CULVERT HYDRAULICS

Introduction

A culvert is defined a conduit that conveys water through a roadway embankment or some other type of structure, such as the dam at a stormwater detention pond. When engineers analyze culvert systems, they are usually trying to do one or more of the following:

1. Determine the size, shape, and number of new or additional culverts required to pass a design discharge.
2. Predict the hydraulic capacity of an existing culvert system under some allowable headwater elevation.
3. Predict the upstream flood level at an existing culvert system resulting from some check discharge or other discharge magnitude of special interest.
4. Develop hydraulic performance curves for a culvert system to assess hydraulic risk at a crossing or as input to another hydraulic or hydrologic model.

Because flow conditions vary from culvert to culvert and over time at any given culvert, a complete theoretical analysis of a particular culvert is both time-consuming and difficult. Research by the National Bureau of Standards funded by the FHWA resulted in a series of reports that provided a comprehensive analysis of culvert hydraulics under various flow conditions. The experimental data were used to develop nomographs which became the basis for design procedures outlined in the document *Hydraulic Design of Highway Culverts*, known as HDS-5 (Norman, et al., 1985)\(^1\). HDS-5 provides performance curves and equations. The equations provide the basis for computer programs such as HY-8 and CulvertMaster.

The design of a culvert generally is one of successive iterations whereby trial culvert type and size are chosen and the headwater elevation is computed for the design discharge. By comparing the calculated headwater elevation to the predetermined maximum allowable headwater elevation, a determination is made whether the trial culvert is too small or too large; if so, a new size culvert is selected and the process repeated.

Terminology

- **Barrel** - Literally, the pipe or conduit that forms the culvert.
- **Inlet** - The entrance to the culvert barrel.
- **Outlet (outfall)** - The discharge or exit end of the culvert.
- **Headwater (HW)** - Depth of water at the entrance (head) of the culvert measured from the culvert invert.
- **Tailwater (TW)** - Depth of water at the outlet (tail) of the culvert measured from the invert.
- **Inlet Control** - The hydraulic control regulating the flow occurs at the culvert entrance. Inlet control occurs when the culvert barrel is capable of conveying more flow than the inlet will accept.
- **Outlet Control** - The hydraulic control regulating the flow occurs downstream of the culvert entrance, either due to resistance in the culvert barrel, critical control at the culvert outlet, or a depth of flow in the downstream channel greater than the depth of flow in the culvert under free flow conditions.

**Performance Curves** - Plots relating headwater and discharge. Typically there are three distinct regions indicating changing flow conditions. At low flow and headwater, the inlet typically is not submerged, flow in the barrel is open channel flow, and the culvert acts as a weir. At high flow and headwater, the inlet may submerge, flow in the pipe barrel is pressure flow, and the culvert acts as an orifice. Between these two regions is the transition.

Culvert Material and Shape

---

Culverts are constructed from a variety of materials and shapes. The most common materials include concrete (RCP), corrugated aluminum, and corrugated steel. The use of plastic pipe (HDPE) is increasing as more is learned about its strength and durability characteristics. Material selection depends on requirements for structural strength, hydraulic roughness, durability, and corrosion and abrasion resistance.

The most commonly used shapes are circular, box (rectangular), elliptical, pipe-arch, and arch. Not all shapes are available in all materials. Shape selection is based on cost of construction, limitations on upstream water surface (HW) elevation, roadway embankment height, and hydraulic performance. Local practice and available suppliers also may influence shape selection.

A wide range of inlet configurations are used on culvert barrels and include both prefabricated and constructed-in-place installations. Commonly used inlet configurations include projecting culvert barrels, cast-in-place concrete headwalls, pre-cast or prefabricated end sections, and culvert ends mitered to conform to the fill slope. Structural stability, aesthetics, erosion control, and fill retention are considerations in inlet configuration selection.

**Culvert Hydraulics**

**Flow Conditions**

The flow in a culvert may be either open channel or closed pipe depending on the operating conditions. A culvert will act as an open channel as long as it is flowing partially full. Culvert hydraulics are quite complicated because the flow conditions are controlled by many variables, including inlet geometry, slope, size, roughness, approach velocity, headwater conditions, tailwater conditions, etc.

A culvert will flow full when the outlet is submerged or when the outlet is non-submerged but the headwater is high and the barrel is long. According to laboratory investigations, the entrance to an ordinary culvert will not be submerged if the headwater is less than a certain critical value while the outlet is not submerged. Based on most sources, the critical value varies from 1.2 to 1.5 times the height of the culvert, depending on the entrance geometry, barrel characteristics, and approach condition.

Laboratory investigations also indicate that a culvert, usually with a square edge at the top of the entrance, will not flow full even if the headwater is above the entrance when the outlet is not submerged. Under these conditions, the flow entering the culvert will contract in depth just like a jet flowing under a sluice gate. This high velocity jet will continue through the barrel length, but the velocity will decrease and the depth increase slowly as energy is lost to friction. If the culvert is so short that the expanding depth of flow does not fill the barrel, the culvert will never flow full. Such a culvert is considered hydraulically short. Otherwise, the culvert is hydraulically long and it will flow full like a pipe. The length of the barrel alone cannot determine if a culvert is hydraulically short or long. It depends on other characteristics, such as slope, size, entrance geometry, headwater, entrance and outlet conditions, etc. A culvert may become hydraulically short; that is, it may flow partially full, even when the headwater is greater than its critical value.

