Highway Hydraulics - Fundamental Concepts

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3 Fundamental Hydraulic Concepts

3.1 GENERAL

The design of drainage structures requires the use of the continuity, energy and momentum equations. From these fundamental equations other equations are derived by a combination of mathematics, laboratory experiments and field studies. These equations are used differently to analyze open-channel flow and closed conduits flowing full. A closed-conduit flowing partially full is open-channel flow. Compared to closed conduits flowing full, open- channel flow has the complexity of a free surface where the pressure is atmospheric and this free surface is controlled only by the laws of fluid mechanics. Another complexity in open- channel flow is introduced when the bed of the stream or conduit is composed of natural material such as sand, gravel, boulders or rock that is movable. In the following sections, the fundamental equations, derived equations and definitions of terms will be given. The equations and methods will not be derived. The user is referred to standard textbooks, FHWA publications and the literature cited for additional information.

Flow can be classified as: (1) uniform or nonuniform flow; (2) steady or unsteady flow; (3) laminar or turbulent flow; and (4) subcritical (tranquil) or supercritical (rapid) flow. In uniform flow, the depth, discharge, and velocity remain constant with respect to distance. In steady flow, no change occurs with respect to time at a given point. In laminar flow, the flow field can be characterized by layers of fluid, one layer not mixing with adjacent ones. Turbulent flow on the other hand is characterized by random fluid motion. Laminar flow is distinguished from turbulent flow by the use of a dimensionless number called the Reynolds Number. Subcritical flow is distinguished from supercritical flow by a dimensionless number called the Froude Number, Fr. If $Fr < 1$, the flow is subcritical; if $Fr > 1$, the flow is supercritical, and if $Fr = 1$, the flow is called critical. These and other terms will be more fully explained in the following sections.

3.2 BASIC PRINCIPLES

3.2.1 Introduction

Basic equations of flow are continuity, energy and momentum. They are derived from the laws of (1) the conservation of mass; (2) the conservation of energy; and (3) the conservation of linear momentum, respectively. Conservation of mass is another way of stating that (except for mass-energy interchange) matter can neither be created nor destroyed. The principle of conservation of energy is based on the first law of thermodynamics which states that energy must at all times be conserved. The principle of conservation of linear momentum is based on Newton's second law of motion which states that a mass (of fluid) accelerates in the direction of and in proportion to the applied forces on the mass.

Analysis of flow problems are much simplified if there is no acceleration of the flow or if the acceleration is primarily in one direction (one-dimensional flow), the accelerations in other directions being negligible. However, a very inaccurate analysis may occur if one assumes accelerations are small or zero when in fact they are not. The concepts given in this manual assume one-dimensional flow. Only the equations will be given. The user is referred to standard fluid mechanics texts or "River Engineering for Highway Encroachments" (HDS 6) for their derivations (Richardson et al. 2001).

3.2.2 Continuity Equation

The continuity equation is based on conservation of mass. For steady flow of incompressible fluids it is:

$$V_1 A_1 = V_2 A_2 = Q = V A \quad (3.1)$$

where:

V	=	Average velocity in the cross section perpendicular to the area, m/s (ft/s)
A	=	Area perpendicular to the velocity, m^2 (ft^2)
Q	=	Volume flow rate or discharge, m^3/s (ft^3/s)

Equation 3.1 is applicable when the fluid density is constant, the flow is steady, there is no significant lateral inflow or seepage (or they are accounted for) and the velocity is perpendicular to the area (Figure 3.1).

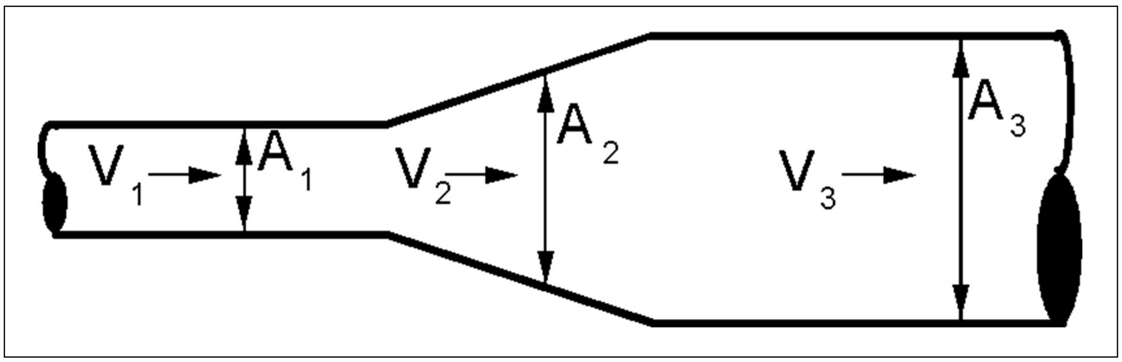
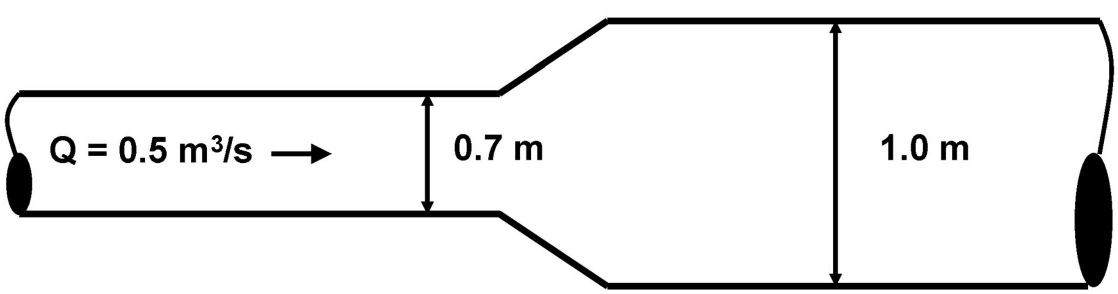


