0.012
<5> INLET TYPE:        CONVENTIONAL
<6> INLET EDGE AND WALL: 1:1 BEVEL (45 DEG. FLARE)
<7> INLET DEPRESSION:  NONE
                        <ENTER> TO CONTINUE
                        <NUMBER> TO EDIT ITEM

1-Help 2-Prog 3    4    5-End 6    7-Edit 8    9-Dos 10

```

Channel Data

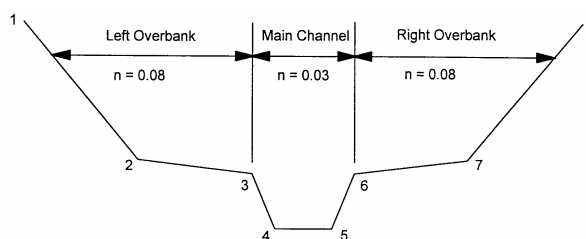
Next the program will prompt for data pertaining to the channel so that tailwater elevations can be determined. Referring to the problem statement, the channel is irregularly shaped and can be described by the 8 coordinates listed. After opening the irregular channel file, the user will be prompted for channel slope (0.05), number of cross-section coordinates (8), and subchannel option. The subchannel option in this case would be option (2), left and right overbanks ($n = 0.08$), and main channel ($n = 0.03$).

IRREGULAR CHANNEL CROSS-SECTION					
CROSS-SECTION		X	Y	CROSS-SECTION	
COORD. NO.	(ft.)	(ft.)	COORD. NO.	(ft.)	(ft.)
1	12	180.0	5	40	172.5
2	22	175.0	6	41	174.5
3	32	174.5	7	51	175.0
4	34	172.5	8	61	180.0

<NUMBER> TO EDIT COORDINATES <I> <D> TO INSERT OR DELETE
 <ENTER> TO CONTINUE <P> TO PLOT CROSS-SECTION

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

The next prompt, for channel boundaries, refers to the number of the coordinate pair defining the left subchannel boundary and the number of the coordinate pair defining the right subchannel boundary. The boundaries for this example are the 3rd and 6th coordinates. After this is input, the program prompts for channel coordinates. Once these are entered, pressing (P) will cause the computer to display the channel cross-section shown above. The user can easily identify any input errors by glancing at the plot. To return to the data input screens, press any key. If data are correct, press <return>. You can then enter the roughness data for the main channel and overbanks.



