Chapter 5 CULVERT

5.1 INTRODUCTION

This chapter provides design procedures for the hydraulic design of highway culverts which are based on the Federal Highway Administration (FHWA) Hydraulic Design Series No. 5 (HDS-5), *Hydraulic Design of Highway Culverts* (FHWA, 1985).

5.1.1 Definition

A culvert is defined as a structure sized hydraulically to convey surface water runoff under a highway, railroad, or other embankment. Culverts are:

- structures distinguished from bridges by being covered with an embankment and generally composed of a structural material around the entire perimeter with some exceptions such as a MN/DOT Arch which may utilize the natural streambed and appropriate erosion protection as the bottom.
- classified as a bridge when horizontal opening width is 10 feet or greater measured perpendicular to the roadway centerline, however, the structure is analyzed using procedures defined in this chapter.

5.1.2 Concept Definitions

The following are discussions of concepts which are important in culvert design.

Barrel Area	Barrel area is measured perpendicular to the flow and refers to the water area in the barrel.
Barrel Length	Barrel length is the total culvert length from the entrance to the exit of the culvert. Because the height of the barrel, barrel slope, and barrel skew influence the actual length, an approximation of barrel length is usually necessary to begin the design process.
Barrel Roughness	Barrel Roughness is a function of the material used to fabricate the barrel. Typical materials include concrete, corrugated metal and plastic. The roughness is represented by a hydraulic resistance coefficient such as the Mannings "n" value.
Barrel Slope	Barrel slope is the actual slope of the culvert barrel, and is often the same as the natural stream slope.
Critical Depth	Critical depth is 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.
Crown	The crown is the inside top of the culvert.
Flowline	The flowline is the bottom invert of a conduit. An exception is when the invert is buried and riprap or other fill material is placed in the culvert, the flowline is then the top of the fill material.
Free Outlet	A free outlet has a tailwater equal to or lower than critical depth. For culverts having free outlets, lowering of the tailwater has no effect on the backwater profile upstream of the tailwater.
Headwater, HW	That depth of water impounded upstream of a culvert due to the influence of the culvert constriction, friction, and configuration.
Improved Inlet	An improved inlet has an entrance geometry which decreases the flow constriction at the inlet and thus increases the capacity of culverts. These inlets are referred to as either side- or slope-tapered (walls or bottom tapered).
Invert	The invert is the inside bottom of the culvert.
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 profile and channel bottom slope will be parallel. This type of flow will exist in a culvert operating on a uniform slope provided the culvert is sufficiently long.
Slope	There are two classifications of slope, steep and mild. • Steep slope occurs where the critical depth is greater than the normal depth. • Mild slope occurs where critical depth is less than normal depth.

Stage Increase	The difference between headwater and the unconstricted water surface just upstream of the culvert.
Submerged	Submergence can occur at either the inlet and/or the outlet. • A submerged outlet occurs where the tailwater elevation is higher than the crown of the culvert. • A submerged inlet occurs where the headwater is greater than 1.2 times the culvert diameter.
Tailwater (TW)	The depth of water at the outlet of a culvert.

5.2 DESIGN CRITERIA

Design criteria are the standards by which a policy is carried out or placed into action. They form the basis for the selection of the final design configuration. There are a number of different culvert sizes, shapes and materials from which a designer can choose. The design selected should be the one that best integrates hydraulic efficiency, serviceability, structural stability, economics, environmental considerations, traffic safety and land use requirements.

Culverts are used in the following conditions:
- where they are more economical than a bridge,
- where bridges are not hydraulically required,
- where higher velocities can be tolerated,
- where greater stage increases can be tolerated, and
- where debris and ice are tolerable.

5.2.1 Policy

Policy is a set of goals that establish a definite course or method of action. These goals are selected to guide and determine present and future decisions. Policy is implemented through design criteria established as standards for making decisions. The policies specific to culverts are listed below.
- All culverts should be hydraulically designed, however the minimum pipe size specified in Section 5.2.4 will sometimes dictate the ultimate design.
- Use 50 year design frequency criteria for minor culverts 48" or less in diameter. The overtopping flood need not be computed. A greater design frequency may be required if there is significant flood damage potential upstream, there are special traffic considerations, or to accommodate FEMA mapped floodplains.
- A risk assessment shall be completed for all major culverts 54" or larger. The 500-year flood or overtopping flood (if less than Q_{500}) shall be computed.
- Culvert location in both plan and profile should be investigated and designed to avoid sediment build-up in culvert barrels.
- The potential for culverts plugging with debris or ice shall be considered in the design.
- Material selection is based on determining the material type which best fulfills all of the engineering requirements for a specific installation. Factors to be considered are hydraulic performance, structural stability, serviceability, and economics. Abrasion and corrosion should be considered when determining serviceability requirements.
- Culverts shall be located and designed to present a minimum hazard to traffic and people.
- The detail of documentation for each culvert site shall be commensurate with the risk and importance of the structure. Design data and calculations should be assembled in an orderly fashion and retained for future reference.
- Culverts should be regularly inspected and maintained.

5.2.2 Site Criteria

Design criteria that are dependant on site factors include: structure type, length, location in plan, location in profile, overfill, debris and ice.
- The length of a culvert should be based on roadway clear zone and embankment geometry.
- Severe or abrupt changes in channel alignment upstream or downstream of culverts are not recommended.
- Small culverts with no defined channel are placed normal to centerline.
- Large culverts perpetuating drainage in defined channels should be skewed as necessary to minimize channel relocation and erosion.
- Culvert location in both plan and profile should be investigated and designed to avoid sediment build-up in culvert barrels. Consider having the invert of one barrel lower than the others in multiple barrel crossings.
- At most locations, the culvert profile will approximate the natural stream profile. Exceptions can be considered to: arrest stream degradation by utilizing a drop inlet or broken back culvert; or improve hydraulic performance by utilizing a slope tapered inlet.
- Culverts shall be located and designed to present a minimum hazard to traffic and people. Full recovery distance is desirable without guardrail. When safety grates are required, the potential for flood damage caused by the grate plugged with debris or ice shall be assessed.
- Minimum and Maximum Overfill
  - Minimum overfill at the shoulder P.I. for reinforced concrete pipe (RCP) and corrugated steel pipe (CSP) on centerline culverts is 1.25 feet to the top of rigid pavement and 1.75 feet to the top of flexible pavement.
  - For precast box culverts fill heights of less than 2.0 feet require a distribution slab.
  - Maximum overfill is controlled by the load tables.

- Survey information used in culvert design shall include topographic features, channel characteristics, fish migration needs, highwater information if available, existing structures, and other related site specific information.
- Debris and Ice
  The potential for plugging with debris or ice shall be considered. The source of the debris or ice and the potential flood damage resulting from plugged culverts are important. Options available to the designer include: attempt to pass the debris or ice through the culvert usually by increasing the culvert height or the placement of relief openings (preferred alternative); retain the debris or ice upstream of the culvert (may require frequent maintenance); non flared sloped end sections allow the ice and debris to ride up the sloped end; use a bridge.
- Where experience or physical evidence indicates the watercourse will transport a heavy volume of controllable debris, the following information should be considered prior to a decision whether to attempt to pass or retain the debris:
  - determine the type and quantity of debris;
  - experience of upstream or downstream culverts in passing or retaining the debris;
  - experience of the subject roadway passing debris at the sag point;
  - large floatable debris will usually ride up the culvert end sections;
  - available access for maintenance to remove debris from the culvert entrance or the debris barrier;
  - assessment of damage due to debris clogging, if protection is not provided;
  - feasibility of relief opening, either in the form of a vertical riser or a relief culvert placed higher in the embankment.
  - review the HEC-9, *Debris Control Structures* (FHWA, 1971).

