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Highway Hydraulics - Open Channel Flow

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Module 4: Open-Channel Flow

Learning Objectives

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

- **Identify** flow regimes and bedform configurations in alluvial sand channels.
- **Calculate** mean velocity and discharge for steady uniform flow using Manning's Equation.
- **Evaluate** water surface profiles and hydraulic controls for gradually varied flow conditions.

Executive Summary: Open-channel flow analysis requires balancing gravitational forces against boundary resistance. In alluvial channels, this resistance is dynamic, shifting with flow regimes and bedforms. For steady uniform flow, Manning's Equation serves as the primary tool, while nonuniform flow requires evaluating specific energy and critical depth to locate hydraulic controls.

Introduction

Open-channel flow is more complex than closed-conduit flow flowing full because the water surface is determined by the mechanics of motion. If the bottom boundary is movable (alluvial boundary), complexity increases because resistance to flow becomes a function of the flow itself. This chapter utilizes the one-dimensional method to describe equations for steady, uniform flow and increasing flow complexities.

Alluvial Channel Flow

Alluvial Channels

Alluvial channels are formed in material, such as sand, gravel, and cobbles, that has been and can be transported by the flow. These materials affect resistance to flow and erosion in drainage design. Even concrete channels may exhibit an alluvial boundary if bed material deposits in the invert.

Bedforms in Sand Channels

Sand-bed streams consist of 50 percent or more sand. The bed material is easily eroded and continually moved and shaped by the flow. Interaction between the water-sediment mixture and the sand bed creates configurations that change resistance, velocity, water surface elevation, and sediment transport. Understanding these bedforms is essential to estimate resistance and compute water surface profiles for drainage design.

Flow Regime

Flow in alluvial channels is divided into two regimes separated by a transition zone:

- **Lower flow regime:** Characterized by large resistance to flow and small sediment transport. Bedforms include ripples, dunes, or a combination. Water-surface undulations are out of phase with the bed surface.
- **Transition zone:** Bed configurations range from lower to upper flow regime types depending on antecedent conditions. Resistance and sediment transport are highly variable in this zone.
- **Upper flow regime:** Characterized by small resistance to flow and large sediment transport. Usual bedforms are plane bed or antidunes, with the water surface in phase with the bed surface.

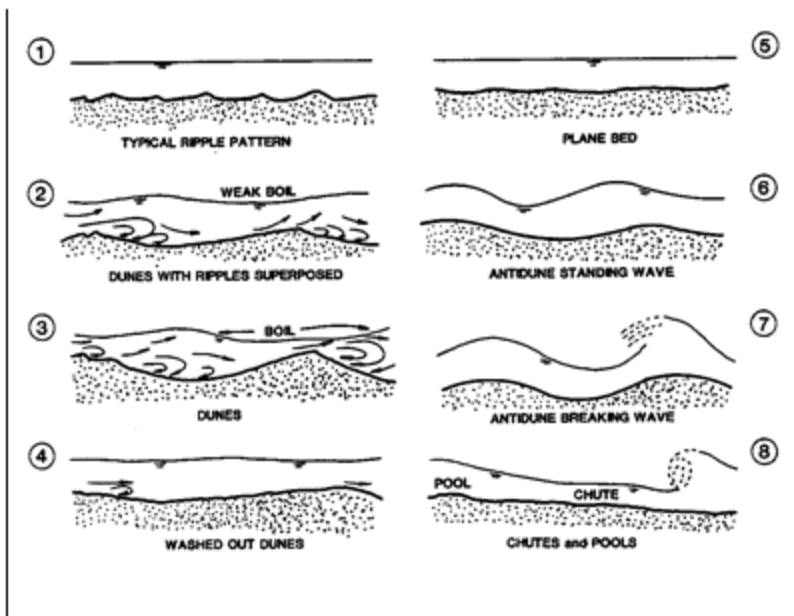


Figure 4.1. Forms of bed roughness in sand channels.

Design Tip: At high flows, sand-bed channels often shift from dune beds to plane bed configurations. In steep slopes, antidune flow can decrease resistance to one-half or one-third of preceding values, increasing scour potential around bridge piers.

Coarse-Bed Material

At moderate or large flows, coarse alluvial material becomes mobile, potentially forming large bars that redirect flow and cause bank erosion or clogging. However, coarse material can benefit drainage channels by armoring the bed to decrease erosion.