5.4.9.3 Rating Curve

The program now has enough information to develop a uniform flow rating curve for the channel and provide the user with a list of options. Selecting option (T) on the Irregular Channel Data Menu will compute the rating curve data and display the following table. Selecting option (I) will permit the user to interpolate data between calculated points.

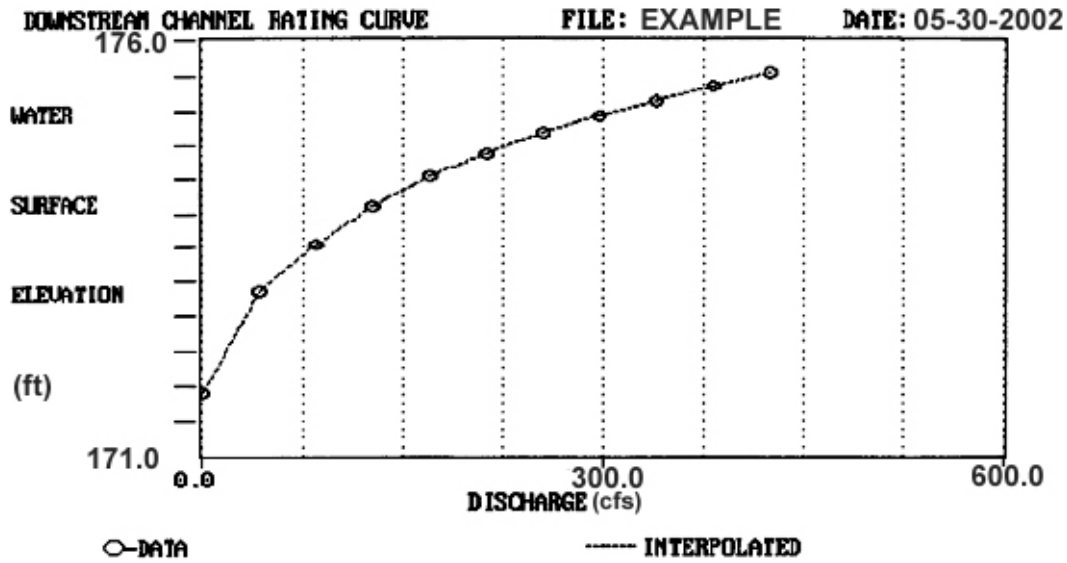
CULVERT FILE: HDS5EX1 FHWA CULVERT ANALYSIS DATE: 03-11-1996
 TAILWATER FILE: AP-GDEX1 HY8, VERSION 6.0 CULVERT NO. 1 OF 1

NO.	FLOW (cfs)	ELEVATION (ft)	DEPTH (ft)	VEL. (fps)	SHEAR (psf)
1	0.00	172.50	0.00	0.00	0.00
2	50.00	173.37	0.87	8.80	2.21
	100.00	173.82	1.32	10.97	3.08
4	150.00	174.18	1.68	12.42	3.70
5	200.00	174.49	1.99	13.52	4.21
6	250.00	174.72	2.22	14.47	4.79
7	300.00	174.92	2.42	15.76	5.30
8	350.00	175.09	2.59	16.61	5.73
9	400.00	175.24	2.74	17.34	6.11
10	450.00	175.36	2.88	18.01	6.47
11	500.00	175.51	3.01	18.67	6.80

PRESS <D> FOR DATA <P> TO PLOT RATING CURVE
 <ESC> FOR CHANNEL SHAPE MENU <ENTER> TO CONTINUE

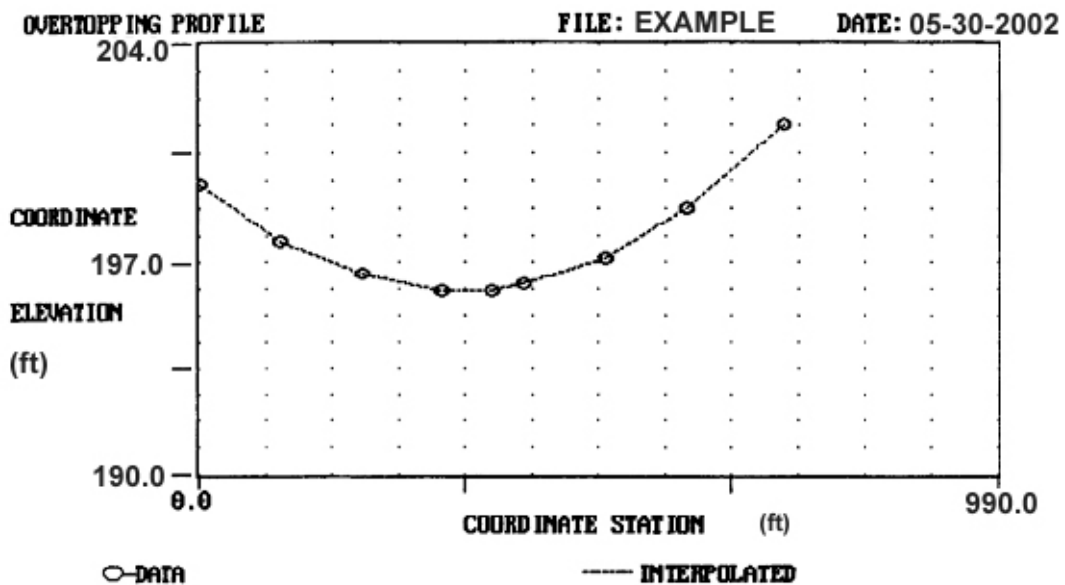
1-Help 2-Progr 3 4 5-End 6 7 8 9-DOS 10

The Tailwater Rating Curve Table consists of tailwater elevation (TWE) at normal depth, natural channel velocity (Vel.) and the shear stress at the bottom of the channel for various flow rates. At the design flow rate of 400 cfs, the tailwater elevation will be 175.24 feet. The channel velocity will be 17.34 fps, and the shear will be 6.11 psf. This information will be useful in the design of channel linings if they are needed. Entering (P) will cause the computer to display the rating curve for the channel. This curve, shown on the next page, is a plot of tailwater elevation vs. flow rate at the exit of the culvert.



