Highway Hydraulics - Closed Channel Flow

Course Number: CE-02-707

PDH: 4

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Module 7: Closed-Conduit Flow

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the three primary flow conditions occurring in closed conduits and their impact on hydraulic capacity.
- **Calculate** required pipe diameters and full-flow velocities using Manning's equation.
- **Evaluate** energy losses in complex pipe systems, including friction, junction, and access hole losses.

Executive Summary: Closed-conduit flow in highway drainage systems transitions between open-channel, gravity full, and pressure flow regimes. Accurate design requires Professional Engineers to account for part-full flow relationships—where peak flow occurs at 93% of pipe height—and to rigorously calculate both friction and form losses at structures to ensure the Hydraulic Grade Line remains below critical roadway elevations.

Types of Flow in Closed Conduits

Flow conditions in a closed conduit are categorized based on their hydraulic boundary conditions:

- **Open-Channel Flow**: Occurs when the water surface is exposed to the atmosphere, which can happen in open conduits or partially full closed conduits.
- **Gravity Full Flow**: A condition where the conduit is flowing full but is not yet under pressure. This is the standard assumption used for **storm drain design**.
- **Pressure Flow**: Occurs when the conduit is flowing full and under pressure.

Part-Full Relationships

Engineers must recognize that a partially full pipe can carry a greater flow than a gravity full pipe due to the lower wetted perimeter and reduced friction.

- **Peak Flow**: Occurs at **93 percent** of the height of a circular conduit.
- **Velocity Equality**: The average velocity at **one-half full** is the same as the velocity at gravity full flow.

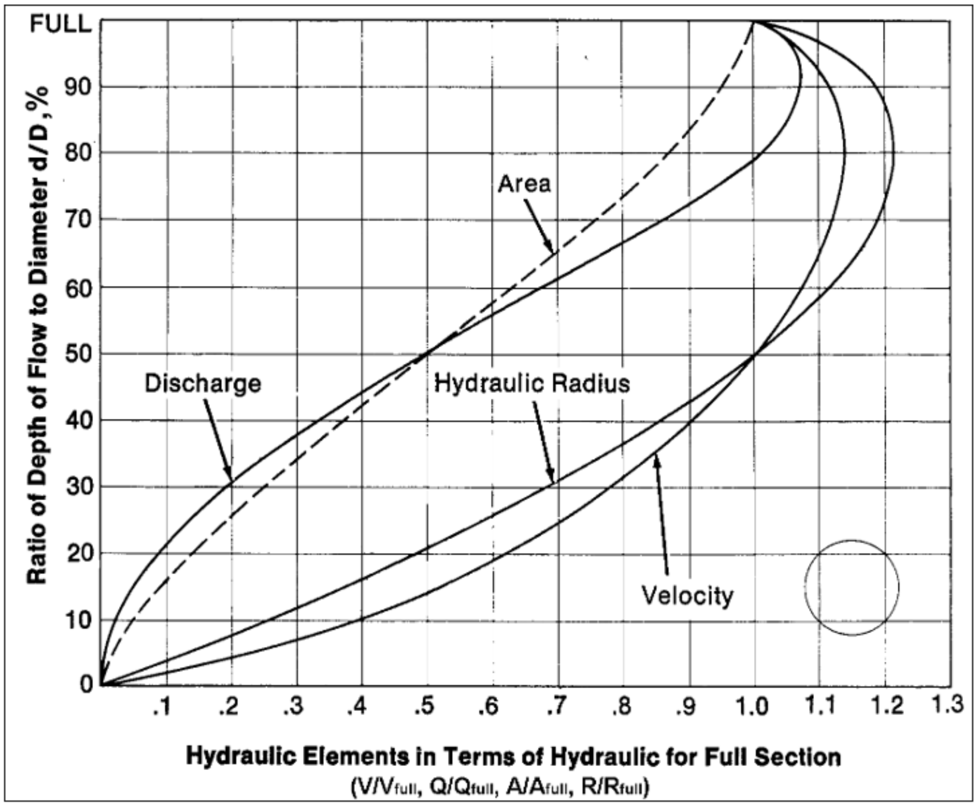

Figure 7.1. Part-full flow relationships for circular pipes.

Conduit Sizing Calculations

Manning's equation is adapted for circular sections flowing full to directly compute required diameters.

Equation 7.1:

$$Q = \frac{K_u}{n} D^{8/3} S^{1/2}$$

Where:

- **Q** = Discharge, m3/s (ft3/s)
- **n** = Manning's coefficient
- **D** = Pipe diameter, m (ft)
- **S** = Slope, m/m (ft/ft)
- **Ku** = 0.312 for SI units (0.46 for English units)

⚠️ **Safety Constraint**: Computed diameters must always be increased to the next larger **nominal dimension** to prevent unintended pressure flow.

