very satisfactorily from the hydraulics point of view. For all combinations of Fr_1 and water surface elevation in the downstream channel, the jump would always form on the sloping apron. However, its main drawback is cost of construction. Construction costs will be reduced as the length, L, of the stilling basin is reduced. Much research has been devoted to the design of stilling basins that will operate properly for all upstream and downstream conditions and yet be relatively short to reduce construction cost. Research by the U.S. Bureau of Reclamation (13) has resulted in sets of standard designs that can be used. These designs include sills, baffle piers, and chute blocks, as shown in Fig. 15.28.

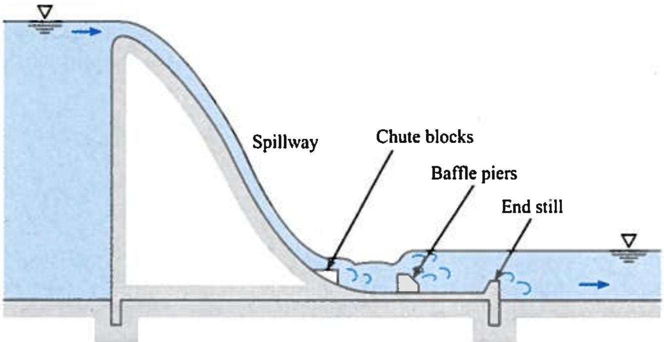


FIGURE 15.28 Spillway with stilling basin Type III as recommended by the USBR (13).

Naturally Occurring Hydraulic Jumps

Hydraulic jumps can occur naturally in creeks and rivers, providing spectacular standing waves, called rollers. Kayakers and white-water rafters must exercise considerable skill when navigating hydraulic jumps because the significant energy loss that occurs over a short distance can be dangerous, potentially engulfing the boat in turbulence. A special case of hydraulic jump, referred to as a submerged hydraulic jump, can be deadly to white-water enthusiasts because it is not easy to see. A **submerged hydraulic jump** occurs when the downstream depth predicted by conservation of momentum is exceeded by the tailwater elevation, and the jump cannot move upstream in response to this disequilibrium because of a buried obstacle [see Valle and Pasternak (14)]. Thus, the visual markers of a hydraulic jump, particularly the rolling waves depicted in Figs. 15.23 and 15.24, are hidden.

A **surge**, or **tidal bore**, is a moving hydraulic jump that may occur for a high tide entering a bay or river mouth. Tides are generally low enough that the waves they produce are smooth and nondestructive. However, in some parts of the world the tides are so high that their entry into shallow bays or mouths of rivers causes a surge to form. Surges may be very hazardous to small boats. The same analytical methods used for the jump can be used to solve for the speed of the surge.

15.7 Gradually Varied Flow

For gradually varied flow, channel resistance is a significant factor in the flow process. Therefore, the energy equation is invoked by comparing S_0 and S_f.

Basic Differential Equation for Gradually Varied Flow

There are a number of cases of open-channel flow in which the change in water-surface profile is so gradual that it is possible to integrate the relevant differential equation from one section to another to obtain the desired change in depth. This may be either an analytical integration or, more commonly, a numerical integration. In Section 15.2, the energy equation was written between two sections of a channel Δx distance apart. Because the only head loss here is the channel resistance, the h_L is given by Δh_f, and Eq. (15.7) becomes

$$y_1 + \frac{V_1^2}{2g} + S_0\,\Delta x = y_2 + \frac{V_2^2}{2g} + \Delta h_f \tag{15.44}$$

The friction slope S_f is defined as the slope of the EGL, or $\Delta h_f/\Delta x$. Thus $\Delta h_f = S_f\Delta x$, and defining $\Delta y = y_2 - y_1$, then

$$\frac{V_2^2}{2g} - \frac{V_1^2}{2g} = \frac{d}{dx}\left(\frac{V^2}{2g}\right)\Delta x \tag{15.45}$$

Therefore, Eq. (15.44) becomes

$$\Delta y = S_0\Delta x - S_f\Delta x - \frac{d}{dx}\left(\frac{V^2}{2g}\right)\Delta x$$

