IV. BASIC CONCEPTS OF OPEN-CHANNEL FLOW

4.1 Introduction

Understanding the basic concepts of open-channel flow is necessary to properly design the channels required on surface mine operations. In open-channel flow, the water surface is not confined. Surface configuration, flow pattern and pressure distribution within the flow depend on gravity. In rigid-boundary open-channel flow, no deformations or movements of the bed and banks are considered, whereas in mobile-boundary hydraulics the bed configuration depends on the flow. Discussions in this chapter pertain primarily to rigid-boundary open-channel flow, since they are most applicable to diversion channel design in the Eastern Coal Province. Part II presents the movable boundary hydraulics necessary for diversion channel design in sandy soils. For greater detail than what is presented here, refer to any basic fluid mechanics textbook.

4.2 Parameters Describing the Hydraulics of Open-Channel Flow

4.2.1 General

All variables used in fluid mechanics and hydraulics fall into one of three classes: those describing the boundary geometry, those describing the flow, and those describing the fluid (Rouse, 1976). Various combinations of these variables define parameters that describe the state of flow in open channels. Understanding these variables and parameters is necessary background knowledge to future discussions of equations and formulas applicable to open-channel flow. Some of the more common variables and parameters are defined below.

4.2.2 Variables Describing the Boundary Geometry

1. Depth of Flow: The depth of flow d is defined as the perpendicular distance from the bed of the stream to the water surface. For channels on mild slopes the depth of flow is often approximated by the vertical distance from the bed.

2. Stage: The stage h is the vertical distance from any selected and defined datum to the water surface.

3. Top Width: The top width T is the width of a stream section at the water surface and it varies with stage in most natural channels.

4. <u>Cross-Sectional Area</u>: The cross-sectional area A is the area of a cross section of the flow normal to the direction of flow.

5. <u>Wetted Perimeter</u>: The wetted perimeter P is the length of wetted cross section normal to the direction of flow.

6. <u>Hydraulic Radius</u>: The hydraulic radius R is the ratio of the cross-sectional area to wetted perimeter,

$$R = A/P \tag{4.1}$$

7. <u>Hydraulic Depth</u>: The hydraulic depth d_h is the ratio of the cross-sectional area to the top width,

$$d_h = A/T \tag{4.2}$$

8. <u>Water Surface Slope</u>: The slope of the water surface or hydraulic gradient is denoted by S_w.

9. <u>Slope of the Energy Grade Line</u>: The energy grade line is a graphical representation with respect to a selected datum of the total head or energy possessed by the fluid. For an open channel, the energy gradient is located a distance $V^2/2g$ above the free water surface. The slope of the energy grade line is designated by the symbol S_f or S_E.

10. <u>Bed Slope</u>: The bed slope S_b is the longitudinal slope of the channel bed.

General formulas for determining area, wetted perimeter, hydraulic radius, and top width in trapezoidal, rectangular, triangular, circular, and parabolic sections are given in Table 4.1 (Soil Conservation Service, 1954).

4.2.3 Variables Describing the Flow

1. <u>Discharge</u>: The discharge Q is the volume of a fluid or solid passing a cross section of a stream per unit time.

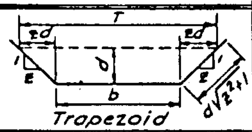
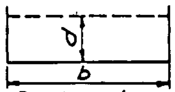
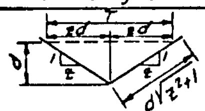
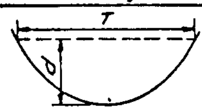
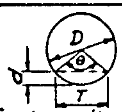
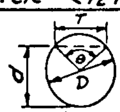
2. <u>Mean Velocity</u>: The mean velocity $V = Q/A$ is the discharge divided by the area of the water cross section.

3. <u>Drag Force</u>: The drag force F_d is the force component exerted by a moving fluid on any object submerged in the fluid. The direction of the force is the same as that of the free stream of fluid.

4. <u>Lift Force</u>: The lift force F_L is the force component exerted on a body submerged in a moving turbulent fluid. The force acts in the direction normal to the free stream of fluid.

5. <u>Shear Force</u>: The shear force is the shear developed on the wetted area of the channel and it acts in the direction of flow. This force per unit wetted area is called the shear stress τ_o and can be expressed as

Table 4.1. Elements of Channel Sections (from Soil Conservation Service, 1954).