5.4.9.4 Roadway Data

The next prompts are for the roadway profile so that an overtopping analysis can be performed. Referring to the problem statement, the roadway profile is a sag vertical curve which will require nine coordinates to define. Once these coordinates are input, the profile will be displayed when (P) is entered, as illustrated below. The other data required for overtopping analysis are roadway surface or weir coefficient and the embankment top width. For this example, the roadway is paved with an embankment width of 50 feet.



5.4.9.5 Data Summary

All the data has now been entered and the summary table is displayed as shown below. At this point any of the data can be changed or the user can save the data and continue by pressing (Enter), which will bring up the Culvert Program Options Menu.

CULVERT FILE: EXAMPLE	FHWA CULVERT ANALYSIS	DATE:05-30-2002
TAILWATER FILE: EXAMPLE	HY8, VERSION 6.1	CULVERT NO. 1 OF 1

SUMMARY TABLE

C	<S> SITE DATA	<C> CULVERT SHAPE, MATERIAL, INLET
U		
L	INLET ELEV. (ft.)	OUTLET ELEV. (ft.)
V	ELEV. (ft.)	LENGTH (ft.)
NO.		
1	187.5	172.5
		300
		1 - RCB
		500
		500
		.012
		CONVENTIONAL

	PRESS TO REVIEW	PRESS TO
<C>	Culvert Data	<E> Edit Culvert Size
<D>	Discharge Data	<M> Minimize Culvert Span
<R>	Roadway Data	<A> Add or Delete Culverts
<S>	Site Data	<N> Edit Number of Barrels
<T>	Tailwater Rating Curve	<F> File - Change Name

<ENTER>	To Save & Exit	<ESC>	For File Menu
---------	----------------	-------	---------------

1-Help	2-Progr	3	4	5-End	6	7	8
--------	---------	---	---	-------	---	---	---

5.4.9.6 Performance Curve (5 feet by 5 feet)

From the Culvert Program Options Menu, the culvert performance curve table can be obtained by selecting option (S). When option (S) is selected, the program will compute the performance curve table without considering overtopping in the analysis. Since this 5-foot by 5-foot culvert is a preliminary estimate, the performance without considering overtopping is calculated and is shown below:

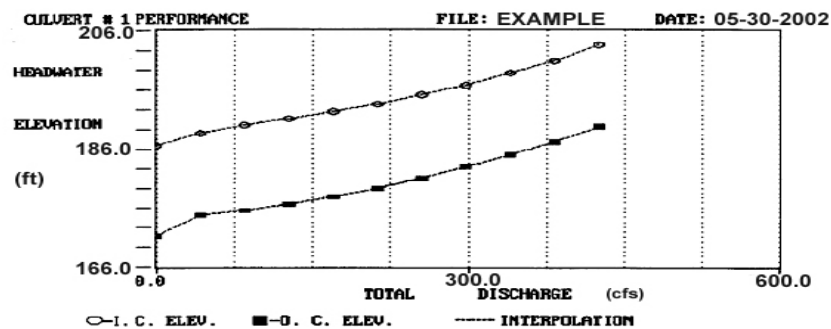
PERFORMANCE CURVE FOR CULVERT 1 - 1(5.00 ft. BY 5.00 ft.) RCB										
DIS- CHARGE FLOW (cfs)	HEAD- WATER ELEV. (ft)	INLET CONTROL DEPTH (ft)	OUTLET CONTROL DEPTH (ft)	ANALYSIS ASSUMES NO OVERTOPPING FLOW TYPE <F4>	NORMAL DEPTH (ft)	CRIT. DEPTH (ft)	OUTLET TW			
							DEPTH (ft)	DEPTH (ft)	VEL. (fps)	VEL. (fps)
0.00	187.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50.00	189.58	2.08	2.08	1-S2n	0.58	1.46	0.46	0.87	21.64	8.80
100.00	190.91	3.41	3.41	1-S2n	0.92	2.32	0.95	1.32	21.10	10.97
150.00	192.11	4.61	4.61	1-S2n	1.22	3.04	1.27	1.68	23.60	12.42
200.00	193.30	5.80	5.80	1-S2n	1.50	3.68	1.58	1.99	25.25	13.52
250.00	194.59	7.09	7.09	1-S2n	1.76	4.28	1.88	2.22	26.66	14.72
300.00	196.04	8.54	8.54	1-S2n	2.01	4.83	2.19	2.42	27.43	15.76
350.00	197.71	10.21	-3.51	6-FFc	2.25	5.00	2.48	2.59	28.23	16.61
400.00	199.62	12.12	-1.53	6-FFc	2.49	5.00	2.76	2.74	28.99	17.34
450.00	201.77	14.27	0.72	6-FFc	2.72	5.00	3.00	2.85	30.00	18.01
500.00	204.41	16.91	3.24	6-FFc	2.95	5.00	3.29	3.01	30.40	18.62

INVERT ELEVATIONS: --> Inlet - 187.5 ft. Crest - 0.00 ft
 Outlet - 172.5 ft. Throat - 0.00 ft

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

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

This table indicates the controlling headwater elevation (HW), the tailwater elevation, and the headwater elevations associated with all the possible control sections of the culvert. It is apparent from the table that at 400 cfs, the headwater is 200 feet, which exceeds the design headwater of 195 feet. Consequently, the 5-foot by 5-foot box culvert is inadequate for the site conditions. The following plot of inlet and outlet control headwater can be obtained by entering (P). In this example, the culvert is operating in inlet control (the upper curve) throughout the discharge range.