5.2.3 Design Limitations

There are several criteria that place limitations on the design of a culvert: allowable headwater, channel tailwater relationship, confluence tailwater relationship, outlet velocity, minimum velocity, temporary upstream ponding and flood frequency.

- Allowable headwater is the depth of water that can be ponded at the upstream end of the culvert which will be limited by one or more of the following: be non-damaging to upstream property, be non-damaging to the roadway, meet stage increase criteria set forth by regulatory agencies, and should not cause disruption to traffic flow.
- Channel tailwater relationship requires the evaluation of the hydraulic conditions of the downstream channel to determine a tailwater depth for a range of discharges which include the design and review discharges.
  - Usually a single section analysis is adequate for culvert design. Backwater curves can be calculated to transfer the tailwater elevation from the cross section to the culvert site.
  - Utilize a step backwater method such as provided in computer applications to determine tailwater elevations at sensitive locations.
  - Use the critical depth and equivalent hydraulic grade line if the culvert outlet is operating with a free outfall. $(d_c + D)/2$ where d_c is the critical depth of flow in feet and D is the culvert diameter in feet.
  - Use the headwater elevation of any nearby, downstream culvert or other control structure if it is greater than the channel depth.
- Consider the confluence tailwater relationship.
  - Evaluate the high water elevation that has the same frequency as the design flood if events are known to occur concurrently and are statistically dependent.
  - If statistically independent, evaluate the joint probability of flood magnitudes and use a likely combination resulting in the greater tailwater depth.
- The maximum velocity at the culvert exit shall be consistent with the velocity in the natural channel or shall be mitigated with: channel stabilization (Channel Chapter), energy dissipation (Energy Dissipator Chapter). In general, outlet velocities less than 6 feet per second will not require energy dissipation or protection.
- The culvert should be designed to maintain a minimum self cleaning velocity. Use 2.5 feet per second for mean annual flood, (2 year frequency) when streambed material size is not known.
- If storage is being contemplated upstream of the culvert in order to reduce the peak outflow through the culvert, consideration shall be given to:
  - limiting ponding in urban areas to non-sensitive locations;
  - limiting ponding in rural areas to non-crop producing locations;
  - limiting the total area of flooding;
  - maintaining storage volume by removing sediment as required; and
  - ensuring that the storage area will remain available for the life of the culvert through the purchase of right-of-way or easement.

- Design recommendations for flood frequency, See Hydrology Chapter for Additional Information.
  - Use 50 year design frequency for minor culverts 48" or less in diameter. The overtopping flood need not be computed. A more conservative design frequency (I.E. 100 year flood event) may be required if there is significant flood damage potential upstream.
  - Minimum overtopping flood frequency for risk assessment is based on projected average daily traffic (ADT)

Projected ADT	Minimum Overtopping Flood Frequency
0 - 10	2 year
11 - 49	5 year
50 - 399	10 year
400 - 1499	25 year
1500 and up	50 year

  - Risk assessment shall be completed for all major culverts greater then 48". The 500-year flood or overtopping flood shall be computed, whichever is less.

Road Classification	Size	Design Frequency
All Centerline	> 48 inches	Need Risk Assessment
All Centerline	≤ 48 inches	50 year
Median Drain	15 inch minimum	50 year
Entrance	15 inch minimum	10 year

5.2.4 Design Features

Basic design features and considerations which must be considered include: culvert size and shape, number of barrels, material selection, end treatment for both inlet and outlet, improved inlets, safety and performance curves.

- The culvert size and shape selected shall be based on engineering and economic criteria related to site conditions. All culverts should be designed to provide adequate hydraulic capacity. However land use requirements and debris or ice potential may dictate a larger or different barrel geometry than required for hydraulic design alone. The following minimum sizes shall be used to avoid maintenance problems and clogging:

Type of Road	Minimum Size
Trunk Highway Centerline	24 inches
CSAH Centerline	18 inches
Local Roads Centerline	18 inches
Ramps, Loops, Rest Area	18 inches
Side Culverts	15 inches
Median Drains	15 inches
Entrances	15 inches

- Multiple barrel culverts shall fit within the natural dominant channel, or with minor widening of the channel. Widening the channel at a culvert to allow multiple barrels typically leads to conveyance loss through sediment deposition in some of the barrels. Multiple barrels are to be avoided where the approach flow is high velocity, particularly if supercritical flow is expected. These sites require either a single barrel or special inlet treatment to avoid adverse hydraulic jump effects.
- Where fish passage is required, special treatment is necessary to insure adequate low flows. Commonly when there are multiple barrels one barrel is lowered.
- Barrel material selection is based on the material type that best fulfills all of the engineering requirements for a specific installation. The following factors shall be considered: hydraulic performance, structural stability, serviceability, economics based on design life of structure, and replacement cost and difficulty of construction.
- Abrasion and corrosion are also considered when determining serviceability requirements. The culvert design sheet shall provide documentation for each centerline pipe installation indicating the engineering considerations that dictate the selection of the specific type of pipe.

- An apron end section is a concrete or metal structure attached to the end of a culvert for purposes of appearance, anchorage, and stabilization of the embankment near the waterway. The culvert inlet type and associated entrance coefficient, k_e values are given in Table 5.1.

Table 5.1 Inlet and Outlet End Treatments

Standard Plate	Entrance Coefficient, k_e
3022	0.7
3100	0.5
3110	0.5
3114	0.5
3122	0.5
3123	0.5
3125	0.2
3126	0.7
3127	0.7
3128	0.7
3129	0.5
3148	0.7
Bridge Details Manual	0.5

- When the potential for vehicle impact exists at the culvert ends consider vehicle safety during end treatment design, since some end treatments can be hazardous to errant vehicles.
  - Culvert ends located outside the clear zone do not need safety aprons or grates.
  - Culvert ends located within the clear zone should be treated in accordance with Mn/DOT Road Design Manual Guidelines.
  - If a safety apron is installed on the downstream end of a culvert, a safety apron, grate or trash rack should also be installed at the upstream end of the culvert.
- Improved inlets are an option for long culverts which will operate under inlet control. While improved inlets can increase the hydraulic performance of the culvert, they may also add to the total culvert cost. Therefore, these inlets should only be used when necessary. Three types of improved inlets are available: apron inlet with reducer, side tapered inlet, and slope tapered inlet.
- Performance curves are developed for culverts > 48" to evaluate the hydraulic capacity and outlet velocity of a culvert for various headwater depths. These curves display the consequence of high flow rates at the site and provide a basis for evaluating flood hazard.

5.2.5 Related Designs

There are additional criteria for designs related to culverts.

Buoyancy Protection

Inlet protection is usually necessary to anchor the inlet end of the culvert and provide buoyancy protection for all flexible culverts. Buoyancy is affected by 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. The standard apron end section is considered adequate protection for corrugated metal culverts 12" through 84". Standard Plates 3128 and 3148 include anchorage that provide some buoyancy protection. Concrete headwalls such as shown in Standard Plates 3125, 3126, and 3127 shall be specified as inlet protection for structural plate culverts 60" or greater in diameter.

Multiple Use Culverts

Consideration may be given to combining drainage culverts with other land use requirements necessitating passage under a highway such as animal passes, boat traffic or pedestrian underpasses:

- during the selected design flood the land use is temporarily forfeited, but available during lesser floods,
- two or more barrels are required with one situated so as to be dry during floods less than the selected design flood,
- shall be sized so as to insure it can serve its intended land use function up to and including a 2-year flood, and
- the height and width constraints shall satisfy the hydraulic or land use requirements, whichever is the larger.

Outlet Protection

Protection against scour at culvert outlets ranges from riprap placement to complex and expensive energy dissipation devices. The most common energy dissipation devices used by Mn/DOT is the riprap apron. Other outlet protection alternatives are listed below, for more details see HEC-14 (FHWA, 1983).