**Flow Control**

Inlet and outlet controls are the two basic types of flow control for culvert hydraulics. The basis for this classification is the location of the control section, which determines the culvert capacity. Inlet control occurs when the culvert barrel is capable of carrying more flow than the inlet will pass. The control section is located just inside the entrance. For non-submerged inlet conditions, critical depth occurs at or near this location, and the flow regime immediately downstream is supercritical. For submerged inlet conditions, the inlet acts as an orifice. Under inlet control, the downstream conditions do not affect the culvert capacity. Outlet control occurs when the culvert barrel cannot carry as much flow as the inlet can pass. The control section is located at the barrel exit or further downstream. Either subcritical or pressure flow exists in the pipe barrel.

**Detailed Procedures for Headwater Calculations**
This section outlines detailed procedures for headwater calculations, and thereby, provides the basis to examine the flow conditions and controls for the most common cases of culvert hydraulics (Figure 1). The method of identifying the different cases is only for clarity of presentation. Other references may identify the various cases differently, but will include the same fundamental group.

Case 1. Inlet control, mild slope, TW<yc
- Starting with y=yc at the outlet, perform flow profile analysis to find ye at the inlet.
- Compute headwater with Eq 1.
- If HW<1.2D, then Case 1.

Case 2. Outlet control, mild slope, TW>yc
- Starting with y=TW at the outlet, perform flow profile analysis to find ye at the inlet.
- Compute headwater with Eq 1.
- If HW<1.2D, then Case 2.

Case 3. Inlet control, steep slope, TW<D
- y=yc at inlet. (weir control)
- Compute headwater with Eq 2.
- If HW<1.2D, then Case 3.

Case 4. Inlet control, steep slope, TW>D
- y=yc at inlet. (weir control)
- Compute headwater with Eq 2.
- If HW<1.2D, then Case 4.

Case 5. Inlet control, pipe flow, TW<D
- First, check if yn<D. If not, culvert will flow full unless hydraulically short.
- ye=CcD where Cc is an orifice contraction coefficient, equal to 0.62 for sharp edged, flush inlets, and 1.0 for well-rounded inlets.
- Compute headwater with Eq 1.
- If HW<1.2D, then Case 5.

Case 6. Outlet control, pipe flow, TW<D
- Check if ye>D. Culvert may flow full unless hydraulically short (Case 5).
- Compute H with Eq. 3.
- Compute headwater from:
  \[HW = y_e + \frac{V_e^2}{2g} (1 + K_{ent})\] (1)

Case 8. Inlet control, pipe flow, TW>D
- ye=CcD at inlet.
- Compute headwater with Eq 1.
- If HW>1.2D, then Case 8.

Case 7. Outlet control, pipe flow, TW>D
- Culvert will flow full. Use the Bernoulli equation to solve for discharge given HW and

Equations

\[HW = y_e + \frac{V_e^2}{2g} (1 + K_{ent})\] (1)

\[HW = y_e + \frac{V_e^2}{2g} (1 + K_{ent})\] (2)

\[H = \frac{V^2}{2g} \left( \frac{fL}{D'} + K_{ent} + K_{cc} \right); \quad D' = 4R\] (3)
Figure 1 Cases of Culvert Hydraulics
Design Considerations

Design and Check Events

The Design Event is the rainfall event that the engineer wishes to design the culvert to safely convey. This will often be specified by local or state design standards. The Check Event is the rainfall event for which the engineer wishes to check the design (performance) of the culvert. This will usually be a more intense storm than the design storm. An example is that the engineer wishes to design the culvert to pass a 25 year (design) storm with several feet of freeboard, but also wants to avoid roadway overtopping in the 100 year (check) storm.

Channel and Roadway Data

Survey data is required to profile the channel (establish local slopes) and set invert and other critical elevations. Survey data may also be required for the channel cross-section and roadway vertical curve over the culvert crossing. These data are necessary when a culvert discharges into a natural channel and/or may overtop the roadway embankment.

Tailwater Conditions

Tailwater conditions are specified either as:

1. A constant elevation, which might occur if the discharge is into a larger stream or lake or if you have performed flow profile analysis from a known downstream control for the design discharge;
2. Normal depth in a constructed downstream channel;
3. Normal depth in a natural downstream channel;
4. Tailwater rating curve, which you have constructed for a range of flows based on known (measured) conditions and/or flow profile analyses from a known downstream control.

Allowable Headwater

The allowable headwater is determined by controlling elevations, such as the elevation at which the roadway will overtop minus some freeboard allowance. Another example is the maximum pond depth that does not lead to flooding upstream of the crossing; such elevations may be established by floor level in a house or other building.

Computer Programs

Two programs are used in local design practice: HY-8 and CulvertMaster. HY-8 was developed by the Federal Highway Administration (FHWA) and is available on-line at http://www.fhwa.dot.gov. HY-8 is based on the HDS-5. CulvertMaster was developed by Haestad Methods, Inc. and currently is marketed by Bentley Corp (http://www.Bentley.com). CulvertMaster also is based on HDS-5.