1-1 Introduction

Liquids are transported from one location to another using natural or constructed conveyance structures. The cross section of these structures may be open or closed at the top. The structures with closed tops are referred to as closed conduits and those with the top open are called open channels. For example, tunnels and pipes are closed conduits whereas rivers, streams, estuaries etc. are open channels. The flow in an open channel or in a closed conduit having a free surface is referred to as free-surface flow or open-channel flow. The properties and the analyses of these flows are discussed in this book. In this chapter, commonly used terms are first defined. The classification of flows is then discussed, and the terminology and the properties of a channel section are presented. Expressions are then derived for the energy and momentum coefficients to account for nonuniform velocity distribution at a channel in a channel section.

1-2 Definitions

The terms open-channel flow or free-surface flow (Fig. 1-1) are used synonymously in this book. The free surface is usually subjected to atmospheric pressure. Groundwater or subsurface flows are excluded from the present discussions. If there is no free surface and the conduit is flowing full, then the flow is called pipe flow, or pressurized flow. (Fig. 1-2)

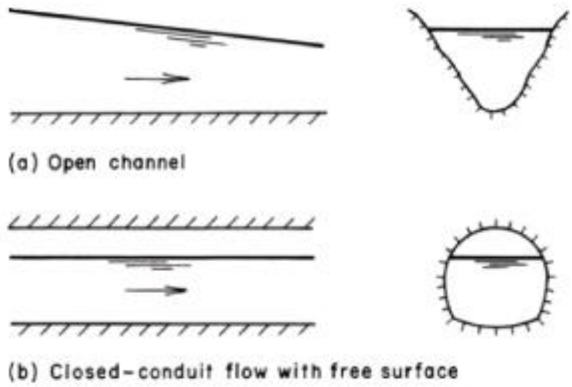

Fig. 1-1. Free-Surface flow

In a closed conduit, it is possible to have both free-surface flow and pressurized flow at different times. It is also possible to have these flows at a given time in different reaches of a conduit. For example, the flow in a storm sewer

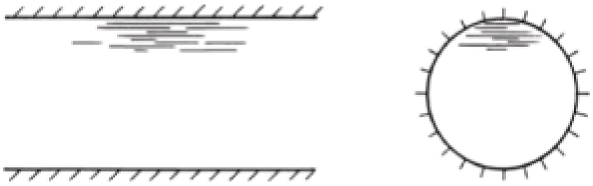

Fig. 1-2. Pipe or pressurized flow

may be free-surface flow at a certain time. Then, due to large inflows produced by a sudden storm, the sewer may flow full and pressurize it. Similarly, the flow in a closed conduit may be free flow in part of the length and pipe flow in the remaining length. This type of combined free-surface, pressurized flow usually occurs in a closed conduit when the downstream end of the conduit is submerged (Fig. 1-3).

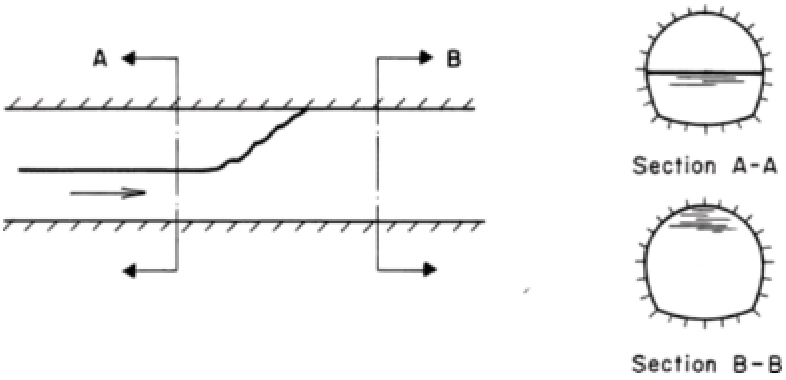

Fig. 1-3. Combined free-surface and pressurized flow

The photographs of Fig. 1-4 show unsteady flow in the 1:84-scale hydraulic model of the tailrace tunnel of Mica Power Plant, located on the Columbia River in Canada. The flow in the two unlined, horseshoe tailrace tunnels, each 18.3 m high and 14.6 m wide, is normally free-surface flow. However, during periods of high tailwater levels, the tunnels may be pressurized following major load changes on the turbogenerators that produce large changes in the inflow to the tunnels. The transient flow conditions shown in Fig. 1-4 are produced by increasing or decreasing in 9 seconds the discharge of three turbines on tunnel no. 2 while the discharge from the three turbines on tunnel no. 1 remains constant. The discharge increase in Fig. 1-4a is from zero to 850 m3/s and the discharge reduction in Fig. 1-4b is from 850 m3/s to zero. The free-surface and pressurized flows in a laboratory experiment are shown in Fig. 1-5. Theinitial steady state flow is from left to right and thus the upstream end is located at the left-hand side of the photographs.