Dividing through by Δx and taking the limit as Δx approaches zero gives us

$$\frac{dy}{dx} + \frac{d}{dx}\left(\frac{V^2}{2g}\right) = S_0 - S_f \tag{15.46}$$

The second term is rewritten as $[d(V^2/2g)/dy]\,dy/dx$, so that Eq. (15.46) simplifies to

$$\frac{dy}{dx} = \frac{S_0 - S_f}{1 + d(V^2/2g)/dy} \tag{15.47}$$

To put Eq. (15.47) in a more usable form, the denominator is expressed in terms of the Froude number. This is accomplished by observing that

$$\frac{d}{dy}\left(\frac{V^2}{2g}\right) = \frac{d}{dy}\left(\frac{Q^2}{2gA^2}\right) \tag{15.48}$$

After differentiating the right side of Eq. (15.48), the equation becomes

$$\frac{d}{dy}\left(\frac{V^2}{2g}\right) = \frac{-2Q^2}{2gA^3}\cdot\frac{dA}{dy}$$

But $dA/dy = T$ (top width), and $A/T = D$ (hydraulic depth); therefore,

$$\frac{d}{dy}\left(\frac{V^2}{2g}\right) = \frac{-Q^2}{gA^2D}$$

or

$$\frac{d}{dy}\left(\frac{V^2}{2g}\right) = -\mathrm{Fr}^2$$

Hence, when the expression for $d(V^2/2g)/dy$ is substituted into Eq. (15.47), the result is

$$\frac{dy}{dx} = \frac{S_0 - S_f}{1 - \mathrm{Fr}^2} \tag{15.49}$$

This is the general differential equation for gradually varied flow. It is used to describe the various types of water-surface profiles that occur in open channels. Note that, in the derivation of the equation, S_0 and S_f were taken as positive when the channel and energy grade line respectively, were sloping downward in the direction of flow. Also note that y is measured fro the bottom of the channel. Therefore, $dy/dx = 0$ if the slope of the water surface is equal to tl slope of the channel bottom, and dy/dx is positive if the slope of the water surface is less tha the channel slope.