Section	Area a	Wetted Perimeter p	Hydraulic Radius r	Top Width T
 Trapezoid	$bd+zd^2$	$b+2d\sqrt{z^2+1}$	$\frac{bd+zd^2}{b+2d\sqrt{z^2+1}}$	$b+2zd$
 Rectangle	bd	$b+2d$	$\frac{bd}{b+2d}$	b
 Triangle	zd^2	$2d\sqrt{z^2+1}$	$\frac{zd}{2\sqrt{z^2+1}}$	$2zd$
 Parabola	$\frac{2}{3}dT$	$T+\frac{8d^2}{3T}$ [1]	$\frac{2dT^2}{3T^2+8d^2}$ [1]	$\frac{3a}{2d}$
 Circle - < ½ full [2]	$\frac{D^2}{8}\left(\frac{\pi\theta}{180}-\sin\theta\right)$	$\frac{\pi D\theta}{360}$	$\frac{45D}{\pi\theta}\left(\frac{\pi\theta}{180}-\sin\theta\right)$	$D\sin\frac{\theta}{2}$ or $2\sqrt{d(D-d)}$
 Circle - > ½ full [3]	$\frac{D^2}{8}\left(2\pi-\frac{\pi\theta}{180}+\sin\theta\right)$	$\frac{\pi D(360-\theta)}{360}$	$\frac{45D}{\pi(360-\theta)}\left(2\pi-\frac{\pi\theta}{180}+\sin\theta\right)$	$D\sin\frac{\theta}{2}$ or $2\sqrt{d(D-d)}$

[1] Satisfactory approximation for the interval $0 < \frac{d}{T} \leq 0.25$
When $d/T > 0.25$, use $p = \frac{1}{2}\sqrt{16d^2+T^2} + \frac{T^2}{8d}\sinh^{-1}\frac{4d}{T}$

[2] $\theta = 4\sin^{-1}\sqrt{d/D}$ } Insert θ in degrees in above equations
[3] $\theta = 4\cos^{-1}\sqrt{d/D}$ }

$$\tau_o = \gamma RS \qquad (4.3)$$

where γ is the specific weight, R is the hydraulic radius, and S is a representative slope.

4.2.4 Variables Describing the Fluid

1. Density: The density ρ ($kg\text{-}sec^2/m^4$ or $lb\text{-}sec^2/ft^4$) of a fluid or solid is the mass that possesses per unit volume. Both the density of the water-sediment mixture and the density of sediment are important variables.

2. Specific Weight: The specific weight γ (kg/m^3, T/m^3, lb/ft^3) is the weight per unit volume. It is related to the density by

$$\gamma = \rho g \qquad (4.4)$$

where g is the gravitational acceleration in m/sec^2, ft/sec^2.

3. Specific Gravity: The specific gravity G_s is the ratio of the specific weight of a fluid, solid or fluid-solid mixture, to the specific weight of water at 4° C or 39.2° F.

4. Viscosity: Viscosity is the property of a fluid that resists relative motion and deformation in the fluid and causes internal shear. Therefore, viscosity is a property exhibited only under dynamic conditions. According to Newton, the shear τ at a point within a fluid is proportional to the velocity gradient du/dy at that point or

$$\tau = \mu \frac{du}{dy} \qquad (4.5)$$

where μ, in $kg\text{-}sec/m^2$ or $lb\text{-}sec/ft^2$, is the dynamic viscosity. When divided by the density ρ, it is the kinematic viscosity $\nu = \mu/\rho$ in m^2/sec or ft^2/sec. Under ordinary conditions of pressure, viscosity varies only with temperature. The viscosity of a liquid decreases with increasing temperature; the reverse is true for gasses.

4.2.5 Parameters Describing Open-Channel Flow

1. Reynolds Number: The Reynolds number is

$$R_e = \frac{VL}{\nu} \qquad (4.6)$$

where V is the velocity, L is a characteristic length and ν is the kinematic viscosity. The Reynolds number relates the inertia forces to the viscous forces and is usually involved wherever viscosity is important, such as in slow movement of fluid in small passages or around small objects.

2. Froude Number: The Froude number is

$$F_r = \frac{V}{\sqrt{gL}} \qquad (4.7)$$

where g is the gravitational acceleration. The Froude number relates the inertia forces to the gravitational effects and is important wherever the gravity effect is dominating, such as with water waves, flow in open channels, sedimentation in lakes and reservoirs, salt water intrusions, and the mixing of air masses of different specific weights. If the Froude number is less than one, equal to zero, or greater than one, the flow is defined as subcritical, critical and supercritical, respectively. Additionally, if the Froude number is less than one, the slope is considered hydraulically mild and when it is greater than one it is considered hydraulically steep.