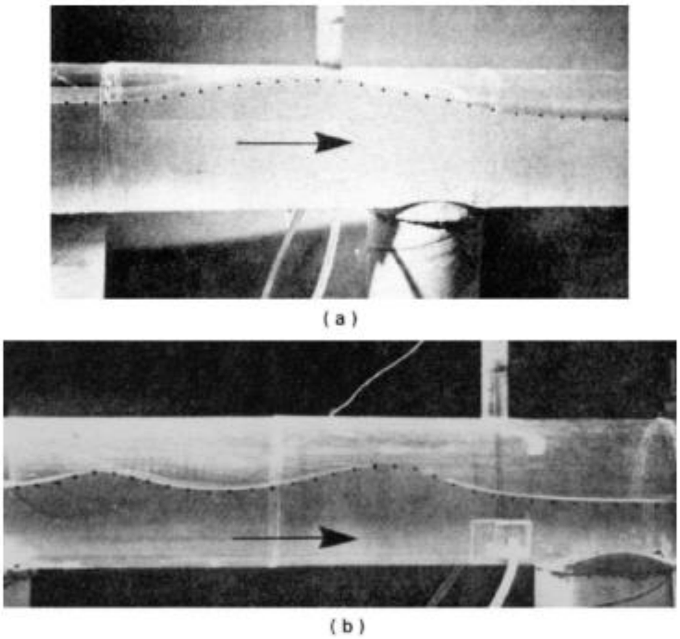

Fig. 1-4. Transient flow in the hydraulic model of Mica Tailrace Tunnel
(Courtesy, British Columbia Hydro and Power Authority, Canada)

The height to which liquid rises in a small-diameter piezometer inserted in a channel or a closed conduit depends upon the pressure at the location of the piezometer. A line joining the top of the liquid surface in the piezometers is called the hydraulic-grade line (Fig. 1-6). In pipe flow, the height of hydraulicgrade line above a specified datum is called the piezometric head at that location. In free-surface flow, the hydraulic grade line usually, but not always, coincides with the free surface (see Section 1-6). If the velocity head, V 2/(2g), in which V = mean flow velocity for the channel cross section, and g = acceleration due to gravity, is added to the top of the hydraulic grade line and the resulting points are joined by a line, then this line is called the energy-grade line. This line represents the total head at different sections of a channel. 1-3 Classification of Flows Based on different criteria, free-surface flows may be classified into various types (Fig. 1-7), as discussed in the following paragraphs.

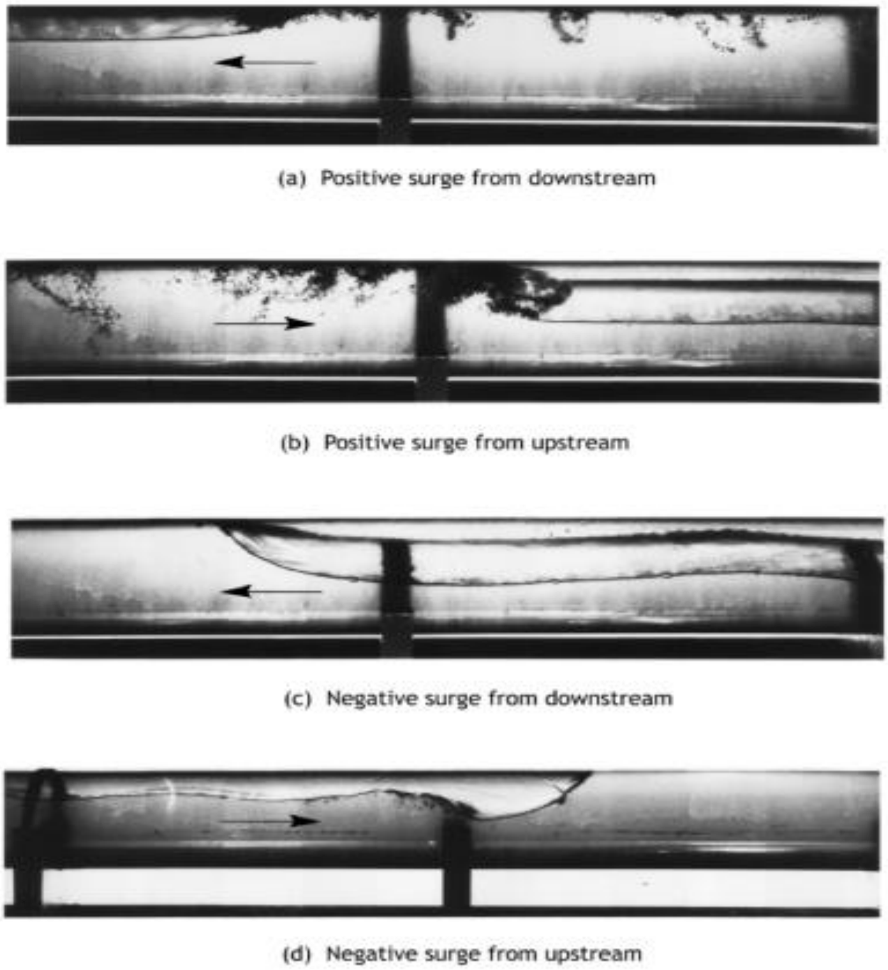

Fig. 1-5. Free-surface and pressurized flows (Courtesy, Professor C. S. Song [1984])