5.4.9.7 Performance Curve (6 feet by 6 feet)

The user can easily modify the existing program file to analyze a larger barrel. Suppose a 6-foot by 6-foot culvert is tried. From the Culvert Program Options Menu, press (E) to edit the file and then (E) to edit the culvert size. The prompts will be the same as they were for the 5-foot by 5-foot culvert, and the user will be returned to the Culvert Data Summary Table directly without going through the tailwater and overtopping menus again. Press (F) to rename the data file, or press <enter> to save the changes into the current file and return to the Culvert Program Options Menu. The performance of this culvert can be checked by selecting option (S) for no overtopping. The following table appears.

PERFORMANCE CURVE FOR CULVERT 1 - 1 (6.00 ft BY 6.00 ft) RCB										
ANALYSIS ASSUMES NO OVERTOPPING										
DIS- CHARGE FLOW (cfs) (fps)	HEAD- WATER ELEV. (ft.)	INLET CONTROL DEPTH (ft.)	OUTLET CONTROL DEPTH (ft.)	FLOW TYPE <F4>	NORMAL DEPTH (ft.)	CRIT. DEPTH (ft.)	OUTLET DEPTH (ft.)	TW DEPTH (ft.)	OUTLET VEL. (ft.)	TW VEL. (fps)
0.00	187.5	1.84	0.00	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
50	189.34	2.93	1.84	1-S2n	0.48	1.29	0.39	0.87	21.11	8.80
100	190.34	2.93	2.93	1-S2n	0.79	2.06	0.76	1.32	22.07	10.97
150	191.44	3.94	3.94	1-S2n	1.05	2.69	0.99	1.68	25.17	12.42
200	192.37	4.87	4.87	1-S2n	1.28	3.29	1.34	1.99	24.83	13.52
250	193.27	5.77	5.77	1-S2n	1.49	3.79	1.59	2.22	26.27	14.74
300	194.18	6.68	6.68	1-S2n	1.70	4.28	1.85	2.42	27.10	15.76
350	195.12	7.62	7.62	1-S2n	1.90	4.74	2.09	2.59	27.94	16.61
400	196.12	8.62	8.62	1-S2n	2.08	5.18	2.33	2.74	28.62	17.34
450	197.21	9.71	9.71	1-S2n	2.27	5.60	2.56	2.88	29.27	18.01
500	198.40	10.90	10.90	1-S2n	2.46	6.00	2.79	3.01	29.57	18.62
INVERT ELEVATIONS-->				Inlet - 187.5 ft.	Crest - 0.00 ft.					
				Outlet - 172.5 ft.	Throat - 0.00 ft.					
PRESS: <KEY> TO CONTINUE					<W> FOR PROFILE TABLE					
<P> TO PLOT					<I> FOR IMPROVED INLET TABLE					
1- Help	2	3	4-Type	5-End	6	7	8	9-DOS	10	

5.4.9.8 Performance Curve (7 feet by 6 feet)

Since the design headwater criterion has still not been met, another size must be selected. Try a 7-foot by 6-foot culvert and modify the file accordingly. The resulting performance table shown below indicates that the design headwater will not be exceeded at 400 cfs. However, the headwater elevation of 196.8 feet at 500 cfs indicates that some overtopping will occur due to the 1 percent chance (100-year) storm.