4.2.6 Parameters Describing Boundary Roughness Conditions

1. Relative Roughness: The relative roughness is

$$k/R \qquad (4.8)$$

where k is the height of the roughness element and R is the hydraulic radius. The inverse of the relative roughness is often encountered in resistance formulas.

2. Particle Size: The boundary of a natural earthen channel or a rock riprap channel is composed of a variety of particle sizes. The size distribution of these particles is often measured and expressed as the particle diameter for which a given percentage of the mixture is finer. For example, the D_{50} is a common measure of the representative particle size of the channel and it is equal to the minimum diameter for which 50 percent of the sediment mixture is finer.

4.3 Governing Equations

In rigid-boundary open-channel flow the equations of continuity, energy and momentum govern all flow processes. For diversion channel design the continuity and energy equations are most often applied.

The continuity equation in its simplest form is

$$Q = V_1A_1 = V_2A_2 \qquad (4.9)$$

where Q is the discharge in cfs and V is the mean velocity in the cross section of area A for locations 1 and 2. This equation applies only to steady, two-dimensional, incompressible flow. These conditions are assumed to exist in most open-channel design procedures.

The most common form of the energy equation for open-channel flow is the Bernoulli equation

$$\frac{V_1^2}{2g} + \frac{P_1}{\gamma} + Z_1 = \frac{V_2^2}{2g} + \frac{P_2}{\gamma} + Z_2 + h_L \quad (4.10)$$

where V is the mean velocity, P is the hydrostatic pressure and Z is the elevation of the channel bed (relative to datum) at sections 1 and 2. The head loss term h_L represents the loss of energy by friction from Sections 1 to 2. The terms of the Bernoulli equation are commonly referred to as the velocity head, pressure head and elevation head, respectively.

The important concepts of the energy grade line and hydraulic grade line are encompassed in the Bernoulli equation. The energy grade line was defined in Section 4.2.2, item 10, as a graphical representation of the total energy possessed by the flow. Therefore, at any section the elevation of the energy grade line (EGL) relative to a datum is

$$\text{EGL} = \frac{V^2}{2g} + \frac{P}{\gamma} + Z \quad (4.11)$$

From Section 1 to Section 2 the energy grade line slopes downward by an amount equal to the head loss h_L between the two sections.

The hydraulic grade line lies below the energy line a distance equal to the velocity head. Therefore, the elevation of the hydraulic grade line (HGL) at any section is

$$\text{HGL} = \frac{P}{\gamma} + Z \quad (4.12)$$

which is simply the water-surface elevation relative to a datum. These concepts are illustrated in Figure 4.1.

In many cases the objective of hydraulic computations in open channels is to determine the curve of the water surface. These problems involve three general relationships between the hydraulic gradient and the energy gradient. For uniform flow the hydraulic gradient and the energy gradient are parallel and the hydraulic gradient becomes an adequate basis for the determination of friction loss, since no conversion between kinetic and potential energy is involved. In accelerated flow where velocity is increasing in the downslope direction, the hydraulic gradient is steeper than the energy gradient. This flow condition typically exists in steep slope diversions. In retarded flow