Steady and Unsteady Flows If the flow velocity at a given point does not change with respect to time, then the flow is called steady flow. However, if the velocity at a given location changes with respect to time, then the flow is called unsteady flow.

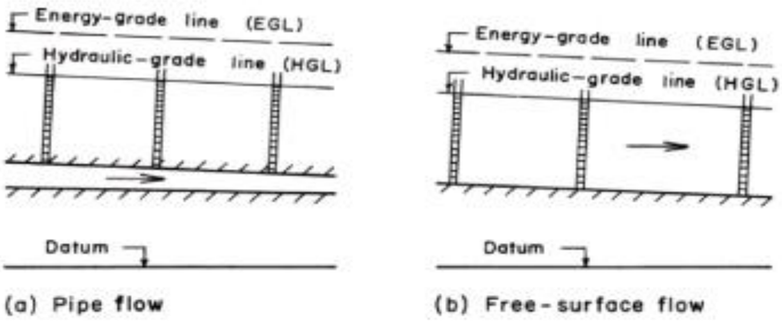

Fig. 1-6. Hydraulic- and energy-grade lines

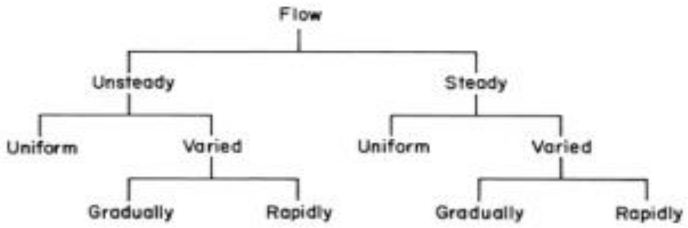

Fig. 1-7. Classification of flows

Note that this classification is based on the time variation of velocity v at a specified location. Thus, the local acceleration, $\partial v/\partial t$, is zero in steady flows. In two- or three-dimensional steady flows, the time variation of all components of velocity is zero. It is possible in some situations to transform unsteady flow into steady flow by having coordinates with respect to a moving reference. This simplification is helpful in the visualization of flow and in the derivation of governing equations. Such a transformation is possible only if the wave shape does not change as the wave propagates. For example, the shape of a surge wave moving in a smooth channel does not change and consequently the propagation of a surge wave in an otherwise unsteady flow may be converted into steady flow by moving the reference coordinates at the absolute surge velocity. This is equivalent to an observer traveling beside the surge wave so that the surge wave appears to the observer to be stationary; thus the flow may be considered as steady. If the wave shape changes as it propagates, then it is not possible to transform such a wave motion into steady flow.

Typical example of such a situation isthe movement of a flood wave in a natural channel, where the shape of the wave is modified as it propagates in the channel. Uniform and Nonuniform flows If the flow velocity at a given instant of time does not vary within a given length of channel, then the flow is called uniform flow. However, if the flow velocity at a time varies with respect to distance, then the flow is called nonuniform flow, or varied flow. This classification is based on the variation of flow velocity with respect to space at a specified instant of time. Thus, the convective acceleration in uniform flow is zero. In mathematical terms, the partial derivatives of the velocity components with respect to x, y, and z direction are all zero. However, many times this strict restriction is somewhat relaxed by allowing a nonuniform velocity distribution at a channel section. In other words, a flow is considered uniform as long as the velocity in the direction of flow at different locations along a channel remains the same. Depending upon the rate of variation with respect to distance, flows may be classified as gradually varied flow or rapidly varied flow. As the name implies, the flow is called gradually varied flow, if the flow depth varies at a slow rate with respect to distance, whereas the flow is called rapidly varied flow if the flow depth varies significantly in a short distance. Note that the steady and unsteady flows are characterized by the variation with respect to time at a given location, whereas uniform or varied flows are characterized by the variation at a given instant of time with respect to distance. Thus, in a steady, uniform flow, the total derivative $dV/dt = 0$. In one-dimensional flow, this means that $\partial v/\partial t = 0$, and $\partial v/\partial x = 0$. In two- and three-dimensional flow, the partial derivatives of the velocity components in the other two coordinate directions with respect to time and space are also zero.