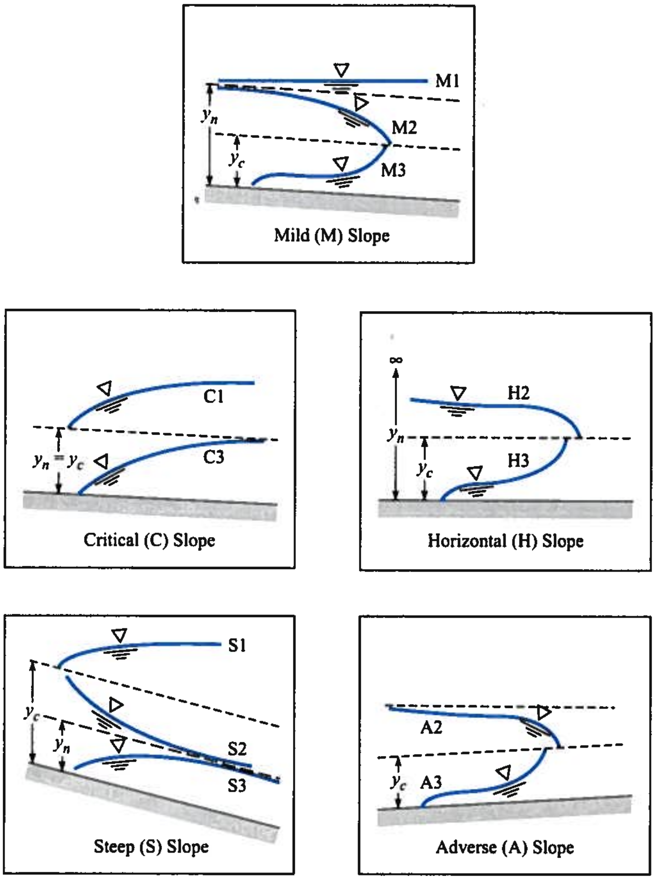
Introduction to Water-Surface Profiles

In the design of projects involving the flow in channels (rivers or irrigation canals, for example the engineer must often estimate the **water-surface profile** (elevation of the water surfa along the channel) for a given discharge. For example, when a dam is being designed for a riv project, the water-surface profile in the river upstream must be defined so that the proje planners will know how much land to acquire to accommodate the upstream pool. The fir step in defining a water-surface profile is to locate a point or points along the channel whe the depth can be computed for a given discharge. For example, at a change in slope from mi to steep, critical depth will occur just upstream of the break in grade (see Fig. 15.32). At th point one can solve for y_c with Eq. (15.25) or (15.27). Also, for flow over the spillway of a dar there will be a discharge equation for the spillway from which one can calculate the wate surface elevation in the reservoir at the face of the dam. Such points where there is a uniqu relationship between discharge and water-surface elevation are called **controls**. Once tl water-surface elevations at these controls are determined, then the water-surface profile ca be extended upstream or downstream from the control points to define the water-surface pr file for the entire channel. The completion of the profile is done by numerical integratio However, before this integration is performed, it is usually helpful for the engineer to sketch the profiles. To assist in the process of sketching the possible profiles, the engineer can refer different categories of profiles (water-surface profiles have unique characteristics dependir on the relationship between normal depth, critical depth, and the actual depth of flow in tl channel). This initial sketching of the profiles helps the engineer to scope the problem and obtain a solution, or solutions, in a minimum amount of time. The next section describes tl various types of water-surface profiles.

Types of Water-Surface Profiles

There are 12 different types of water-surface profiles for gradually varied flow in channels, ar these are shown schematically in Fig. 15.29. Each profile is identified by a letter and numb designator. For example, the first water-surface profile in Fig. 15.29 is identified as an M1 pr file. The letter indicates the type of slope of the channel—that is, whether the slope is mild (M critical (C), steep (S), horizontal (H), or adverse (A). The slope is defined as mild if the unifor flow depth, y_n, is greater than the critical flow depth, y_c. Conversely, if y_n is less than y_c, the char nel would be termed steep. Or if $y_n = y_c$, this would be a channel with critical slope. The desi nation M, S, or C is determined by computing y_n and y_c for the given channel for a given di charge. Equations (15.11) through (15.15) are used to compute y_n, and Eq. (15.27) is used compute y_c. Figure 15.30 shows the relationship between y_n and y_c for the H, M, S, C, and designations. As the name implies, a horizontal slope is one where the channel actually has zero slope, and an adverse slope is one where the slope of the channel is upward in the dire tion of flow. Normal depth does not exist for these two cases (for example, water cannot flow uniform depth in either a horizontal channel or one with adverse slope); therefore, they a given the special designations H and A, respectively.

FIGURE 15.29
Classification of water-surface profiles of gradually varied flow.



The number designator for the type of profile relates to the position of the *actual* water surface in relation to the position of the water surface for uniform and critical flow in the channel. If the actual water surface is above that for uniform and critical flow ($y > y_n; y > y_c$), then that condition is given a 1 designation; if the actual water surface is between those for uniform and critical flow, then it is given a 2 designation; and if the actual water surface lies

FIGURE 15.30
Letter designators as a function of the relationship between y_n and y_c.

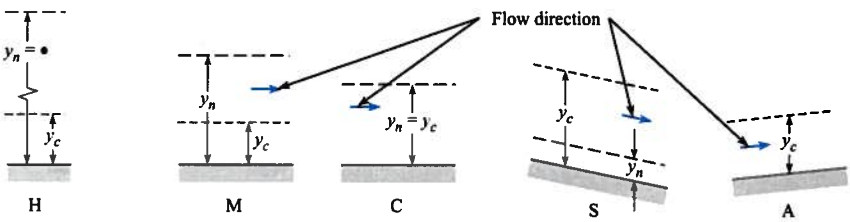
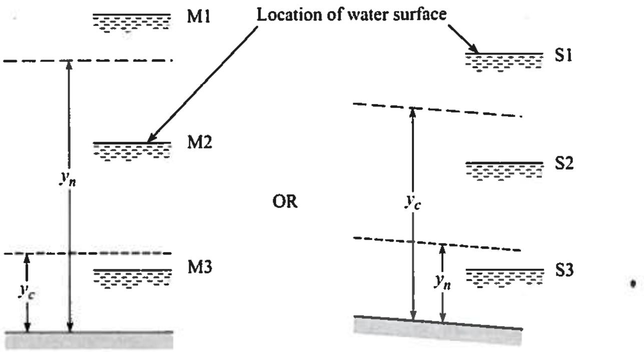


FIGURE 15.31

Number designator as a function of the location of the actual water surface in relation to y_n and y_c.