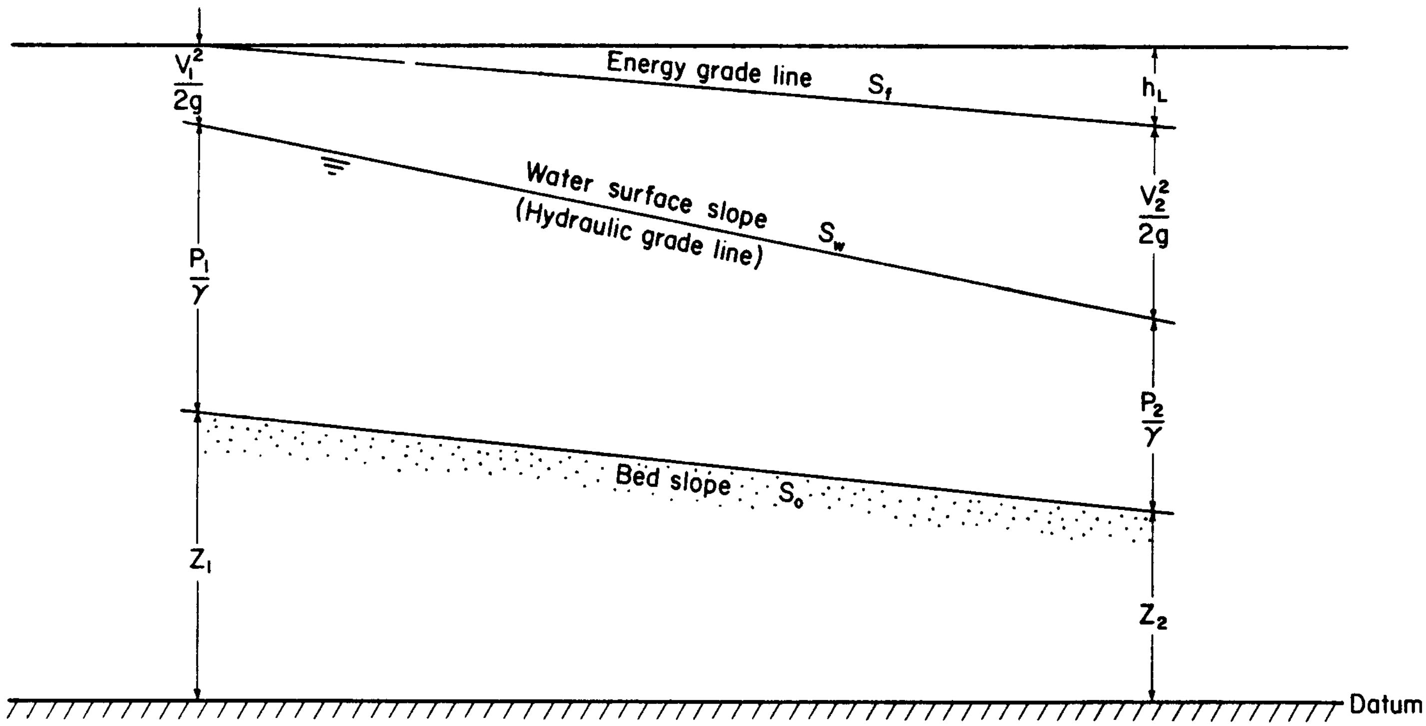


Figure 4.1. Definition sketch of the energy and hydraulic grade lines in open-channel flow.

where velocity is decreasing in the downslope direction, the energy gradient is steeper than the hydraulic gradient. An adequate anlaysis of flow under both these conditions cannot be made without consideration of both the energy and the hydraulic gradient.

4.4 Steady and Uniform Flow Formulas for Open Channels - The Manning Equation

Many formulas have been proposed to determine the mean characteristics of flow. However, the Manning relation remains the most commonly used. The Manning Equation in English units is

$$V = \frac{1.49}{n} R^{2/3} S^{1/2} \qquad (4.13)$$

where n is defined as the Manning roughness coefficient with the dimension $L^{1/6}$. Since the flow rate (discharge) of a stream is defined by the continuity equation as

$$Q = VA \qquad (4.9)$$

where Q is the discharge, V is the mean velocity and A is the cross-sectional area normal to the flow, the Manning equation can be expressed as

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2} \qquad (4.14)$$

Because of simplicity of form and satisfactory results for practical applications, the Manning formula has become one of the most widely used of all open-channel uniform-flow formulas.

The depth of a uniform flow in an open channel is the normal depth. Although uniform flow seldom occurs in nature, most hydraulic computations are simplified and approximated by assuming uniform flow conditions. Therefore, the Manning Equation must often be solved for the normal depth d. However, since both velocity (or discharge) and the hydraulic radius depend on the flow depth, the equation cannot be directly solved for the normal depth. Many charts and nomographs have been developed to solve the Manning equation. Additionally, procedures have been developed for small programmable calculators providing efficient solution. Charts given in Appendix C provide solution of the Manning equation for trapezoidal channels of 2:1 side slope and bottom widths of 2, 4, 6, 8, 10, 12 and 14 feet. For additional charts see

"Design Charts for Open Channel Flow" by the U.S. Department of Transportation (1979).

4.5 Resistance to Flow

The three most common parameters for describing the resistance to steady uniform flow are:

1. The Darcy-Weisbach friction factor, f
2. The Manning roughness coefficient, n
3. The Chezy resistance factor, C

A study of friction factors in open channels by the ASCE Task Force Committee (1963) provided specific recommendations on the use of these three resistance parameters. The results of the study are summarized below.