- A ring dissipator is used where right of way area is limited, debris is not a problem, Fr is >1, a riprap apron is not adequate, and moderate velocity reduction is needed.
- A drop box inlet was initially a grade control structure developed by SCS. It can be used at the culvert inlet to flatten the grade of culvert and thereby reduce the velocity.
- A riprap basin is used where adequate right-of-way is available, the Froude Number (Fr) is less than 3.0, only a moderate amount of debris is present, adequate riprap is available, and other methods are not appropriate or are more expensive.
- An impact basin is used when little debris potential exists, design discharge is less than 150 cfs, no tailwater is required for successful operation, and is economically feasible.
- A stilling basin (SAF Basin) utilizes a hydraulic jump to dissipate energy. This option is an economical mean of dissipating large amounts of energy, but a tailwater is required and the Froude number must be between 1.7 and 17.
- For outlet velocities less then or equal to 6 fps, check shear stress to determine if vegetation will be adequate. If vegetation is used consider temporary erosion control during and immediately following construction until vegetation becomes established.
- Riprap Apron for minor culverts (equivalent diameter ≤ 48"), the riprap apron detailed in Std. Plates 3133 and 3134 will generally be adequate. Geotextile fabric may be substituted for granular filter. Use the following guidelines:

Outlet Velocity, V_o	Riprap Specifications	Filter Specifications
$0 < V_o \leq 6$ fps	Riprap or stable vegetation	
$6 < V_o \leq 8$ fps	12" Class II riprap	6" granular or geotextile filter
$8 < V_o \leq 10$ fps	18" Class III riprap	9" granular or geotextile filter
$10 < V_o \leq 12$ fps	24" Class IV riprap	12" granular or geotextile filter
$V_o > 12$ fps	Consider other energy dissipator	

Improved Inlets

Culverts operating under inlet control generally flow part full. In many cases it is possible to use a smaller pipe having about the same cross sectional area as the area of flow by using special inlets such as the side tapered or slope tapered inlets. These types of inlets work well for box culverts and round culverts but do require special design and fabrication. Another method which utilizes suppliers' standard materials is also available and has been used successfully by Mn/DOT for many years. This method sizes the inlet by conventional means utilizing the inlet control nomographs. Then the size and location of the reducer is calculated in order to minimize the size of the culvert for the balance of the length. Two significant factors then need to be considered: the amount of reduction, and the location of the reducer.

The allowable amount of diameter reduction is determined by comparing critical depth of the smaller pipe with its diameter. Too much constriction of the flow area can cause a choking effect, creating orifice flow at the reducer throat, by sealing off the throat entrance to the smaller pipe with standing waves and other losses in the reducer.

The longitudinal location of the reducer is based on the assumption that the velocity of flow entering the reducer should be equal or greater than the critical velocity in the smaller pipe. Starting with the critical depth, the standard incremental energy equation is used in determining the length of the larger pipe and its associated velocity. The velocity used to determine the total length of the pipe, should be 10% greater than the critical velocity of the smaller pipe to help overcome any other losses that are developed by the flow contraction. Since the depth of flow crosses critical depth in the larger pipe at an approximate distance of 0.5 times the diameter from the inlet of the larger pipe, this length should be added to the total length of the pipe.

5.2.6 Design Methods

The designer has several computational methods to choose from when designing a culvert. These methods include: nomographs, hand calculations or computer applications. Computer applications are most commonly used and have the advantage of being able to rapidly perform iterations and compare different designs. Computer applications solve equations and give answers, but it does not mean the answers are correct. The designer still needs to understand culvert design and be able to assess the reasonableness of the solution. Occasional hand or nomograph computations are a good way to perform a quick check of computer results.

Culverts are designed by assuming either a constant discharge (peak flow) or routing a hydrograph. Constant discharge is utilized for most culvert designs. The analysis is performed using the peak discharge, however a range of discharges and a performance curve is recommended for the major culverts (diameter > 48"). Using a constant discharge will yield a conservatively sized structure where temporary storage is available, but is not considered in the design. Acceptable methods are detailed in the Hydrology Chapter and include: Regression Equations developed by USGS for ungaged streams, Log Pearson III analysis for gaged streams, SCS Method, and Rational Method for drainage areas less than 200 acres.

Flood routing through a culvert is a practice that evaluates the effect of temporary upstream ponding caused by the culvert's back-water. Flood routing requires synthesis of a hydrograph and should be used when significant storage upstream will reduce the required culvert size, or storage capacity behind a highway embankment attenuates a flood hydrograph and reduces the peak discharge. When a culvert is initially down sized to take advantage of potential storage the designer is placing an obstruction in the drainage way. This should only be considered in locations that will not damage crops or other property. Control of the upstream right of way by purchase or easement may be necessary. Flood routing equations and procedures are detailed in the Storage Facilities chapter.

5.3 CULVERT ANALYSIS

An exact analysis of culvert flow is complex because the following are required:

- analyzing nonuniform flow with regions of both gradually varying and rapidly varying flow,
- determining how the flow type changes as the flow rate and tailwater elevations changes,
- applying backwater and drawdown calculations, energy and momentum balance,
- applying the results of hydraulic model studies, and
- determining if hydraulic jumps occur, and if they are inside or downstream of the culvert barrel.

The procedures in this chapter utilize the concepts of minimum performance and control sections. The concept of minimum performance means that although the culvert may operate more efficiently at times, (more flow for a given headwater level), it will never operate at a lower level of performance than calculated. Minimum performance is assumed by analyzing both inlet and outlet control and using the highest headwater.

The control section is the location where there is a unique relationship between the flow rate and the upstream depth of water. Inlet control is governed by the inlet geometry which includes the barrel shape, cross-sectional area, and inlet edge. Outlet control is governed by a combination of the culvert inlet geometry, the barrel characteristics, and the tailwater.

5.3.1 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, either inside or outside of the pipe.

Headwater depth is measured from the inlet invert 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 apron inlet, beveled edge, mitered to conform to slope, socket end, square edge in a headwall, and thin edge projecting. 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 the geometry varies, such as in an improved inlet.

Three regions of flow are shown in the Figure 5.1, unsubmerged, transition and submerged.

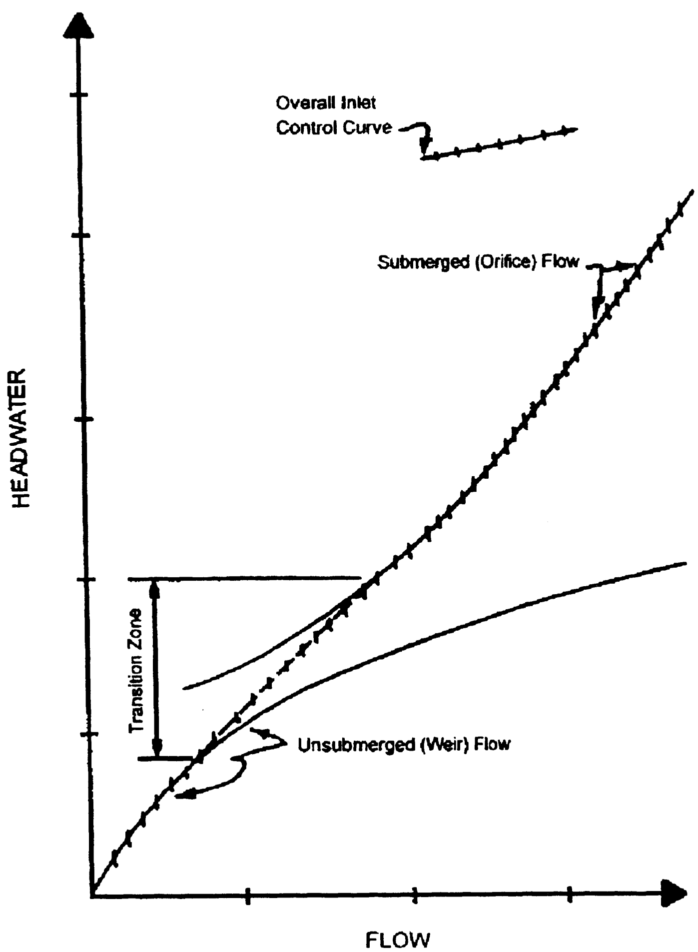

Figure 5.1 Unsubmerged, Transition and Submerged Flow
Source: HDS-5, Figure III-4 (FHWA, 1985)

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 HDS-5 (FHWA, 1985) contains the equations which were developed from model test data. Figure 5.2 shows an unsubmerged inlet in inlet control.