PERFORMANCE CURVE FOR CULVERT 1 - 1 (7.00 ft. BY 6.00 ft.) RCB

DIS- CHARGE FLOW (cfs)	HEAD- WATER ELEV. (ft.)	INLET CONTROL DEPTH (ft.)	OUTLET CONTROL DEPTH (ft.)	ANALYSIS ASSUMES NO OVERTOPPING CONTROL FLOW TYPE <F4>	NORMAL DEPTH (ft.)	CRIT. DEPTH (ft.)	OUTLET DEPTH (ft.)	TW DEPTH (ft.)	OUTLET TW VEL. (fps)	TW VEL. (fps)
0.00	187.5	0.00	0.00	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
50	189.16	1.66	1.66	1-S2n	0.40	1.17	0.37	0.87	19.39	8.80
100	190.14	2.64	2.64	1-S2n	0.71	1.85	0.65	1.32	21.82	10.97
150	191.02	3.521	3.52	1-S2n	0.92	2.43	0.96	1.68	22.32	12.42
200	191.85	4.35	4.35	1-S2n	1.13	2.94	1.18	1.99	24.13	13.52
250	192.63	5.13	5.13	1-S2n	1.32	3.42	1.40	2.22	25.58	14.74
300	193.40	5.90	5.90	1-S2n	1.49	3.86	1.61	2.42	26.66	15.76
350	194.18	6.68	6.68	1-S2n	1.66	4.28	1.82	2.59	27.55	16.61
400	194.98	7.48	7.48	1-S2n	1.82	4.67	2.02	2.74	28.24	17.34
450	195.83	8.33	8.37	1-S2n	1.98	5.05	2.22	2.88	28.89	15.01
500	196.80	9.24	9.24	1-S2n	2.13	5.42	2.42	3.01	29.48	18.62

INVERT ELEVATIONS-->

Inlet - 187.5 ft.

Crest - 0.00 ft.

Outlet - 172.5 ft.

Throat - 0.00 ft.

PRESS: <KEY> TO CONTINUE

<W> FOR PROFILE TABLE

<P> TO PLOT

<I> FOR IMPROVED INLET TABLE

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

5.4.9.9 Minimize Culvert Span of HY8

Rather than using a series of trials to reduce the culvert headwater to an acceptable level, as in the preceding examples, the "Minimize Culvert Span" feature of HY8 can be used. This feature is intended to allow the designer to use HY8 as a tool to perform culvert design for circular, box, elliptical, and arch shape culverts based on a user's defined allowable headwater elevation, assuming no overtopping. This feature can be activated by selecting the letter "M." Once this option is selected, the user inputs the allowable headwater elevation. That elevation will be the basis for adjusting the user's defined culvert size for the design discharge. The program will adjust the culvert span by increasing or decreasing by 0.5-foot increments. It will compute the headwater elevation for the span and compare it with the user's defined allowable headwater. If the computed headwater elevation is equal to or less than the defined allowable headwater elevation the minimization routine will stop, and the adjusted culvert can be used for the remainder of the program. Several hydraulic parameters are also computed while performing the minimization routine. These hydraulic parameters, which are part of the output of the minimization routine table, as shown below, must be printed from this screen because they are not printed with the output listing routine.

CULVERT FILE: EXAMPLE	FHWA CULVERT ANALYSIS	DATE:05-30-2002
TAILWATER FILE: EXAMPLE	HY8, VERSION 6.1	CULVERT NO. 1 OF 1

SUMMARY TABLE

C	<S> SITE DATA	<C> CULVERT SHAPE, MATERIAL, INLET						
U								
L	INLET	OUTLET	CULVERT	BARRELS				
V	ELEV.	ELEV.	LENGTH	3SHAPE	SPAN	RISE	MANNING	INLET
NO.	(ft.)	(ft.)	(ft.)	MATERIAL	(ft.)	(ft.)	n	TYPE
1	187.5	172.5	300	1 - RCB	6.50	60	.012	CONVENTIONAL
2								
	HEADWATER ELEVATION	(ft.)	FLOW VELOCITY	(fps)	FLOW DEPTHS	(ft)		
	ENTER ALLOWABLE =	196.0	V culvert =	28.49	CULVERT	= 2.60		
	CONTROLLING =	195.0	V channel =	17.34	CHANNEL	= 2.74		
	INLET CONTROL =	195.5	Q (cfs) =	400.00	NORMAL	= 1.94		
	OUTLET CONTROL =	195.5	SLOPE =	0.0500	CRITICAL	= 4.91		

MAXIMUM HEADWATER <ENTER> TO RETURN <S> TO SAVE FILE
<H> TO CHANGE HEADWATER

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

This feature proves to be a time saver for designers because it avoids the need for repetitively editing a culvert size to obtain a controlling headwater elevation.

