Highway Hydraulics - Open Channel Flow

Course Number: CE-02-708

PDH: 6

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CHAPTER 4

OPEN-CHANNEL FLOW

4.1 INTRODUCTION

Open-channel flow is more complex than closed-conduit flow flowing full because the water surface is determined by the mechanics of motion. In addition, if the bottom boundary is movable (alluvial boundary) another complexity is introduced. When the channel is mobile, the resistance to flow is a function of the flow.

In this course the concepts and equations for the simplest flow condition (steady, uniform flow) will be described, as well as the bedform conditions that occur in an alluvial channel. Flow conditions and equations for solving problems of increasing flow complexity will be given. The one-dimensional method will be used in the descriptions of the equations.

4.2 ALLUVIAL CHANNEL FLOW

4.2.1 Alluvial Channels

Alluvial channels are channels formed in material that has been and can be transported by the flow. They are commonly made up of bed material composed of sand-, gravel-, and cobble-sized material. These materials are important in drainage design because they affect resistance to flow and erosion. Concrete channels and culverts may have an alluvial boundary because of deposition of bed material in the invert.

4.2.2 Bedforms in Sand Channels

The predominant material in sand-bed streams ranges from coarse silt to sand. There may be finer or coarser material in the bed, but the dominant size will be sand (50 percent or more). In sand-bed streams, the bed material is easily eroded and continually being moved and shaped by the flow. Interaction between the flow of water-sediment mixture and the sand bed creates different bed configurations which change the resistance to flow, velocity, water surface elevation, and sediment transport. Consequently, it is necessary to understand what bedforms will be present so that the resistance to flow can be estimated and flood stages, depth of flow, and water surface profiles can be computed in order to design drainage channels.

4.2.3 Flow Regime

Flow in alluvial channels is divided into two regimes separated by a transition zone. Forms of bed roughness in sand channels are shown in Figure 4.1. The flow regimes are:

- Lower flow regime, where resistance to flow is large and sediment transport is small. The bedform is either ripples or dunes or some combination of the two. Water-surface undulations are out of phase with the bed surface, and there is a relatively large separation zone downstream from the crest of each ripple or dune. The velocity of the downstream movement of the ripples or dunes depends on their height and the velocity of the grains moving up their backs.

- The transition zone, where the bed configuration may range from that typical of the lower flow regime to that typical of the upper flow regime, depending mainly on antecedent conditions. If the antecedent bed configuration is dunes, the depth or slope can be increased to values more consistent with those of the upper flow regime without changing the bedform; or, conversely, if the antecedent bed is plane, depth and slope can be decreased to values more consistent with those of the lower flow regime without changing the bedform.

  Resistance to flow and sediment transport also have the same variability as the bed configuration in the transition. This phenomenon can be explained by the changes in resistance to flow and, consequently, the changes in depth and slope as the bedform changes.

- Upper flow regime, in which resistance to flow is small and sediment transport is large. Usual bedforms are plane bed or antidunes. Water surface is in phase with the bed surface except when an antidune breaks, and normally the fluid does not separate from the boundary.

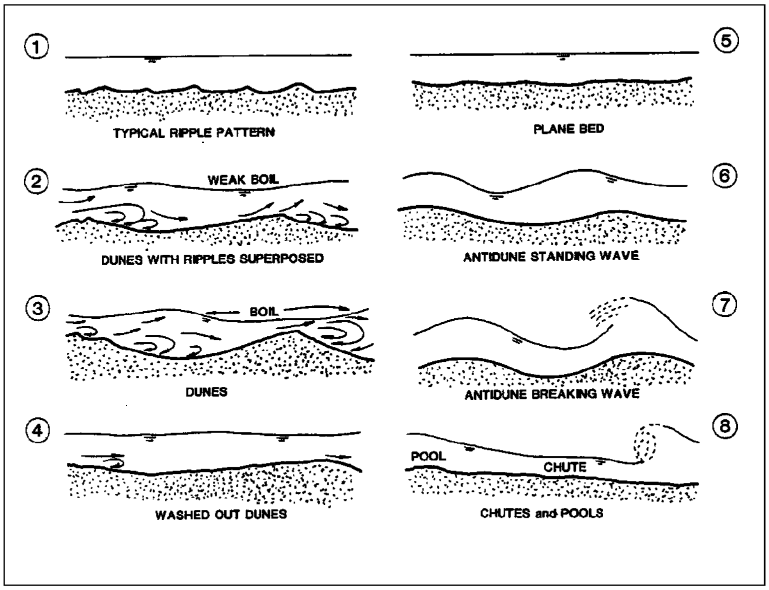

Figure 4.1. Forms of bed roughness in sand channels.

Resistance to flow for the different bedforms and coarser bed material will be given later in this section. For information on sediment transport and additional information on bedforms the reader is referred to HDS 6 (Richardson et al. 2001).