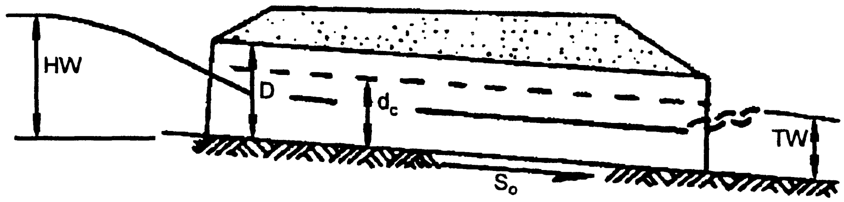

Figure 5.2 Unsubmerged Inlet in Inlet Control

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 (FHWA, 1985) contains flow equations which were developed from model test data. Figure 5.3 shows a submerged inlet under inlet control.

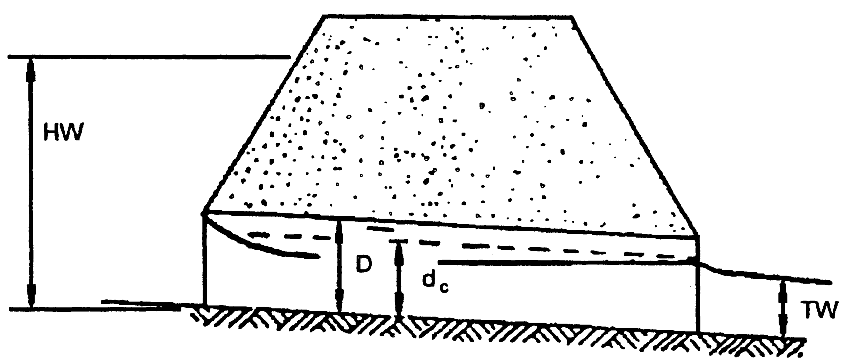

Figure 5.3 Submerged Inlet in Inlet Control

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. (Figure 5.1)

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 (HW) is measured to the total upstream energy grade line including the approach velocity head. Culvert Design nomographs are provided in Appendix C.

5.3.2 Outlet Control

Outlet control has depths and velocity which are subcritical. The control of the flow is at the downstream end of the culvert (the outlet). Tailwater (TW) is based on the downstream water surface elevation and is assumed to be critical depth near the culvert outlet or the downstream channel depth, whichever is higher. Backwater calculations from a downstream control, a normal depth approximation, or field observations are used to define the tailwater elevation. In a given culvert, the type of flow is dependent on all of the barrel factors: barrel roughness, barrel area, barrel length and barrel slope. The inlet control factors also influence culverts in outlet control.

In the analysis of outlet control hydraulics, full flow condition is assumed when TW depth is above the crown of the culvert. The outlet control nomographs are accurate for the analysis of full flow condition. Partial full condition is used when TW is below the crown of the culvert. A backwater calculation is necessary to accurately analyze partial flow conditions, however an approximate method utilizing $TW = (d_c+D)/2$ yields reasonable results, especially with pipes less than 48" diameter. Outlet control flow conditions can be calculated based on an energy balance from the tailwater pool to the headwater pool.

Velocity

Velocity is computed by rearranging the continuity equation. Keep in mind that unless a round or arch pipe is full, the formula for determining area used in this equation is complex. The alternative is to use the design charts provided in Appendix C.

$$V = \frac{Q}{A} \tag{5.1}$$

Where: V = velocity (fps)
Q = flow rate (cfs)
A = cross sectional area of the flow area in the barrel (ft^2)

Head Losses

$$H_L = H_e + H_f + H_o + H_b + H_j + H_g \tag{5.2a}$$

Where:
- g = acceleration due to gravity (32.2 ft/s^2)
- H_b = bend losses (ft)
- H_e = entrance loss (ft)
- H_f = friction losses (ft)
- H_g = losses at grates (ft)
- H_j = junction losses (ft)
- H_L = total energy head loss (ft)
- H_o = exit loss (ft)
- H_v = full flow velocity head (ft)
- k_e = entrance loss coefficient (Table 5.2)
- L = length of the culvert barrel (ft)
- n = Manning's roughness coefficient (Table 5.3)
- P = wetted perimeter of the barrel (ft)
- R = hydraulic radius of the full culvert barrel (ft)
  R = area/wetted parameter
- V = average barrel velocity (ft/s)
- V_d = channel velocity downstream of the culvert (ft/s)

Entrance Loss

$$H_e = k_e\left(\frac{V^2}{2g}\right) \tag{5.2b}$$

Friction Loss

$$H_f = \left(\frac{29n^2L}{R^{1.33}}\right)\left(\frac{V^2}{2g}\right) \tag{5.2c}$$

Velocity Head

$$H_v = \frac{V^2}{2g} \tag{5.2d}$$

Exit Loss

$$H_o = 1.0\left[\left(\frac{V^2}{2g}\right) - \left(\frac{V_d^2}{2g}\right)\right] \tag{5.2e}$$

V_d is usually neglected, then:

$$H_o = H_v = \frac{V^2}{2g} \tag{5.2f}$$

Barrel Losses

$$H = H_e + H_o + H_f$$

Substituting in equations:

$$H = \left[1 + k_e + \left(\frac{29n^2L}{R^{1.33}}\right)\right]\left[\frac{V^2}{2g}\right] \tag{5.3}$$

Table 5.2 Entrance Loss Coefficients, k_e for Outlet Control, Full or Partly Full

Type of Structure	Design of Entrance	Coefficient k_e
Pipe, Concrete	Mitered to conform to fill slope	0.7
	End-section[1] conforming to fill slope	0.5
	Projecting from fill, square cut end	0.5
	Headwall or headwall and wingwall Square-edge Rounded (radius=1/12D) Socket end of pipe (grooved-end)	 0.5 0.2 0.2
	Projecting from fill, socket end (grooved-end)	0.2
	Beveled edges, 33.7° or 45° bevels	0.2
	Side or slope tapered inlet	0.2
Pipe or Pipe-arch, Corrugated Metal	Projecting from fill (no headwall)	0.9
	Mitered to conform to fill slope, paved or unpaved slope	0.7
	Headwall or headwall and wingwalls square-edge	0.5
	End-section[1] conforming to fill slope	0.5
	Beveled edges, 33.7°or 45° bevels	0.2
	Side or slope tapered inlet	0.2
Box, Reinforced Concrete	Wingwalls parallel (extension of sides), square-edged at crown	0.7
	Wingwalls at 10°to 25° to barrel, square edged at crown	0.5
	Headwall parallel to embankment (no wingwalls) Squared edged on 3 edges Rounded on 3 edges to radius of 1/12 barrel dimension Beveled edges on 3 sides	 0.5 0.2 0.2
	Wingwalls at 30° to 75° to barrel Crown edge rounded to radius of 1/12 barrel dimension Beveled top edge Squar edge crown	 0.2 0.2 0.4
	Side or slope tapered inlet	0.2