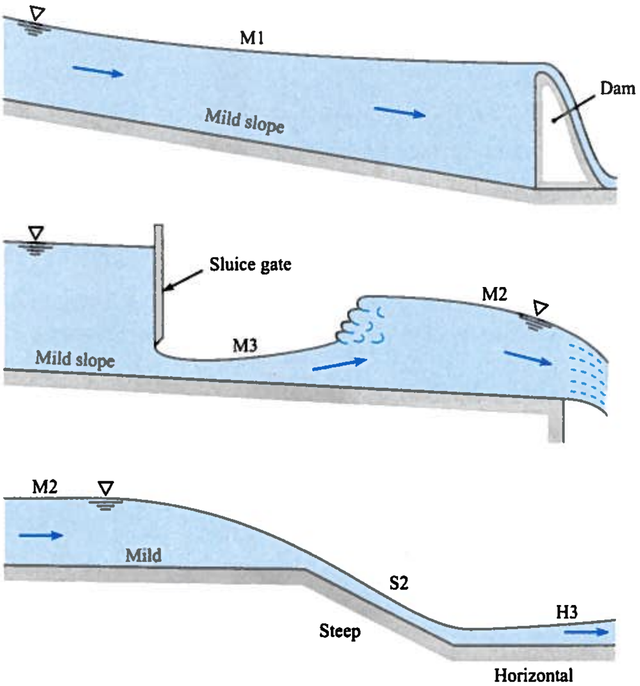


below those for uniform and critical flow, then it is given a 3 designation. Figure 15.31 depic these conditions for mild and steep slopes.

Figure 15.32 shows how different water-surface profiles can develop in certain field situ tions. More specifically, if one considers in detail the flow downstream of the sluice ga (see Fig. 15.33), one can see that the discharge and slope are such that the normal depth greater than the critical depth; therefore the slope is termed mild. The actual depth of flc shown in Fig. 15.33 is less than both y_c and y_n. Hence a type 3 water-surface profile exists. Tl complete classification of the profile in Fig. 15.33, therefore, is a mild type 3 profile, or simp an M3 profile. Using these designations, one would categorize the profile upstream of tl sluice gate as type M1.

FIGURE 15.32

Water-surface profiles associated with flow behind a dam, flow under a sluice gate, and flow in a channel with a change in grade.



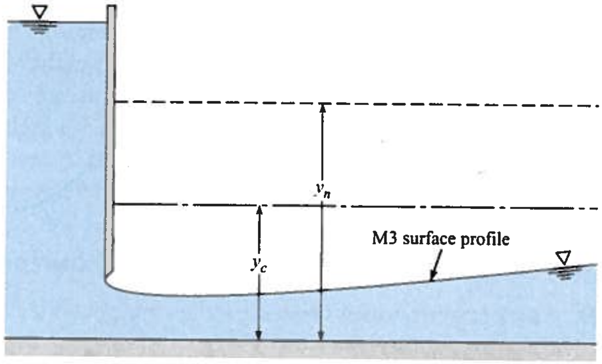


FIGURE 15.33 Water-surface profile, M3 type.

EXAMPLE 15.12

Classification of Water-Surface Profiles

Problem Statement

Classify the water-surface profile for the flow downstream of the sluice gate in Fig. 15.9 if the slope is horizontal, and that for the flow immediately downstream of the break in grade in Fig. 15.15.

Define the Situation

Nonuniform flow is occurring in a channel.

State the Goal

Find the water-surface profile classification for the two different flow situations.

Generate Ideas and Make a Plan

1. Select a number designator based on the location of the actual water surface relative to y_n and y_c (see Fig. 15.31).
2. Select a letter designator to describe the steepness of the slopes, which can also be characterized by the relative size of y_n and y_c (see Fig. 15.30).