Figure 3.1. Sketch of continuity concept.

EXAMPLE PROBLEM 3.1 (SI Units)

Given: A storm drain flowing full transitions from 0.7 m to 1.0 m diameter pipe. Determine the average velocity in each section of pipe for a discharge 0.5 m^3/s.



Find:

(a) Velocity at section 1 (0.7 m pipe)
(b) Velocity at section 2 (1.0 m pipe)

Solution:

Since the discharge at the beginning of the pipe must equal the discharge at the end of the pipe, the continuity equation can be used.

Basic equation: Q = V A   Rearrange to get   V = Q / A   For a circular pipe: $A = \frac{\pi D^2}{4}$

At cross section 1:

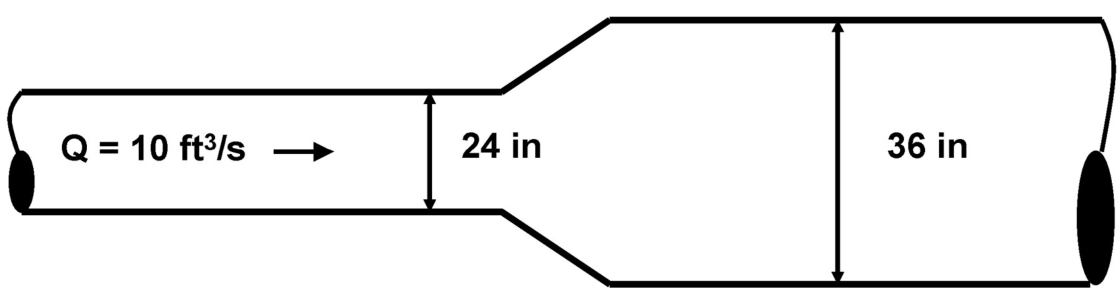
$$V = \left[\frac{0.5}{\pi (0.7)^2 / 4}\right] = 1.30\,\text{m/s}$$

At cross section 2:

$$V = \left[\frac{0.5}{\pi (1)^2 / 4}\right] = 0.64\,\text{m/s}$$

EXAMPLE PROBLEM 3.1 (English Units)

Given: A storm drain flowing full transitions from 24- to 36-inch diameter pipe. Determine the average velocity in each section of pipe for a discharge 10 ft^3/s.



Find:

(a) Velocity at section 1 (24-inch pipe)
(b) Velocity at section 2 (36-inch pipe)

Solution:

Since the discharge at the beginning of the pipe must equal the discharge at the end of the pipe, the continuity equation can be used.

Basic equation: Q = V A   Rearrange to get   V = Q / A   For a circular pipe: $A = \frac{\pi D^2}{4}$

At cross section 1:

$$V = \left[\frac{10}{\pi(2)^2/4}\right] = 3.18 \text{ ft/s}$$

At cross section 2:

$$V = \left[\frac{10}{\pi(3)^2/4}\right] = 1.42 \text{ ft/s}$$

3.2.3 Energy Equation

The energy equation is derived from the first law of thermodynamics which states that energy must be conserved at all times. The energy equation is a scalar equation. For steady incompressible flow it is:

$$\alpha_1 \frac{V_1^2}{2g} + \frac{p_1}{\gamma} + Z_1 = \alpha_2 \frac{V_2^2}{2g} + \frac{p_2}{\gamma} + Z_2 + h_L \qquad (3.2)$$

where:

α = Kinetic energy correction factor
V = Average velocity in the cross section, m/s (ft/s)
g = Acceleration of gravity, 9.81 m/s^2 (32.2 ft/s^2)
p = Pressure, N/m^2 or Pa (lbs/ft^2)
γ = Unit weight of water, 9,800 N/m^3 (62.4 lbs/ft^3) at 15EC (59EF)
Z = Elevation above a horizontal datum, m (ft)
h_L = Headloss due to friction and form losses, m (ft)
A = Area of the cross section, m^2 (ft^2)

The kinetic energy correction factor α is to correct for the velocity distribution across the flow. This allows the use of the average velocity (V) rather than the point velocity (v). It is given by the following equation:

$$\alpha = \frac{1}{V^3 A} \int_A v^3 \, dA \qquad (3.3)$$

where:

v = Velocity at a point or average in a vertical, m/s (ft/s)