[1] "End section conforming to fill slope" refers to the sections commonly available from manufacturers and may be made of either metal or concrete. From limited hydraulic tests they are equivalent in operation to a headwall under either inlet or outlet control. Some end sections, incorporating a closed taper in their design have a superior hydraulic performance. These latter sections can be designed using the information given for the beveled inlet.
Source: HDS-5 (FHWA, 1985)

Table 5.3 Mannings "n" Values for Culverts

Type of Culvert	Roughness or Corrugation	Manning's n
Concrete Pipe	Smooth	0.010 - 0.011
Concrete Box	Smooth	0.012 - 0.015
Spiral Rib Metal Pipe	Smooth	0.012 - 0.013
Corrugated Metal Pipes, Pipe-Arch and Box (Annular or Helical Corrugations, Manning's n varies with barrel size)	2⅔ by ½ inch Annular	0.022 - 0.027
	2⅔ by ½ inch Helical	0.011 - 0.023
	6 by 1 inch	0.022 - 0.025
	5 by 1 inch	0.025 - 0.026
	3 by 1 inch	0.027 - 0.028
	6 by 2 inch Structural Plate	0.033 - 0.035
	9 by 2 ½ inch Structural Plate	0.033 - 0.037
Corrugated Polyethylene	Smooth	0.009 - 0.015
Corrugated Polyethylene	Corrugated	0.018 - 0.025
Polyvinyl Chloride (PVC)	Smooth	0.009 - 0.011

The Manning's n values indicated in this table were obtained in the laboratory. Actual field values for culverts may vary depending on the effect of abrasion, corrosion, deflection and joint conditions.
Source: excerpt from Table 4 HDS-5 (FHWA, 1985, reprinted1998)

Stage Increase

The stage increase is the increase in water surface due to the constriction of the culvert. It is computed as the difference between the water surface elevation prior to installation and the head water just upstream of the culvert. Headwater must be measured sufficiently distant from the pipe to exclude local drawdown effects.

$$S.I. = HW - \left(TW + LS_o\right) \tag{5.4}$$

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 5.4, the following relationship results:

$$HW_o + \frac{V_u^2}{2g} = TW + \frac{V_d^2}{2g} + H_L \tag{5.5}$$

Where: HW_o = headwater depth above the outlet invert (ft)
V_u = approach velocity (ft/s)
TW = tailwater depth above the outlet invert (ft)
V_d = downstream velocity (ft/s)
H_L = sum of all losses (Equation 5.2a)
L = Length of culvert barrel (ft)
S_o = slope of culvert invert (ft/ft)

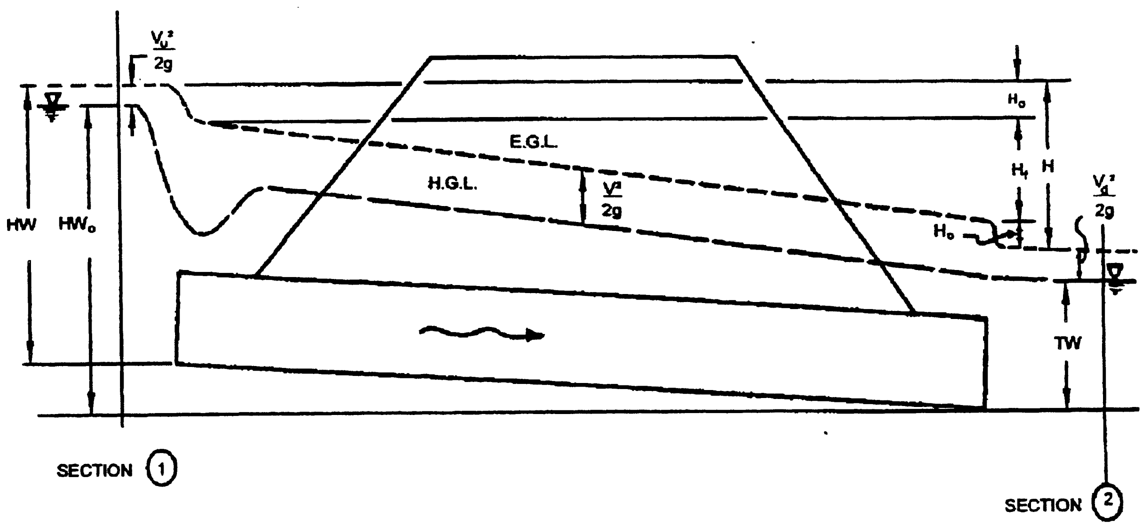

Figure 5.4 Full Flow Energy and Hydraulic Gradelines

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.

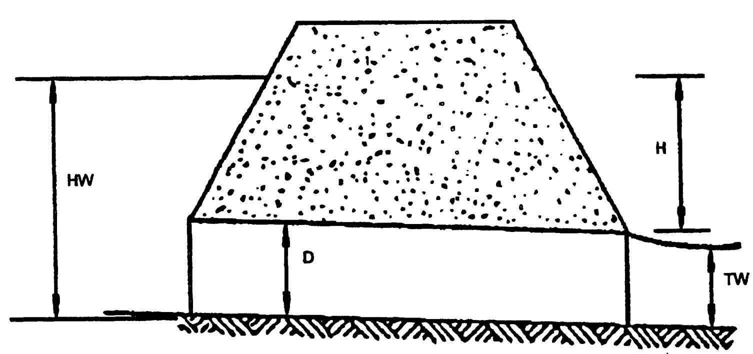

Figure 5.5 Flowing Full in Outlet Control, Where d_c > D

Nomographs (Full Flow)

The nomographs were developed assuming that the culvert barrel is flowing full. Two flow conditions occur in outlet control when the barrel is flowing full: TW > D, Flow Type IV (see Figure 5.4) or $d_c > D$, Flow Type VI (see Figure 5.5)
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 5.5 becomes:

$$HW = TW + H - S_o L \tag{5.6}$$

Where: HW = depth from the inlet invert to the energy grade line (ft)
H = is the value read from the nomographs (ft) or Equation 5.3
S_oL = drop from inlet to outlet invert (ft)

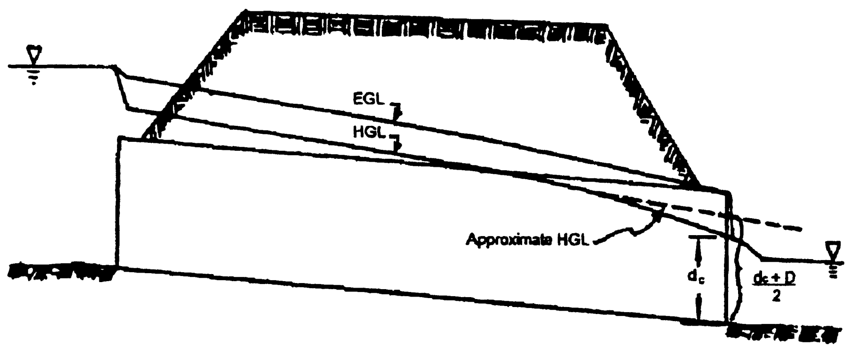

Figure 5.6 Effectively Full Flow in Outlet Control, Where TW < d_c

Nomographs (Partly Full Flow)

Equations 5.1 through 5.5 were developed for full barrel flow. The equations also apply to the flow situations which are effectively full flow conditions, when TW < d_c, (see Figure 5.6).

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

Based on model studies and 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 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 for culverts that are partially full when determining the Headwater (HW) for outlet control:

$$HW = h_o + H - S_o L \tag{5.7}$$

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

Adequate results are obtained down to a HW = 0.75D. For lower headwaters and major culverts, backwater calculations are recommended. Figures 5.7 and 5.8 show partially full flow conditions under outlet control with TW < d_c and TW > d_c respectively.