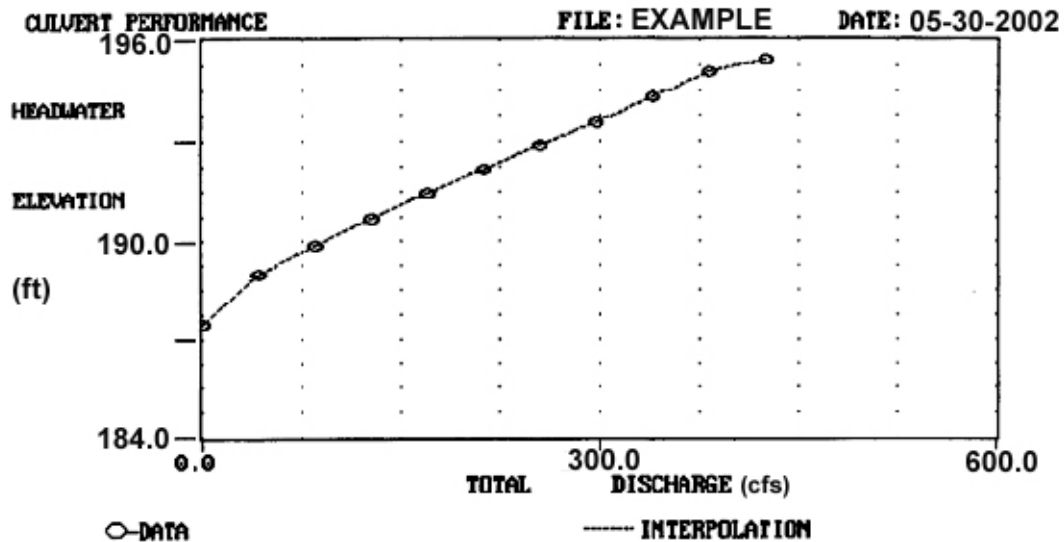
5.4.9.10 Overtopping Performance Curve (7 feet by 6 feet)

Returning to the 7-foot by 6-foot culvert, select (O) for overtopping to determine the amount of overtopping and the actual headwater, from the Culvert Program Options Menu. A Summary of Culvert Flows will appear on the screen, as shown below:

HY8, VERSION 6.0									
FILE: EXAMPLE		SUMMARY OF CULVERT FLOWS (cfs)						DATE:05-30-2002	
ELEV(ft.)	TOTAL	1	2	3	4	5	6	ROADWAY	ITER
187.5	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
189.16	50	50	0.00	0.00	0.00	0.00	0.00	0.00	1
190.14	100	100	0.00	0.00	0.00	0.00	0.00	0.00	1
191.02	150	150	0.00	0.00	0.00	0.00	0.00	0.00	1
191.85	200	200	0.00	0.00	0.00	0.00	0.00	0.00	1
192.63	250	250	0.00	0.00	0.00	0.00	0.00	0.00	1
193.40	300	300	0.00	0.00	0.00	0.00	0.00	0.00	1
194.18	350	350	0.00	0.00	0.00	0.00	0.00	0.00	1
194.98	400	400	0.00	0.00	0.00	0.00	0.00	0.00	1
195.83	450	450	0.00	0.00	0.00	0.00	0.00	0.00	1
196.19	500	500	0.00	0.00	0.00	0.00	0.00	26	8
196.00	459	459	0.00	0.00	0.00	0.00	0.00	Q = Qo	

PRESS: <P> TO PLOT TOTAL RATING CURVE
 <T> TO DISPLAY TABLE FOR EACH CULVERT
 <E> TO DISPLAY ERROR TABLE
 <R> TO PRINT REPORT Output stored in EXAMPLE.PC
 <H> TO RETURN TO HEADWATER TABLE
 <ENTER> TO RETURN TO OPTION MENU

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



This computation table is used when overtopping and/or multiple culvert barrels are used. It shows the headwater, total flow rate, the flow through each barrel, the overtopping flow, and the number of iterations it took to balance the flows. From this information, a total (culvert and overtopping) performance curve, shown below, can be obtained by selecting option (P). This curve is a plot of the headwater elevation vs. the total flow rate, which indicates how the culvert or group of culverts will perform over the selected range of discharges. It is especially useful for comparing the effects of various combinations of culverts.