Steady Uniform Flow

In steady uniform flow, there are no accelerations, streamlines are straight and parallel, and the pressure distribution is hydrostatic. The slope of the water surface (S_w), bed surface (S_o), and energy gradient (S_f) are equal. Depth in this state is called normal depth (y_o).

Manning's Equation for Mean Velocity and Discharge

Water flows in sloping channels due to gravity, resisted by friction between the water and the wetted surface. Mean velocity (V) is determined by Manning's equation:

Equation 4-1:

$$V = \frac{K_u}{n} R^{2/3} S^{1/2}$$

Where:

- V = Mean velocity, m/s (ft/s)
- n = Manning's coefficient of channel roughness
- R = Hydraulic radius, m (ft)
- S = Energy slope, m/m (ft/ft); for steady uniform flow $S = S_o$
- K_u = Units conversion factor equal to 1 (1.49 in English units)

Numerical Approach for n Value Estimates


For natural channels, a base roughness value can be selected and additive values applied:

Equation 4-2:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m_5$$

Where:

- n_0 = Base value for straight uniform channels
- n_1 = Additive value due to cross-section irregularity
- n_2 = Additive value due to variations of the channel
- n_3 = Additive value due to obstructions
- n_4 = Additive value due to vegetation
- m_5 = Multiplication factor due to sinuosity

 **Calculation Note:** For rock riprap, Manning's n is often a function of rock size (D_{50}) and flow depth

$$(y): n = \frac{K_u y^{1/6}}{2.25 + 5.23 \log\left(\frac{y}{D_{50}}\right)}$$

Hydraulic Radius and Discharge

The hydraulic radius (R) is a shape factor:

Equation 4-4:

$$R = \frac{A}{P}$$

Where:

- **A** = Cross-sectional area perpendicular to the direction of flow
- **P** = Wetted perimeter

Discharge (Q) is calculated by combining velocity and area: **Equation 4-5:**

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

Where:

- **Q** = Discharge
- **K_u** = Units conversion factor
- **n** = Manning's coefficient of channel roughness
- **A** = Cross-sectional area perpendicular to the direction of flow
- **R** = Hydraulic radius
- **S** = Energy slope

Channel Conveyance (K)

Conveyance groups cross-sectional properties: **Equation 4-6:**

$$K = \frac{K_u}{n} AR^{2/3}$$

Where:

- **K** = Channel conveyance
- **K_u** = Units conversion factor
- **n** = Manning's coefficient of channel roughness
- **A** = Cross-sectional area perpendicular to the direction of flow
- **R** = Hydraulic radius

Equation 4-7: $Q = KS^{1/2}$

Where:

- Q = Discharge
- K = Channel conveyance
- S = Energy slope

Aids in the Solution of Manning's Equation

For rectangular and trapezoidal channels, area (A) and wetted perimeter (P) are defined as:

Equation 4-8: $A = By + Zy^2$

Where:

- A = Cross-sectional area
- B = Bottom width of the channel
- y = Flow depth
- Z = Side slope horizontal component (Z:1)

Equation 4-9: $P = B + 2y(1 + Z^2)^{1/2}$

Where:

- P = Wetted perimeter
- B = Bottom width of the channel
- y = Flow depth
- Z = Side slope horizontal component (Z:1)

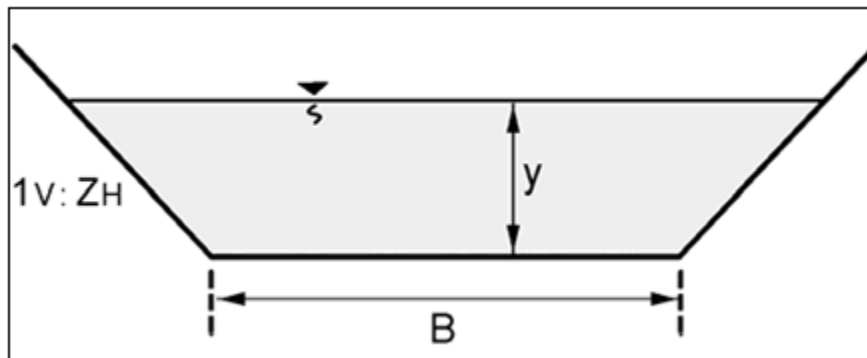


Figure 4.2. Trapezoidal channel.



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