The Darcy-Weisbach f has great utility in expressing resistance to steady, fully developed flow in uniform channels. Experimental measurements of friction in open channels over a wide range of conditions appear to be better correlated and understood through the use of f. Additionally, f is commonly used in other branches of engineering, particularly closed conduit flow, and therefore provides a basis for pooling all experience and knowledge on frictional resistance. The friction factor f may be defined from

$$S = \frac{f}{4R}\,\frac{V^2}{2g} \tag{4.15}$$

where S is the slope of the hydraulic gradeline and channel bed, R is the hydraulic radius, V is the mean velocity and g is the acceleration of gravity. The dimensionless friction factor f depends on the Reynolds number and bed roughness, and therefore must be evaluated separately for each open-channel flow condition. The relationships between f, n and C are

$$C = \sqrt{\frac{8g}{f}} \tag{4.16}$$

$$n = 1.49\, R^{1/6} \sqrt{\frac{f}{8g}} \qquad \text{(English units)} \tag{4.17}$$

The Manning n has traditionally been widely used to evaluate resistance in open-channel flows. The ASCE report indicates that, when applied with judgment, n and f are probably equally effective in the solution of practical problems. The following recommendations were given for obtaining specific values of f or n for design purposes:

1. For roughnesses typical of those found in pipe flow (i.e. concrete), pipe resistance diagrams (i.e. Moody-type diagram) may be used to estimate f if the pipe diameter D is replaced by 4R.

2. For roughnesses found in unlined channels and for high Reynolds numbers, f (as defined by Equation 4.11) is independent of the Reynolds number and depends only on the hydraulic radius, R. Under these conditions f is nearly proportional to $1/R^{1/3}$, and Manning's n (as defined by Equation 4.13) is nearly constant. For this "fully rough" condition the constant values of Manning's n can be taken from the literature, such as Chow's book (1959). A detailed listing of values applicable to surface mine conditions in OSM Regions I and II is given in Appendix C. A shorter listing of values is given in Table 4.2. If desired, the value of f may then be computed. (It should be noted that not all turbulent flows are "fully rough.")

3. For other than fully rough flow, f or n may be larger or smaller than for the fully rough case. Therefore, caution should be used when using the Manning formula and n to insure that fully rough conditions exist.

4. For movable boundary conditions none of the formulas or methods discussed apply. However, the concept of expressing resistance with a friction factor is still valid. For a movable boundary condition, the fixed-bed friction factor may be increased by the bed form (pattern) that develops or decreased by the sediment carried in suspension. The final estimate of roughness relies greatly on individual judgment. Simons and Senturk (1976) review some of the available methods for estimating roughness in a movable boundary.

For most situations encountered in diversion channel design, the Manning n is the easiest and most appropriate estimate of flow resistance. A useful formula for evaluating n based on data from laboratory channels to large rivers is (Highway Research Board, 1970)

$$n = 0.0395\, D_{50}^{1/6} \tag{4.18}$$

where D_{50} is in feet. Grain sizes used in developing this formula ranged from 0.001 ft to nearly 1.0 ft.

4.6 Selection of Channel Cross Section

Typical channel cross sections are triangular, trapezoidal and parabolic (see Table 4.1). A triangular channel is a special type of trapezoidal with a bottom width of zero, and their application is limited to relatively low flow conditions. Trapezoidal channels of varying bottom widths and side slopes are

Table 4.2. Manning's Coefficients of Channel Roughness.

Constructed Channel Condition	Values of n		
	Minimum	Maximum	Average
Earth channels, straight and uniform	0.017	0.025	0.0225
Dredged earth channels	0.025	0.033	0.0275
Rock channels, straight and uniform	0.025	0.035	0.033
Rock channels, jagged and irregular	0.035	0.045	0.045
Concrete lined, regular finish	0.012	0.018	0.014
Concrete lined, smooth finish	0.010	0.013	--
Grouted rubble paving	0.017	0.030	--
Corrugated metal	0.023	0.025	0.024

Natural Channel Condition	Value of n
Smoothest natural earth channels, free from growth with straight alignment.	0.017
Smooth natural earth channels, free from growth, little curvature.	0.020
Average, well-constructed, moderate-sized earth channels in good condition.	0.0225
Small earth channels in good condition, or large earth channels with some growth on banks or scattered cobbles in bed.	0.025
Earth channels with considerable growth, natural streams with good alignment and fairly constant section, or large floodway channels well maintained.	0.030
Earth channels considerably covered with small growth, or cleared but not continuously maintained floodways.	0.035
Mountain streams in clean loose cobbles, rivers with variable cross section and some vegetation growing in banks, or earth channels with thick aquatic growths.	0.050

