Open Channel Flow

A. Introduction

The beginning of any channel design or modification is to understand the hydraulics of the stream. The procedures for performing uniform flow calculations aid in the selection or evaluation of appropriate depths and grades for natural or man-made channels. Allowable velocities are provided, along with procedures for evaluating channel capacity using Manning's equation.

All the methods described herein will be based on the conservation of mass, momentum and energy (in the form of Bernoulli's theorem), and the Manning formula for frictional resistance. Steady uniform flow and steady non-uniform flow are the types of flow addressed in this section.

B. Definitions

Critical flow: The variation of specific energy with depth at a constant discharge shows a minimum in the specific energy at a depth called critical depth at which the Froude number has a value of one. Critical depth is also the depth of maximum discharge, when the specific energy is held constant.

Froude number: The Froude number is an important dimensionless parameter in open-channel flow. It represents the ratio of inertia forces to gravity forces. This expression for Froude number applies to any single-section channel of nonrectangular shape.

Hydraulic jump: Hydraulic jumps occur at abrupt transitions from supercritical to subcritical flow in the flow direction. There are significant changes in the depth and velocity in the jump, and energy is dissipated. For this reason, the hydraulic jump is often employed to dissipate energy and control erosion at storm water management structures.

Kinetic energy coefficient: As the velocity distribution in a river varies from a maximum at the design portion of the channel to essentially zero along the banks, the average velocity head.

Normal depth: For a given channel geometry, slope, and roughness, and a specified value of discharge Q, a unique value of depth occurs in a steady uniform flow. It is called the normal depth. The normal depth is used to design artificial channels in a steady, uniform flow and is computed from Manning's equation.

Specific energy: Specific energy (E) is the energy head relative to the channel bottom. If the channel is not too steep (slope less than 10%), and the streamlines are nearly straight and parallel (so that the hydrostatic assumption holds), the specific energy E becomes the sum of the depth and velocity head. The kinetic energy correction coefficient is taken to have a value of one for turbulent flow in prismatic channels but may be significantly different from one in natural channels.

Steady and unsteady flow: A steady flow is when the discharge passing a given cross section is constant with respect to time. When the discharge varies with time, the flow is unsteady. The maintenance of steady flow requires that the rates of inflow and outflow be constant and equal.

Subcritical flow: Depths of flow greater than critical depths, resulting from relatively flat slopes. Froude number is less than one. Flow of this type is most common in flat streams.

Supercritical flow: Depths of flow less than critical depths resulting from relatively steep slopes. Froude number is greater than one. Flow of this type is most common is steep streams.

Total energy head: The total energy head is the specific energy head plus the elevation of the channel bottom with respect to some datum. The curve of the energy head from one cross section to the next defines the energy grade line.

Uniform flow and non-uniform flow: A non-uniform flow is one in which the velocity and depth vary over distance, while they remain constant in uniform flow. Uniform flow can occur only in a channel of constant cross section, roughness, and slope in the flow direction; however, non-uniform flow can occur in such a channel or in a natural channel with variable properties.

C. Uniform flow (Manning's equation)

1. **Manning's equation.** The normal depth is used to design artificial channels in a steady, uniform flow and is computed from Manning's equation:

$Q = AV$ **Equation 1**

Equation 2

$$Q = [(1.49 / n)AR^{2/3}S^{1/2}]$$ **Equation 3**

where Q = discharge (cfs)
n = Manning's roughness coefficient (see Section 2C-3, Table 2 for n values)
A = cross-sectional area of flow (ft)
R = hydraulic radius = A/P (ft)
P = wetted perimeter (ft)
S = channel slope (ft/ft)
V = channel velocities (see Tables 3 and 4 for permissible channel velocities)

The selection of Manning's n is generally based on observation; however, considerable experience is essential in selecting appropriate n values. If the normal depth computed from Manning's equation is greater than critical depth, the slope is classified as a mild slope, while on a steep slope, the normal depth is less than critical depth. Thus, uniform flow is subcritical on a mild slope and supercritical on a steep slope.

Strictly speaking, uniform flow conditions seldom, if ever, occur in nature because channel sections change from point to point. For practical purposes in highway engineering, however, the Manning equation can be applied to most stream flow problems by making judicious assumptions. When the requirements for uniform flow are met, the depth (d_n) and the velocity (V_n) are said to be normal and the slopes of the water surface and channel are parallel. For practical purposes, in open channel design, minor undulations in streambed or minor deviations from the mean (average) cross-section can be ignored as long as the mean slope of the channel can be represented as a straight line. The Manning equation can readily be solved either graphically or mathematically for the average velocity in a given channel if the normal depth is known, because the various factors in the equation are known or can be determined (the hydraulic radius can be computed from the normal depth in a given channel). Discharge (Q) is then the product of the velocity and the area of flow(A).

2. **Continuity equation.** The continuity equation is the statement of conservation of mass in fluid mechanics. For the special case of steady flow of an incompressible fluid, it assumes the simple form:

$$Q = A_1V_1 = A_2V_2$$ **Equation 3**

where Q = discharge (cfs)
A = flow cross-sectional area (ft)
V = mean cross-sectional velocity (ft/s) (which is perpendicular to the cross section)

The subscripts 1 and 2 refer to successive cross sections along the flow path. The continuity equation can be used with Manning's equation to obtain steady uniform flow velocity as:

$$V = Q / A = [(1.49 / n)R^{3/2}]S^{1/2}$$ **Equation 4**