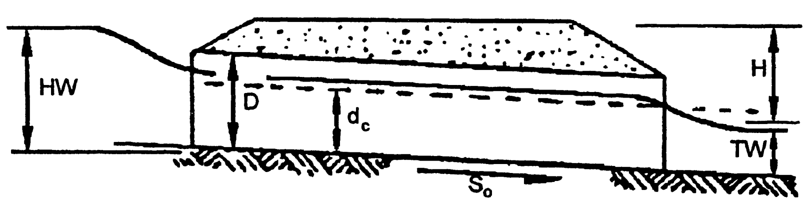

Figure 5.7 Partly Full Flow in Outlet Control, Where TW < d_c

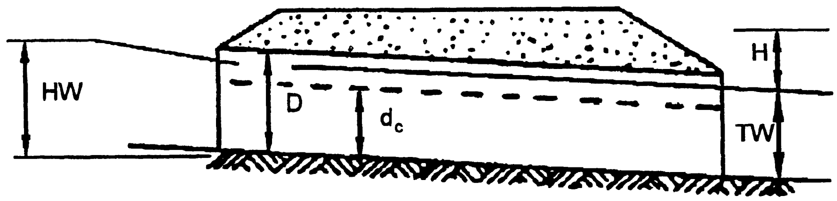

Figure 5.8 Partly Full Flow in Outlet Control ,Where TW > d_c

5.3.3 Outlet Velocity

Culvert outlet velocities shall be calculated to determine the need for erosion protection at the culvert exit. Since the culvert outlet velocity is usually higher than the natural stream velocity, energy dissipation may be necessary to prevent downstream erosion. If outlet erosion protection is necessary, the flow depths and Froude number may also be needed. Outlet velocities for inlet and outlet control are computed as follows:

Inlet Control

- If water surface profile calculations are necessary, begin at d_c at the entrance and proceed downstream to the exit. Determine at the exit the depth and flow area. The velocity is calculated from Equation 5.1. While water surface profiles can be computed by hand, typically when water surface profile calculations are necessary a computer application will be selected to preform the iterative computations.
- Use 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. The normal depth velocity may be higher than the actual velocity at the outlet determined from running a water surface profile. Normal depths and velocities may be obtained from the open channel flow charts for circular pipe provided in Appendix C.

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.

5.3.4 Roadway Overtopping

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. The flow will be similar to flow over a broad crested weir. Flow coefficients for flow overtopping roadway embankments are found Figure 5.9.

$$Q_r = C_d L\left(HW_r\right)^{1.5} \qquad \textbf{(5.8)}$$

Where: Q_r = overtopping flow rate (cfs)

C_d = overtopping discharge coefficient = $k_t\, C_r$

k_t = submergence coefficient

C_r = discharge coefficient

L = length of the roadway crest (ft)

HW_r = the upstream depth, measured above the roadway crest (ft)

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 of the upstream pool above the roadway. The length is difficult to determine when the crest is defined by a roadway sag vertical curve. The length should be subdivided 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.

Total flow is calculated for a given upstream water surface elevation by adding the roadway overflow plus culvert flow. Performance curves for the culvert and the road overflow may be summed to yield an overall performance curve. A trial and error process is necessary to determine the flow passing through the culvert and the amount flowing across the roadway. Assume HW_r and solve for Q_r, then solve for Q through the culvert by computing HW-TW and solving for V and then Q. Summation of the Q's must balance with the total Q.

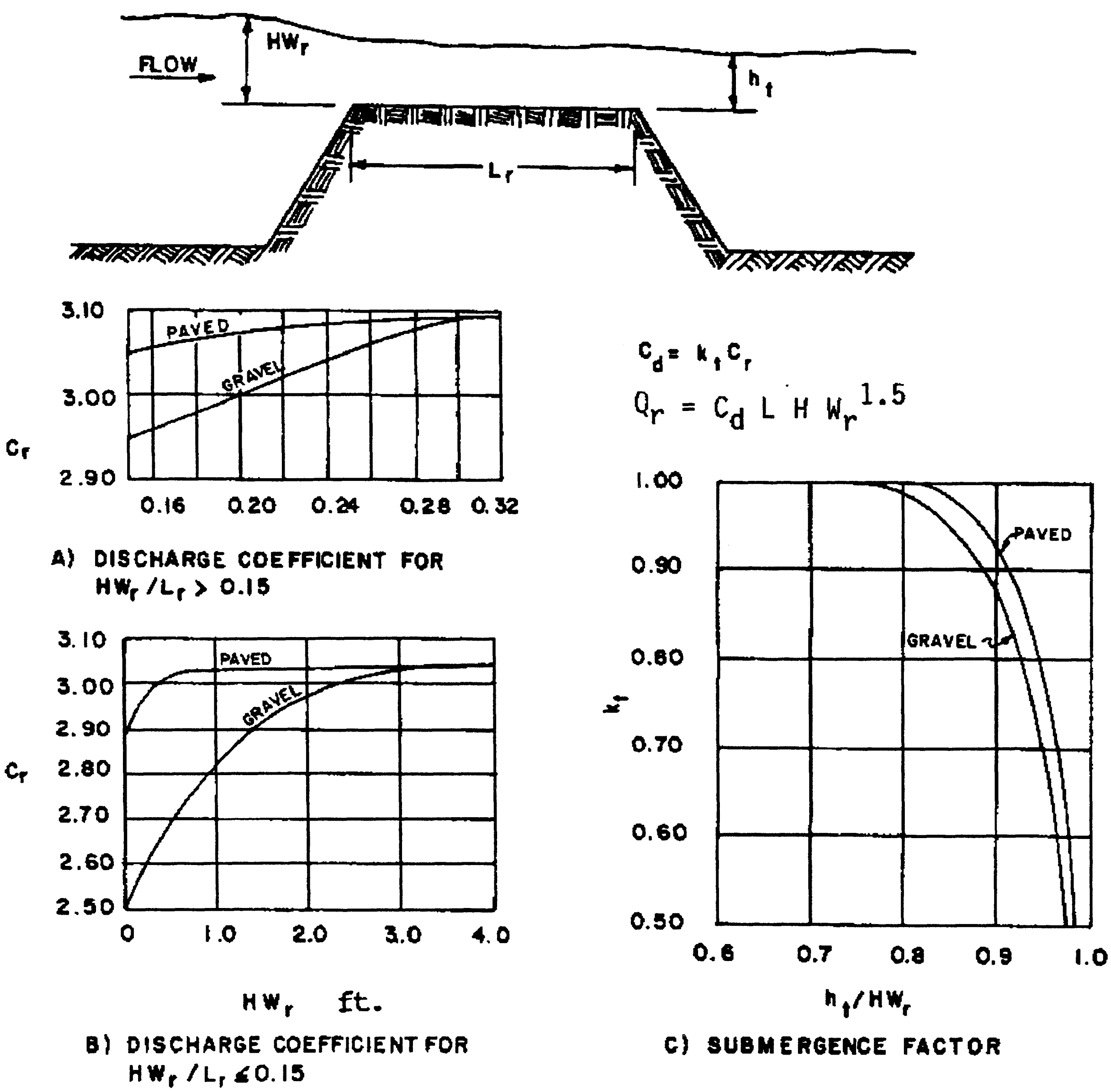

Figure 5.9 Discharge Coefficients for Roadway Overtopping
Source: HDS-5, Figure III-11 (FHWA, 1985)

5.3.5 Performance Curves

A performance curve is a plot of flow rate versus headwater depth or elevation. The culvert performance curve is made up of the controlling portions of the inlet, outlet and roadway overtopping performance curves (See Figure 5.10). The overall performance curve is the sum of the flow through the culvert and the flow across the roadway and can be determined by performing the following steps.

Step 1 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 should be calculated.

Step 2 Combine the inlet and outlet control performance curves to define a single performance curve for the culvert

Step 3 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 5.8 to calculate flow rates across the roadway.

Step 4 Add the culvert flow and the roadway overtopping flow at the corresponding headwater elevations to obtain the overall culvert performance curve similar to the one shown in Figure 5.10.