At high flows, most sand-bed stream channels shift from a dune bed to a transition or a plane bed configuration. If the slope is steep antidune flow may occur. Resistance to flow is then decreased to one-half to one-third of that preceding the shift in bedform. The increase in velocity and corresponding decrease in depth may increase erosion and scour around bridge piers and abutments and increase the required size of riprap. If flow transitions to antidune flow significant wave action may occur.

4.2.4 Coarse-Bed Material

At low flow, coarse alluvial bed material may not move, but at moderate or large flows, the material may become mobile. With the movement of coarse-bed material, large bars may form which will be residual at low flow. These bars can re-direct flow and cause bank erosion, scour holes, and clog drainage channels. Resistance to flow for coarse-bed material is caused by the grain roughness of the material and the form loss caused by the bars. However, coarse-bed material in drainage channels can have a beneficial effect by decreasing erosion by armoring of the bed. Information on armoring is given in HEC-20 (Lagasse et al. 2001) and HDS 6 (Richardson et al. 2001). The determination of Manning's n for coarse-bed material is given later.

4.3 STEADY UNIFORM FLOW

In steady, uniform open-channel flow, there are no accelerations, streamlines are straight and parallel, and the pressure distribution is hydrostatic. The slope of the water surface S_w, the bed surface S_o, and the energy gradient S_f are equal (Figure 3.2). It is the simplest flow condition to analyze. Steady uniform flow is an idealized concept for open-channel flow and is difficult to obtain even in laboratory flumes. For many applications, the flow is essentially steady and changes in width, depth, or direction (resulting in nonuniform flow) are so small that the flow can be considered uniform. In other cases, the changes occur over such a long distance the flow is a gradually varied flow.

Depth in steady uniform flow is called the normal depth and the symbol for it is given the subscript o as in Y_o. Velocity (V) is often given the same subscripts, i.e., V_o. Other variables of interest for steady uniform flow are (1) the discharge (Q), (2) the velocity distribution v_y in the vertical, (3) the headloss h_L through the reach, and (4) the shear stress, both local and at the bed τ_o. All these variables are interrelated. In the following section, engineering equations will be given along with example problems for obtaining values for these variables.

4.3.1 Manning's Equation for Mean Velocity and Discharge

Water flows in a sloping drainage channel because of the force of gravity. Flow is resisted by the friction between the water and wetted surface of the channel. The quantity of water flowing (Q), the depth of flow (y), and the velocity of flow (V) depend upon the channel shape, roughness (n), and slope (S_0). Various equations have been devised to determine the velocity and discharge in open channels. A useful equation is the one that is named for Robert Manning, an Irish engineer. The Manning's equation for the velocity of flow in open channels is:

$$V = \frac{K_u}{n} R^{2/3} S^{1/2} \tag{4.1}$$

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 $S = S_0$
K_u	=	Units conversion factor equal to 1 (1.49 in English units)

Over many decades, typical Manning's n values have been compiled allowing an engineer to estimate the appropriate value by knowing the general nature of the channel boundaries. Most hydraulics textbooks and drainage design manuals provide tables of typical Manning’s n values. An abbreviated list of such Manning's roughness coefficients is given in Appendix B, Table B.2. Several pictorial guides are also available showing the Manning’s n value for different types of channels and floodplains (Barnes 1967 and Acrement and Schneider 1984). Special considerations exist for very steep channels (Jarrett 1985).

A numerical approach for n value estimates consists of the selection of a base roughness value for a straight, uniform, and smooth channel in the materials involved, and then adding values for the channel under consideration:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)\, m_5 \qquad (4.2)$$

where:

n_o = 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_2 = Additive value due to obstructions
n_4 = Additive value due to vegetation
m_5 = Multiplication factor due to sinuosity

A discussion of this method and coefficients can be found in Cowan (1956) and Chow (1959). This method may be useful for natural channels, but has limited application for most roadway drainage design work.

For rock riprap channels the Manning’s n is often described as some function of the rock size. Several equations are provided in HEC-15, including:

$$n = (K_u)(y^{1/6}) \,/\, (2.25 + 5.23 \log (y/D_{50})) \qquad (4.3)$$

where:

y = Flow depth (average) in the channel, m (ft)
D_{50} = Median riprap/gravel size, m (ft)
K_u = Unit conversion constant, 0.319 (SI) and 2.262 (English)

This equation is valid for y/D_{50} ranging from 1.5 to 185 which should be typical of most conditions encountered in roadside and other small channels. For conditions outside this range see HEC-15.

Roughness characteristics on the floodplain are complicated by the presence of vegetation, natural and artificial irregularities, buildings, undefined direction of flow, varying slopes, and other complexities. Resistance factors reflecting these effects must be selected largely on the basis of past experience with similar conditions. In general, resistance to flow is large on the floodplains. In some instances, conditions are further complicated by deposition of sediment and development of dunes and bars which affect resistance to flow and direction of flow.

The presence of ice affects channel roughness and resistance to flow in various ways. When an ice cover occurs, the open channel is more nearly comparable to a closed conduit. There is an added shear stress developed between the flowing water and ice cover. This surface

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