Table 4.2 (continued)

Natural Channel Condition	Value of n
Rivers with fairly straight alignment and cross section, badly obstructed by small trees, very little underbrush or aquatic growth.	0.075
Rivers with irregular alignment and cross section, moderately obstructed by small trees and underbrush.	0.100
Rivers with fairly regular alignment and cross section, heavily obstructed by small trees and underbrush.	0.100
Rivers with irregular alignment and cross section, covered with growth of virgin timber and occasional dense patches of bushes and small trees, some logs and dead fallen trees.	0.125
Rivers with very irregular alignment and cross section, many roots, trees, large logs, and other drift on bottom, trees continually falling into channel due to bank caving.	0.200

the most commonly constructed channels. Parabolic channels are generally used only when a vegetated lining is required, although other cross sections are also used in vegetated channels.

The selection of the channel sideslope largely depends on the angle of repose of the parent material or channel lining. The angle of repose is the slope angle formed by particulate material under the critical equilibrium condition of incipient sliding (Simons and Senturk, 1977). For a stable channel the side slope must be smaller than the angle of repose. If θ is the side slope angle of the channel design and ϕ is the angle of repose, then a general relation for the maximum side slope angle for a stable channel is $\theta \leq \phi - 5$ (degrees). The relationship between the side slope angle θ and the side slope value z is depicted in Figure 4.2. Table 4.3 lists suggested z values to be used in designing channels. For channels lined with riprap, the angle of repose can be determined from Figure 4.3. In this case, the suggested value for z must be less than the angle of repose of the riprap.

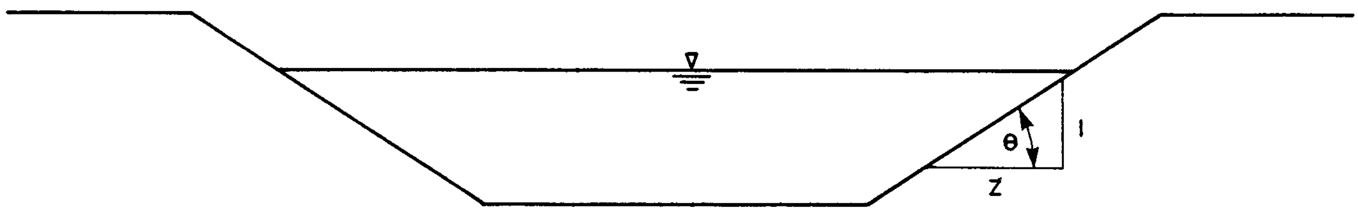
The selection of the channel bottom width for trapezoidal channels depends on the hydraulic conditions and the available equipment for construction. Specific guidelines or recommendations for selection of the channel cross section are given in later sections.

4.7 Variances in Flow Conditions

In open-channel flow, problems have been encountered with maintaining the flow within the designed channel, that is, the flow overtops the channel lining, resulting in serious erosion problems and possible failure. Many of these problems can be prevented when design consideration is given to (1) centrifugal forces that occur where the channel is turned and (2) additional channel depth to account for debris accumulation or variance in construction that results in differences in roughness coefficients. These two design concepts are known as superelevation and freeboard. For smaller channels the freeboard is often sufficient to account for centrifugal forces and superelevation need not be considered.

4.7.1 Superelevation

Because of the change in flow direction that results in centrifugal forces, there is a superelevation of the water surface in river bends (Figure 4.4). The water surface is higher at the concave bank and lower at the convex



$$\tan \theta = \frac{1}{z}$$

Figure 4.2. Relationship between side slope value, z and slope angle, Θ.

Table 4.3. Suggested Sideslope z Values.