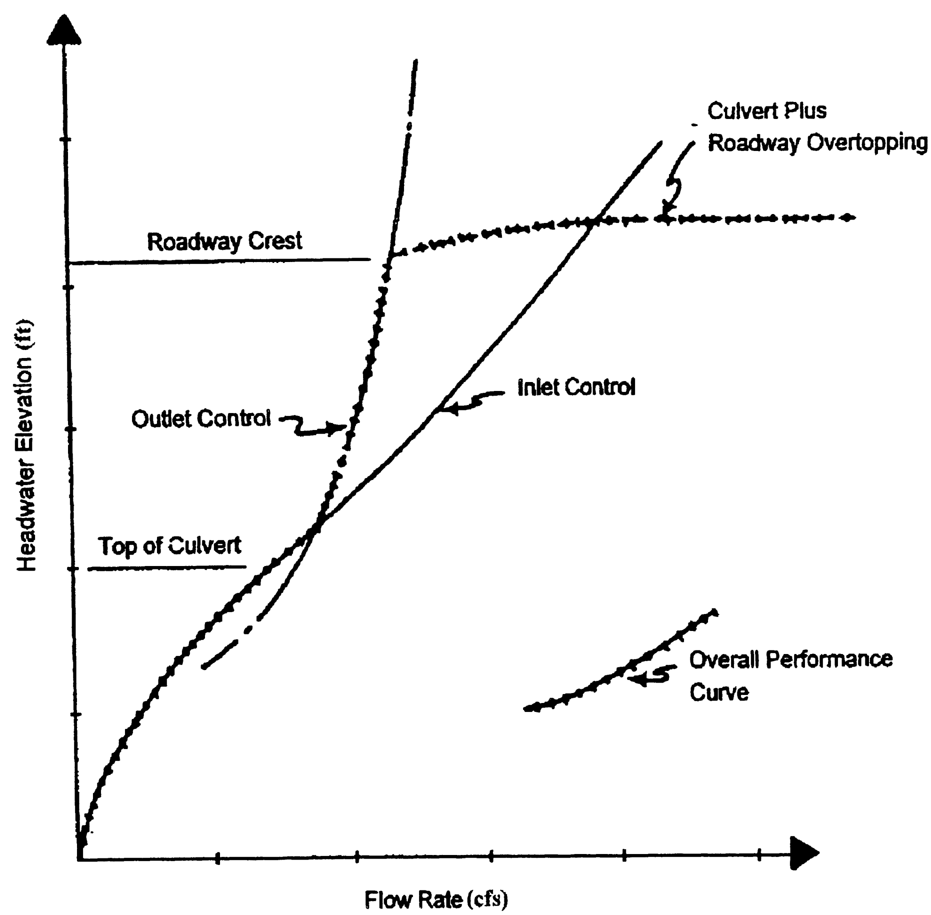

Figure 5.10 Overall Performance Curve
Source: HDS-5, Figure III-16 (FHWA, 1985)

5.4 DESIGN PROCEDURE

The following design procedure provides a convenient and organized method for designing culverts for a constant discharge, considering inlet and outlet control. The procedure does not address the affect of storage which is discussed in the Storage Chapter.

- The designer should be familiar with all the equations in Section 5.5 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 Figure 5.10 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 HW, culvert barrel selected, and comments.
- The culvert design procedure adopted by Mn/DOT is less rigorous for culverts 48" diameter and less, than for greater than 48".

Step 1 **Determine Scope of Culvert Design**

Minor Culvert Designs (48" and less)

- Design Frequency 50 year
- Hydraulic Data on plans not necessary
- DNR Permits generally not necessary
- Overtopping calculations generally not necessary
- Tailwater (TW) elevation can be estimated from known condition or $(d_c+D)/2$
- Nomographs usually adequate for design
- Specify culvert material
- Determine pipe class or gage and bedding
- Estimate outlet velocity using pipe flow charts
- Design outlet protection
- Documentation is Culvert Design Sheet

Major Culvert Designs (> 48")

- Risk Assessment necessary
- Hydraulic Data on plans
- Permit usually required using Basic Flood (100 year frequency)
- Overtopping or Q_{500} necessary
- Compute tailwater (TW) (See Channel Chapter)
- Water surface profile necessary for outlet control with partial full flow
- Nomograph solution is OK for full flow conditions
- Computer method preferred for design
- Performance curve required
- Investigate opportunity for improved inlet if inlet control
- Compute outlet velocity
- Design outlet protection where necessary
- Specify culvert material
- Documentation includes risk assessment, computer run, performance curve and material selection

Step 2 **Assemble Site Data and Project File**

Table 5.4 Data Needs

TYPE OF DATA	MAJOR CULVERTS	MINOR CULVERTS
MAPS	USGS Quadrangle Maps Site and Location Maps Drainage Area Maps	Drainage Area Maps
PHOTOGRAPHS	Aerial and land photographs	Aerial and land photographs
PLANS	Existing and Proposed Roadway Plans and Profiles Embankment Cross Sections Inplace Structures	Existing and Proposed Roadway Plans and Profiles Embankment Cross Sections Inplace Structures
SURVEYS	Stream profile and cross sections Elevations of inplace structure Elevations of flood prone property Maximum observed highwater elevations Ordinary highwater if feasible	Stream profile Channel cross-section if confined channel Flood damage potential
REVIEW FILES	Design data for nearby structures Previous recommendations Highwater or flood data Maintenance problems	Previous recommendations Flooding or Maintenance Problems
STUDIES BY OTHERS	Flood Insurance Studies (DNR) Watershed Districts Overall Plan Water Planning Organizations Water Quality Studies (MPCA) Flood retention (SCS,COE,Counties) Future development (Cities & Counties) Public Ditch Authorities Land use	Any applicable studies Land use plans Future development plans
ENVIRONMENTAL CONSTRAINTS	Boat Passage (DNR) Fish Migration (DNR) Wild Life Passage (DNR) Domestic Animal Passage Wetland Mitigation Protected Waters (DNR) Right of Way Limitations Commitments in review Documents Elevation of Flood Prone Property	Fish migration (DNR) Protected waters (DNR) Wetland mitigation Elevation of flood prone property Other as available

Step 3 **Determine Hydrology**

A. See Hydrology Chapter.
B. Use procedure for major or minor culvert.

Step 4 **Select Design Discharge Q_d**

A. See Section 5.2.3 Design Limitations.
B. Determine flood frequency from criteria.
C. Determine Q from appropriate procedure.
D. Prorate Q to each barrel if more than one.

Step 5 **Compute Tailwater Elevation**

A. See Channel Chapter
B. Minimum data are cross section, "n" values, and slope of channel to compute the rating curve for channel.

Step 6 **Summarize Data On Design Form**

A. See Culvert Design Form (Figure 5.11).
B. Use data from steps 1-5.

Step 7 **Select Design Alternative**

See Section 5.2.4 Design Features.
Choose trial culvert material, shape, size, and entrance type.

Step 8 **Determine Inlet Control Headwater Depth (HW_i)**

Use the inlet control nomograph (Appendix C).

A. Use the appropriate nomographs for the material types and shapes being considered. The nomographs are self explanatory.
B. Calculate headwater depth (HW_i).
   - Multiply HW/D by D to obtain HW to energy gradeline.
   - For minor culverts neglect the approach velocity $HW_i = HW$.
   - For major culverts in confined channels include the approach velocity $HW_i = HW$ - approach velocity head.