5.4.9.11 Review

The summary table shows that the total flow is 500 cfs, and 474 cfs passes through the culvert while 26 cfs flows over the road. The headwater elevation will be 196.2 feet. Assume that in this case, overtopping at the 1 percent chance (100-year) frequency can be tolerated, and the 7-foot by 6-foot culvert will be used. When overtopping occurs, the performance of the culvert will differ from that without overtopping. By selecting option (T), the culvert performance data can be obtained. The user also has the option to plot these data.

Referring to the performance curve data shown below, the outlet velocity at 400 cfs is 28.24 fps. Since the tailwater rating curve generated previously indicates that the natural channel velocity at 400 cfs is 17.34 fps, an energy dissipator or channel protection is warranted.

PERFORMANCE CURVE FOR CULVERT 1 - 1(7.00 ft. BY 6.00 ft.) RCB										
DIS- CHARGE FLOW (cfs)	HEAD- WATER ELEV. (ft.)	INLET CONTROL DEPTH (ft.)	OUTLET CONTROL DEPTH (ft.)	ANALYSIS ASSUMES NO OVERTOPPING FLOW TYPE <F4>	NORMAL DEPTH (ft.)	CRIT. DEPTH (ft.)	OUTLET DEPTH (ft.)	TW DEPTH (ft.)	OUTLET VEL. (fps)	TW VEL. (fps)
0.00	187.5	0.00	0.00	0-NF	0.00	0.00	0.00	0.00	0.00	0.00
50	189.16	1.66	1.66	1-S2n	0.40	1.17	0.37	0.87	19.39	8.80
100	190.14	2.64	2.64	1-S2n	0.71	1.85	0.65	1.32	21.82	10.97
150	191.02	3.52	3.52	1-S2n	0.92	2.43	0.96	1.68	22.32	12.42
200	191.85	4.35	4.35	1-S2n	1.13	2.94	1.18	1.99	24.13	13.52
250	192.63	5.13	5.13	1-S2n	1.32	3.42	1.40	2.22	25.58	14.74
300	193.40	5.90	5.90	1-S2n	1.49	3.86	1.61	2.42	26.66	15.76
350	194.18	6.68	6.68	1-S2n	1.66	4.28	1.82	2.59	21.55	16.61
400	194.98	7.48	7.48	1-S2n	1.82	4.67	2.02	2.74	28.24	17.34
450	195.83	8.33	8.33	1-S2n	1.98	5.05	2.22	2.88	28.89	18.01
500	196.18	8.68	8.68	1-S2n	2.03	5.20	2.30	3.01	29.16	18.62
INVERT ELEVATIONS-->			Inlet - 187.5 ft.			Crest - 0.00 ft.				
			Outlet - 172.5 ft,			Throat - 0.00 ft.				
PRESS: <KEY> TO CONTINUE						<W> FOR PROFILE TABLE				
<P> TO PLOT						<I> FOR IMPROVED INLET TABLE				
1- Help	2	3	4-Type	5-End	6	7	8	9-DOS	10	

By pressing <enter>, the program returns to the Summary of Culvert Flows menu. Selecting option (E), a Summary of Iterative Solution Errors is produced. This table, shown below, lists the amount of error present in the solution for a flow rate of 500 cfs is 4.78 cfs.