Nature of Bank Material	z
Rock	0.2
Smooth or weathered rock, shell	0.5 ~ 1.0
Soil (clay, silt and sand mixtures)	1.5
Sandy soil	1.5
Silt and loam (loose sandy earth)	2
Fine sand	3
Flowing fine and other very fine material	>3
Compacted clay	1.5

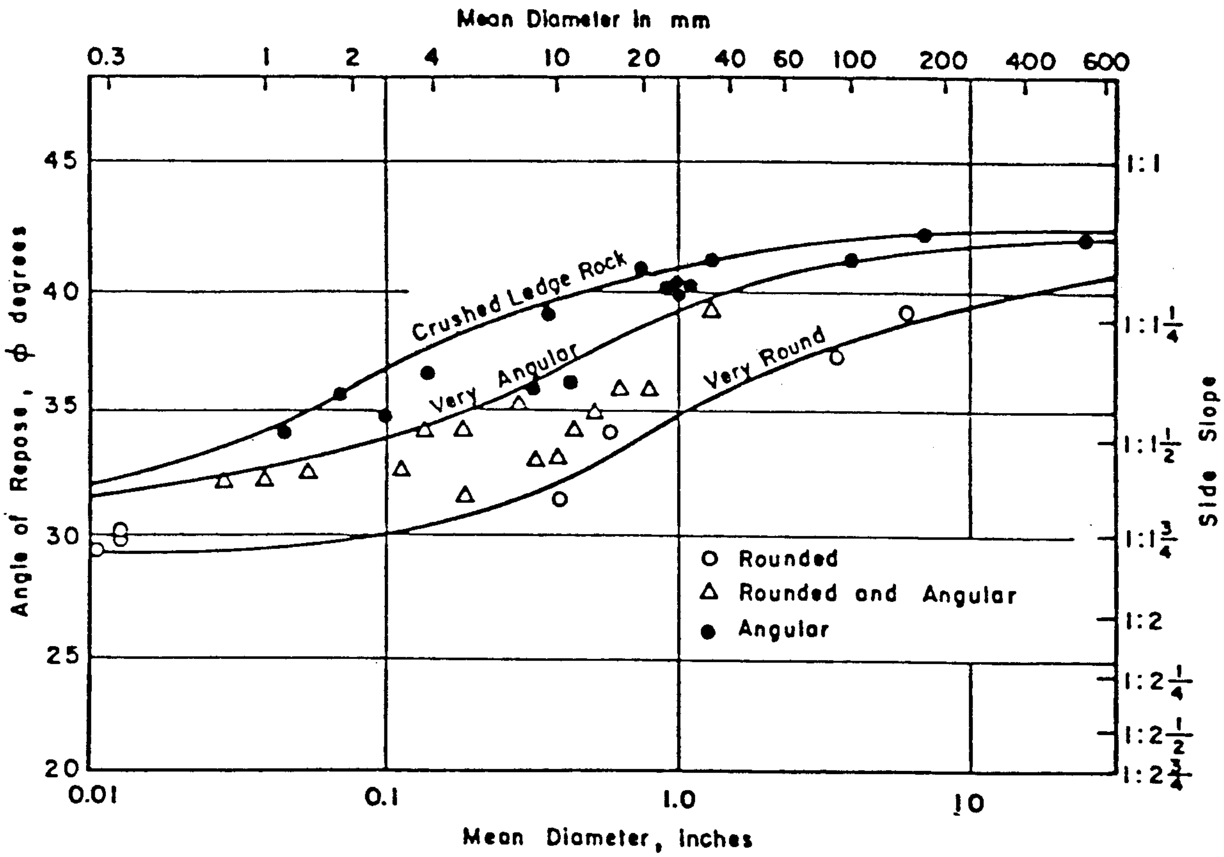


Figure 4.3. Angle of repose.

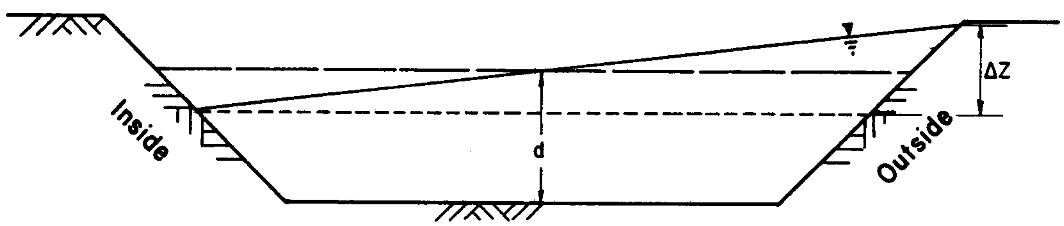


Figure 4.4. Definition sketch of superelevation in a channel bend.

bank than what the water surface would be under uniform conditions. The resulting transverse slope can be evaluated quantitatively. Several different equations have been proposed for evaluating superelevation. However, the differences between results by using the various equations is not significant. Therefore, one of the simpler procedures is suggested. Woodward (1920) assumed V equal to the average velocity Q/A and r equal to the radius to the center of the stream r_c and obtained

$$\Delta Z = Z_o - Z_i = \frac{V^2}{gr_c}(r_o - r_i) \qquad (4.19)$$

in which Z_i and r_i are the water surface elevation and the radius at the inside of the bend, and Z_o and r_o are the water surface elevation and the radius at the outside of the bend. The value $(r_o - r_i)$ can be taken as the top width W of the channel.