Step 9 **Determine Outlet Control Headwater Depth At Inlet (HW_{oi})**

A. Compare tailwater depth calculated in Step 5 with the rise of the culvert. If tailwater (TW) ≥ to rise, nomographs will provide accurate results. Skip to step "E". If TW < D, a computer analysis is recommended for an exact solution for major culverts; nomographs will give approximate solution for minor culverts.
B. Calculate critical depth (d_c) using appropriate chart in Appendix C. Note that d_c cannot exceed D.
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). k_e = entrance loss coefficient, Table 5.2.
F. Determine losses through the culvert barrel (H).
   Use nomograph (Appendix C) or Equation 5.3b if outside range.
   Locate culvert length (L) or (L_1):
   The nomographs can be used for different values of "n" by modifying the culvert length as follows:

$$L_1 = L\left(\frac{n_1}{n}\right)^2 \tag{5.9}$$

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

G. Calculate outlet control headwater depth (HW_{oi}).
   - Use Equation 5.10, if the approach velocity (V_u) and the downstream velocity (V_d) are neglected:

$$HW_{oi} = H + h_o - S_o L \tag{5.10}$$

   - use Equation 5.2a, 5.2e and 5.5 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 profile calculations should be used to check the result,
     - if the headwater depth falls below 0.75D, the nomograph method shall not be used for major culverts.

Step 10 **Determine Controlling Headwater (H_{wc})**

- Compare HW_i and HW_{oi}, use the higher.
- Compare HW_c with allowable HW and adjust culvert size if necessary.

Step 11 **Compute Discharge Over The Roadway (Q_r) (Major Culverts when Appropriate)**

A. Assume the upstream depth over the roadway (HW_r), calculate length of roadway crest (L), and calculate the overtopping flowrate (Q_r). See Section 5.3.4 and Equation 5.8.

B. Calculate the flow in the culvert by using the equations in Section 5.3.2 and solving for V and then Q.

Step 12 **Compute Total Discharge (Q_t)**

Sum the flow over the road (Q_r) and the flow in the culvert (Q_c). This sum should equal the total flow (Q_t). If not, assume a new HW_r and make another iteration.

Step 13 **Calculate Outlet Velocity (V_o) And Depth (d_n) See Section 5.3.4**

If inlet control is the controlling headwater:

A. Calculate flow depth at culvert exit.
   - use normal depth (d_n)
   - 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 $d_c > TW$ for minor culverts
   - use ($d_c + TW/2$) if $d_c > TW$ for major culverts
   - use (TW) if $d_c < TW < D$
   - use (D) if $D < TW$

   where: TW = tailwater
   d_c = critical depth
   D = Pipe diameter (height)

B. Calculate flow area (A).

C. Calculate exit velocity (V_o) = Q/A.

Step 14 **Review Results**

Compare alternative design with constraints and assumptions. If any of the following are exceeded, repeat Steps 4 through 13:

- the barrel must have adequate cover, (See Site Criteria Section 5.2.2)
- the length shall be reasonably accurate,
- the proper end treatment is used, (See Design Features Section 5.2.4)
- the allowable headwater shall not be exceeded, and
- the allowable overtopping flood frequency shall not be exceeded.

Step 15 **Plot Performance Curve (Major Culverts Only)**

A. Repeat steps 4 through 13 with a range of discharges which include Q_{design}, Q_{100}, & Q_{OT} or Q_{500}.

B. Use the following upper limit for discharge:
   - Q_{100} if $Q_{OT} \leq Q_{100}$
   - Q_{500} if $Q_{OT} > Q_{500}$

Step 16 **Related Designs**

Consider the following options (See Section 5.2.5).

- Tapered inlet or larger inlet with reducer if culvert is in inlet control, very long or has limited available headwater.
- Flow routing if a large upstream headwater pool exists (Storage Facilities Chapter).
- Energy dissipators if V_o exceeds design criteria. (See Energy Dissipator Chapter).
- Sediment control storage for sites with sediment concerns such as alluvial fans .
- Fishery passage (Consult with DNR).

Step 17 **Documentation**

- Culvert Design Form (Minor Culverts)
- Design Computations and letter of recommendation. (Major Culverts)
- Risk Assessment (Major Culverts)

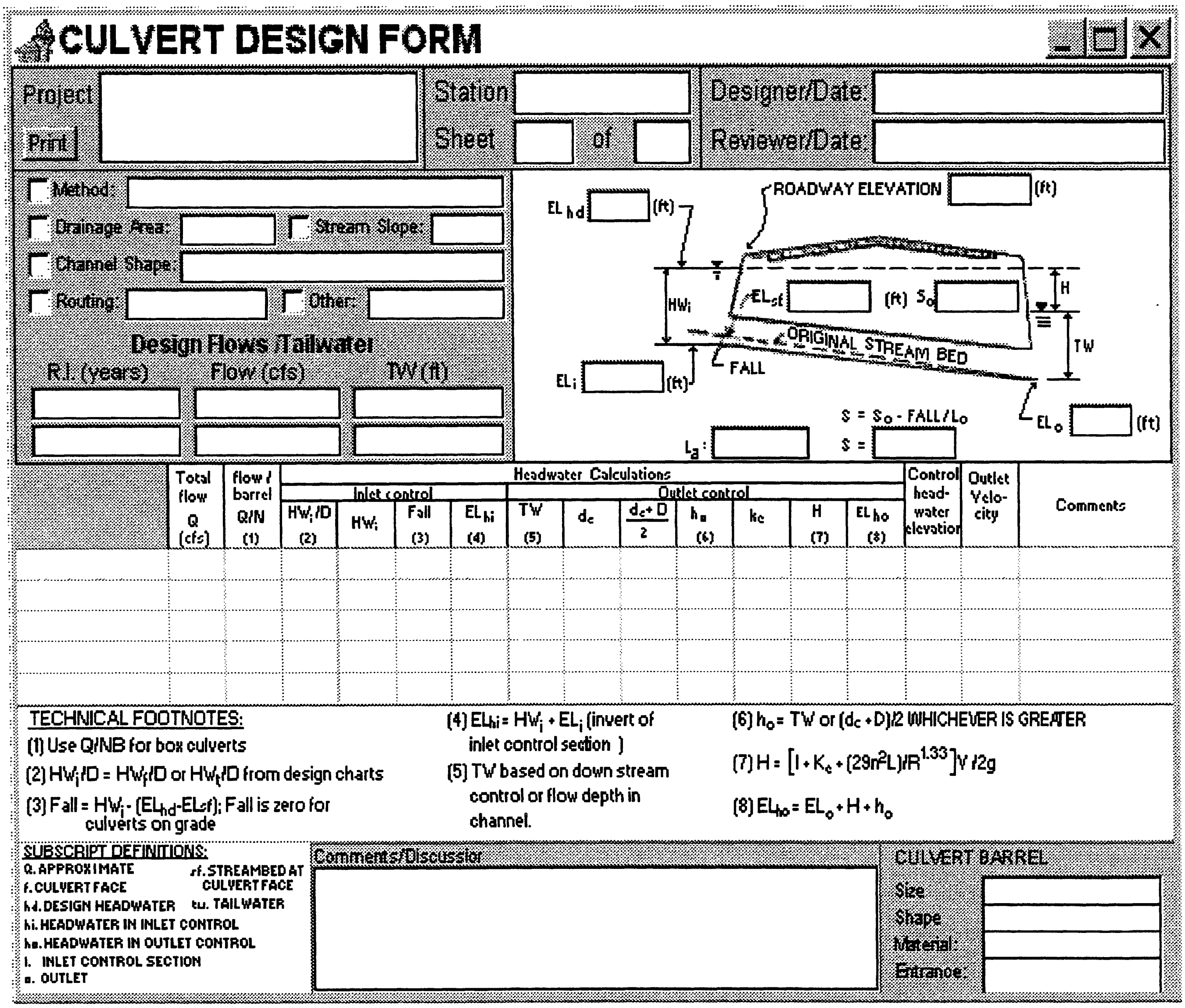

Figure 5.11 Culvert Design Form
Source: Pallas, Inc., 1996

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