CHAPTER 3 HYDRAULICS

3.1 Hydraulic Calculations for Pipes, Culverts, and Open Channels

3.1.1 Gravity versus Pressure Flow for Enclosed Systems

Two design philosophies exist for sizing storm drains under the steady uniform flow assumption. The first is referred to as open channel, or gravity flow design, in which the water surface within the conduit remains open to atmospheric pressure. Pressure flow design, on the other hand, requires that the flow in the conduit be at a pressure greater than atmospheric. For a given flow rate, design based on open channel flow requires larger conduit sizes than those sized based on pressure flow. While it may be more expensive to construct storm drainage systems designed based on open channel flow, this design procedure provides a margin of safety by providing additional headroom in the conduit to accommodate an increase in flow above the design discharge. Under most ordinary conditions, it is recommended that storm drains be sized based on a gravity flow criteria at full flow or near full. However, pressure flow design is allowed. As hydraulic calculations are performed, frequent verification of the existence of the desired flow condition should be made. Storm drainage systems can often alternate between pressure and open channel flow conditions from one section to another (U.S. Department of Transportation Federal Highway Administration, 1996).

A. Gravity Flow

For gravity flow conditions, Manning's formula shall be used as described below.

$$Q = \frac{1.486}{n} A \cdot R^{2/3} S^{1/2}$$ where:

Q = Discharge in cubic feet per second

A = Cross sectional area of flow in square feet

n = Roughness Coefficient (see Table 3.1.1.1 in Appendix F)

R = Hydraulic radius $R = \frac{A}{P}$ in feet

S = Slope in feet per foot

P = Wetted perimeter in feet

B. Pressure Flow

In closed conduits flowing under pressure flow, the hydraulic grade line (HGL) will be above the crown of the pipe. In this case, the Bernoulli equation shall be used to calculate pipe capacity: $\frac{p_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{\gamma} + \frac{v_2^2}{2g} + z_2 + h_f + h_m$ where:

$\frac{p_1}{\gamma}$ = upstream system pressure head (ft)

$\frac{v_1^2}{2g}$ = upstream velocity head (ft)

z_1 = elevation of upstream system invert (ft)

$\frac{p_2}{\gamma}$ = downstream pressure head (ft)

$\frac{v_2^2}{2g}$ = downstream velocity head (ft)

z_2 = downstream invert elevation (ft)

h_f = system friction loss (ft)

h_m = system junction (so-called minor) losses (ft)

Pipe friction losses, h_f, may be calculated using the friction slope method. This derivation of Manning's equation is from (FHWA, 1996).

$$h_f = S_f \cdot L = \frac{(Q \cdot n)^2}{(1.486A \cdot R^{2/3})^2} \cdot L \quad \text{where:}$$

S_f = friction slope, ft/ft

> Note: For normal flow, S_f = HGL slope. However, due to numerous inlets, junctions, changes in direction and slope etc., and due to the nature of rainfall, storm drainage systems are often in unsteady, gradually varied or rapidly varied flow regimes in which this is not true.

Junction (so-called minor) losses, h_m, shall be calculated by:

$$h_m = k \cdot \frac{v^2}{2g} \quad \text{where:}$$

k = Coefficient as shown in Table 3.1.1.2 in Appendix F

$\frac{v_2^2}{2g}$ = downstream velocity head (ft)

A step-by-step procedure for manual calculation of the HGL using the energy loss method is presented in Section 7.5 of FHWA's Urban Drainage Design Manual (FHWA, 1996). For most drainage systems, computer methods such as HYDRA, StormCAD, CulvertMaster, SWMM, or InteliSOLVE are the most efficient means of evaluating the HGL and designing the system elements.

3.1.2 Culverts

Classified as having either entrance or outlet control. Either the inlet opening (entrance control), or friction loss within the culvert and/or backwater from the downstream system (outlet control) will control the discharge capacity. Culverts must be analyzed for both types of flow. Whichever produces the highest headwater depth must be used.

A. Entrance Control

Entrance control occurs when the culvert is hydraulically short (when the culvert is not flowing full) and steep. The flow regime at the entrance is critical as the water falls over the brink (water passes from subcritical to supercritical flow). If the tailwater covers the culvert completely (i.e., a submerged exit), the culvert will be full at that point, even though the inlet control forces the culvert to be only partially full at the inlet. The transition from partially full to full occurs in a hydraulic jump, the location of which depends on the flow resistance and water levels. If the flow resistance is very high, or if the headwater and tailwater levels are high enough, the jump will occur close to or at the entrance. Design variables for culverts operating under entrance control shall be determined from Figures 3.1.2.1 through 3.1.2.7.

B. Outlet Control

If the flow in a culvert is full for its entire length, then the flow is said to be under outlet control. The discharge will be a function of the differences in tailwater and headwater levels, as well as the flow resistance along the barrel length. Design variables for culverts operating under outlet control shall be determined from Figures 3.1.2.8 through 3.1.2.14.

Alternatively, refer to the Federal Highway Administration website for these charts and more (www.fhwa.dot.gov/bridge/hec05.pdf). Download applicable design manuals, reports, and FHWA hydraulics engineering software such as Bridge Waterways Analysis Model (WSPRO), FHWA Culvert Analysis, and HDS 5 Hydraulic Design of Highway Culverts from:www.fhwa.dot.gov/bridge/hydsoft.htm. HEC-RAS may also be used for culvert analysis.

3.1.3 Open Channels/Bridges

Proper evaluation of the velocity, depth, and width of flow requires analyses of the structures and conditions that impact the flow. Boundary flow conditions upstream and downstream from the open channel system must be established. The standard-step backwater method, using the energy equation, can be used to determine the depth, velocity, and width of flow. Major stream obstructions, changes in slope, changes in cross-section, and other flow controls can cause significant energy loss. In these cases, the energy equation does not apply and the momentum equation must be used to determine the depth, velocity, and width of flow.

Hydraulic calculations for open channels may also be made by the U.S. Army Corps of Engineer's 'HEC-RAS River Analysis System' computer programs. The HEC-RAS system is intended for calculating water surface profiles for steady and unsteady, gradually varied flow. The system can handle a full network of channels, a dendritic system, or a single river reach. HEC-RAS is capable of modeling subcritical, supercritical, and mixed flow regime water surface profiles. (Available from http://www.hec.usace.army.mil/software/hec-ras/).

3.2 Analysis of Systems by Computer Models

The following list provides commonly used computer programs for analyzing specific hydraulic systems. This is not an exhaustive list and alternates may be used with approval by the Director.

A. Enclosed pipe systems in gravity flow

SWMM Transport (EPA)
HYDRA (FHWA)
StormCad (Haested Methods)
DR3M (USGS)
InteliSOLVE

B. Enclosed pipe systems in pressure flow

SWMM EXTRAN (EPA)
MOUSE (DHI)
HYDRA (FHWA)
StormCad (Haested Methods)
InteliSOLVE

C. Culverts

HY8 (FHWA)
WSPRO (USGS)
CulvertMaster (Haested Methods)
HEC-RAS (USACE)

D. Open Channels and Culverts/Bridges

HEC-RAS (USACE)
WSPRO (USGS)
HYCHL (FHWA)
SWMM Transport and EXTRAN (EPA)
DR3M (USGS)

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