4.7.2 Freeboard

Freeboard is the vertical distance from the water-surface elevation of the design flow to the top of the channel. Freeboard is used as a safety measure to prevent overtopping as a result of sedimentation, additional depth due to a rougher friction coefficient than used in the design, or wave action. The freeboard for a channel will depend on a number of factors such as size of channel, velocity of water, channel curvature, and transition conditions. In normal channel designs, the wave action due to wind is not usually significant. Freeboard is commonly defined as a percentage of the depth of flow. The Soil Conservation Service (1977) recommends that freeboard for trapezoidal channels at subcritical flow (mild slope) should be equal to or greater than 20 percent of the flow depth at the design discharge, but not less than one foot. For supercritical flow (steep slope) the recommended value is 25 percent of flow depth. These values are in addition to any other increase in channel depth required for superelevation or extremely turbulent flow. Therefore, for riprap-lined channels using large rock, the values should be greater due to anticipated turbulent flow conditions. The recommended freeboard for diversion channels on a surface mine operation is

$$F.B. = c_{fb}d + \frac{1}{2}\Delta Z \qquad (4.20)$$

where c_{fb} is a coefficient defined according to Table 4.4 and ΔZ is defined in Figure 4.4. In all cases the recommended minimum freeboard is 1.0 foot (Soil Conservation Service minimum) plus one-half superelevation. The 1.0 foot minimum is greater than the 0.3 feet minimum specified in OSM Regulations. However, the regulations state that if necessary, the design freeboard may be increased by the regulatory authority. In this manual it is recommended that the 1.0 foot minimum be adopted.

4.8 Example

Given the design flow computed by the SCS TP-149 method in the example of Section 3.4, determine the following:

1. If the flow passes through a 14-foot trapezoidal channel of 2:1 side slopes, bottom slope of ten percent, on a cobble bed with $D_{50} = 1.5$ inches, what is the flow depth?

$$n = 0.0395\ (1.5/12)^{1/6} \qquad \text{Equation 4.18}$$

$$n = 0.028$$

$$Qn = 114\ (0.028) = 3.18$$

Therefore from Appendix C charts $d = 0.70$ feet and

$$Vn = 0.33, \quad V = \frac{Vn}{n} = 11.8 \text{ fps}$$

2. What is the Froude number?

$$Fr = \frac{V}{\sqrt{gL}} \qquad \text{Equation 4.6}$$

where the characteristic length L is usually taken as the flow depth. Therefore,

$$Fr = \frac{11.8}{\sqrt{32.2(0.70)}} = 2.5$$

Since the Froude number is greater than 1 the flow is supercritical and the slope condition is hydraulically steep (see Section 4.2.5).

3. If the channel contains a bend with an inside radius of 50 feet and an outside radius of 65 feet, what is the superelevation?

$$\Delta Z = \frac{V^2}{g r_c}\ (r_o - r_i) \qquad \text{Equation 4.19}$$

Table 4.4. Freeboard Coefficients.

Flow Condition	Minimum Freeboard Coefficient (c_{fb})
Subcritical (mild slope), unlined or vegetation-lined	0.20
supercritical (steep slope), unlined or vegetation-lined	0.25
subcritical (mild slope), rock riprap-lined	0.25
supercritical (steep slope), rock riprap-lined	1.00

Therefore

$$\Delta Z = \frac{(11.8)^2}{32.2(57.5)} (65-50) = 1.1 \text{ ft}$$

4. What are the freeboard requirements?

a. For supercritical flow, Table 4.4 gives

$C_{fb} = 0.25$

$0.25(d) = 0.25\ (0.70) = 0.18 < 1.0$ ft; use 1.0 ft

$F.B. = 0.25(d) + \frac{1}{2}\Delta Z = 1.0 + 0 = 1.0$ Equation 4.20

b. In the channel bend?

$F.B. = 1.0 + \frac{1}{2}(1.1) = 1.55$ ft

4.9 References

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