FILE: EXAMPLE SUMMARY OF ITERATIVE SOLUTION ERRORS DATE: 05-30-2002

HEAD ELEV (ft.)	HEAD ERROR (ft.)	TOTAL FLOW (cfs)	FLOW ERROR (cfs)	% FLOW ERROR
187.5	0.000	0	0.000	0.000
189.163	0.000	50	0.000	0.000
190.141	0.000	100	0.000	0.000
191.016	0.000	150	0.000	0.000
191.847	0.000	200	0.000	0.000
192.633	0.000	250	0.000	0.000
193.402	0.000	300	0.000	0.000
194.178	0.000	350	0.000	0.000
194.981	0.000	400	0.000	0.000
195.829	0.000	450	0.000	0.000
196.186	-0.007	500	4.78	0.956

<1> TOLERANCE (ft.) = 0.003 <2> TOLERANCE (%) = 1.000
PRESS <NUMBER> TO EDIT DISPLAY ITERATIONS
PRESS <ENTER> TO RETURN <3> FOR HEADWATER - NO
PRESS <ESC> TO RECOMPUTE <4> FOR DISCHARGE - NO
 <5> TONE AT FINISH - NO

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

5.5 MAINTENANCE

5.5.1 Culvert Maintenance and Inspection

Culverts must be kept free of obstructions. Sand or sediment deposits should be removed as soon as possible. Inlet and outlet channels should be kept in alignment and vegetation controlled in order to minimize any significant restriction of flow. Reinforced concrete box culverts require little maintenance, but they should be inspected every 2 years for cracks, bottom erosion, and undermining at outlets. Undermining is generally the result of high outlet velocities. Inspect small diameter culverts (less than or equal to 48-inch diameter) with closed circuit cameras. This activity can locate structural deficiencies in pipes. Correction of undermining usually requires adding an energy dissipator.

For more details see *Culvert Inspection Manual*, FHWA-IP-86-2, July 1986.

5.5.2 Cleaning

Culverts may become clogged if the flow line grade prevents self-cleaning. A permanent correction is to re-position the pipe on a steeper grade, but this is not always possible and is often very expensive. The alternative is to clean the pipe frequently.

Small culverts may be cleaned by flushing away debris with water pressure. An alternate method of cleaning small culverts is to use mobile heavy-duty industrial vacuum equipment.

Some large culverts over 36-inch diameter must be cleaned by hand. A small sled or wagon is useful for transporting material from inside the barrel to the culvert ends. In some cases a small rubber-tired tractor, equipped with a push blade, may be used to remove sand and silt deposits from the larger concrete culverts.

Culverts with trash racks should be frequently inspected and promptly cleaned, when needed. Inspection at least twice a year is suggested (once in late fall and again in spring or summer).

5.5.3 Lining Culverts (updated January 2004)

When a culvert has structural deterioration, it may be possible to line the culvert instead of replacing it. Caution must be used by the designer, and a hydraulic analysis should be done to determine the potential hydraulic impacts of inserting the liner. The analysis should cover the range of flows passed by the culvert.

Lining may be in the form of inserting plastic pipe and grouting the annulus or insertion of a resin-impregnated flexible liner. Installation is covered by appropriate Special Provision, e.g., "In-Place Culvert Rehabilitation, Liner." The installation of a liner may be allowed for the following conditions:

- The culvert is a cross-culvert that acts as an equalizer between two bodies of water (e.g., between two wetlands).
- A driveway culvert that is only carrying ditch flow generated from MDOT R.O.W. For the range of design flows, the water surface elevation upstream of the culvert is contained within the R.O.W.
- The culvert is a CMP that will not experience inlet control over the range of design flows.

Any questions regarding the hydraulic analysis or potential impacts should be directed to the Design Engineer – Hydraulics.

High-velocity flows, containing large quantities of stone and rock, will scour the culvert bottom. Scour may be reduced by securing steel plates longitudinally along the bottom. Scour around footings, cutoff walls, and headwalls is repaired by replacing the eroded material in kind or by filling the void with riprap or sacked concrete. In an emergency, a bituminous mix may be used.

When concrete pipe culverts settle, joints pull apart. Joints are repaired by tamping or rodding grout into the cracks.

To prevent erosion, energy dissipators are sometimes placed at outlets of culverts and drains. It is important that these be inspected periodically, particularly after major flows, to ensure that they are in place and functional.

References

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King, H.W., and E.F. Brater. *Handbook of Hydraulics*, Sixth Edition, McGraw-Hill Book Co. 1976.

Note: References in bold type are recommended for the engineer's library.