Table 7.1. Nominal Pipe Sizes. | Nominal Size as Manufactured in English Units (Inches)

Table 7.1. Nominal Pipe Sizes.		
Nominal Size as Manufactured in English Units		Nominal Size Converted to SI Metric Units
Pipe Diameter		Pipe Diameter (mm)
Inches	Feet	
18	1.5	450
24	2.0	600
30	2.5	750
36	3.0	900
42	3.5	1,050
48	4.0	1,200
54	4.5	1,350
60	5.0	1,500
66	5.5	1,650
72	6.0	1,800
78	6.5	1,950
84	7.0	2,100
90	7.5	2,250
96	8.0	2,400
102	8.5	2,550
108	9.0	2,700
114	9.5	2,850
120	10.0	3,000
126	10.5	3,150
132	11.0	3,300
138	11.5	3,450
144	12.0	3,600

🧮 **Calculation Note**: When calculating **Time of Concentration (tc)**, use the **part-full velocity** if the pipe is not surcharged, as velocity varies based on depth.

Energy Equation

The energy equation maintains that the energy head at any cross section equals the head at a downstream section plus intervening loss.

Energy Components

- **Velocity Head**: $\frac{V^2}{2g}$
- **Pressure Head**: $\frac{P}{\gamma}$
- **Elevation Head**: (Z)

Grade Lines

- **Energy Grade Line (EGL)**: Represents the total energy at any given cross section.

- **Hydraulic Grade Line (HGL)**: Located below the EGL by the velocity head. In open-channel flow, the HGL is equal to the water surface elevation.

⚠️ **Safety Constraint**: In systems designed for pressure flow, the HGL **should** remain lower than the roadway elevation to prevent flooding through inlets or access holes.

Energy Losses

Energy losses are classified as friction losses or form losses.

Calculating Friction Losses

Friction losses (**hf**) are calculated as the product of the conduit length (**L**) and the friction slope (**Sf**).

Equation 7.2:

$$h_f = L \cdot S_f$$

Where:

- **hf** = friction loss, m (ft)
- **L** = conduit length, m (ft)
- **Sf** = friction slope, m/m (ft/ft)

Equation 7.3 (Manning's Sf):

$$S_f = \left[\frac{Qn}{K_u A R^{2/3}}\right]^2$$

Where:

- **Sf** = friction slope, m/m (ft/ft)
- **Q** = Discharge, m3/s (ft3/s)
- **n** = Manning's coefficient
- **Ku** = 1.0 for SI units (1.486 for English units)
- **A** = Cross-sectional area of flow, m2 (ft2)
- **R** = Hydraulic radius, m (ft)

💡 **Design Tip**: Although Darcy-Weisbach is theoretically superior, engineers frequently prefer Manning's equation due to its simpler application.

Calculating Form Losses

Form losses occur at structures like access holes, bends, and transitions. The general method uses a coefficient (K) multiplied by the velocity head.

Equation 7.6:

$$h_L = K\frac{V^2}{2g}$$

Where:

- **hL** = form loss, m (ft)
- **K** = form loss coefficient
- **V** = velocity, m/s (ft/s)
- **g** = acceleration due to gravity, 9.81 m/s2 (32.2 ft/s2)

Junction Losses

A junction connects a lateral to a trunk pipe without an access hole. The FHWA recommends an approach based on pressure and momentum.

Equation 7.7:

$$H_j = \frac{(Q_o V_o) - (Q_i V_i) - (Q_1 V_1 \cos\theta)}{0.5g(A_o + A_i)} + h_o - h_i$$

Where:

- **Hj** = Junction headloss, m (ft)
- **Qo, Qi, Q1** = Outlet, inlet, and lateral flows, m3/s (ft3/s)
- **Vo, Vi, V1** = Outlet, inlet, and lateral velocities, m/s (ft/s)
- **θ** = Angle of lateral with respect to outlet pipe
- **g** = Gravitational acceleration (9.81 m/s2 or 32.2 ft/s2)
- **Ao, Ai** = Outlet and inlet cross-sectional areas, m2 (ft2)
- **ho, hi** = Outlet and inlet water surface elevations (or pressure heads), m (ft)

Calculating Access Hole Losses

For preliminary design, a simple K value (e.g., 0.15 for straight-through flow) is used. For EGL calculations, the FHWA three-step method is required.