Take Action (Execute the Plan)

For Fig. 15.9

1. The actual depth is less than critical; thus the profile is type 3.
2. The channel is horizontal; hence the profile is designated **type H3.**

For Fig. 15.15

1. The actual depth is greater than normal but less than critical, so the profile is type 2.
2. The uniform-flow depth (normal depth y_n) is less than the critical depth; hence the slope is steep. Therefore the water-surface profile is designated **type S2.**

With the previous introduction to the classification of water-surface profiles, one can refer to Eq. (15.49) to describe the shapes of the profiles. Again, for example, if one considers the M3 profile, it is known that $\mathrm{Fr} > 1$ because the flow is supercritical ($y < y_c$), and that $S_f > S_0$ because the velocity is greater than normal velocity. Hence a head loss greater than that for normal flow must exist. Inserting these relative values into Eq. (15.49) reveals that both the numerator and the denominator are negative. Thus dy/dx must be positive (the depth increases in the direction of flow), and as critical depth is approached, the Froude number approaches unity. Hence the denominator of Eq. (15.49) approaches zero. Therefore, as the depth approaches critical depth, $dy/dx \to \infty$. What actually occurs in cases where the critical depth is approached in supercritical flow is that a hydraulic jump forms and a discontinuity in profile is thereby produced.

Certain general features of profiles, as shown in Fig. 15.29, are evident. First, as the depth becomes very great, the velocity of flow approaches zero. Hence $\mathrm{Fr} \to 0$ and $S_f \to 0$ and dy/dx approaches S_0 because $dy/dx = (S_0 - S_f)(1 - \mathrm{Fr}^2)$. In other words, the depth increases at the same rate at which the channel bottom drops away from the horizontal. Thus the water surface approaches the horizontal. The profiles that show this tendency are types M1, S1, and C1.

A physical example of the M1 type is the water-surface profile upstream of a dam, as show in Fig. 15.32. The second general feature of several of the profiles is that those that approac normal depth do so asymptotically. This is shown in the S2, S3, M1, and M2 profiles. Also note Fig. 15.29 that profiles that approach critical depth are shown by dashed lines. This is done b cause near critical depth either discontinuities develop (hydraulic jump), or the streamlines a very curved (such as near a brink). These profiles cannot be accurately predicted by Eq. (15.4 because this equation is based on one-dimensional flow, which, in these regions, is invalid.

Quantitative Evaluation of the Water-Surface Profile

In practice, most water-surface profiles are generated by numerical integration, that is, l dividing the channel into short reaches and carrying the computation for water-surface elev tion from one end of the reach to the other. For one method, called the **direct step method**, tl depth and velocity are known at a given section of the channel (one end of the reach), and o arbitrarily chooses the depth at the other end of the reach. Then the length of the reach solved for. The applicable equation for quantitative evaluation of the water-surface profile is tl energy equation written for a finite reach of channel, Δx:

$$y_1 + \frac{V_1^2}{2g} + S_0\Delta x = y_2 + \frac{V_2^2}{2g} + S_f\Delta x$$

or

$$\Delta x(S_f - S_0) = \left(y_1 + \frac{V_1^2}{2g}\right) - \left(y_2 + \frac{V_2^2}{2g}\right)$$

or

$$\Delta x = \frac{(y_1 + V_1^2/2g) - (y_2 + V_2^2/2g)}{S_f - S_0} = \frac{(y_1 - y_2) + (V_1^2 - V_2^2)/2g}{S_f - S_0} \qquad \text{(15.5}$$

The procedure for evaluation of a profile starts by ascertaining which type applies to t given reach of channel (using the methods of the preceding subsection). Then, starting fron known depth, one computes a finite value of Δx for an arbitrarily chosen change in depth. T process of computing Δx, step by step, up (negative Δx) or down (positive Δx) the channel repeated until the full reach of channel has been covered. Usually small changes of y are tak so that the friction slope is approximated by the following equation:

$$S_f = \frac{h_f}{\Delta x} = \frac{fV^2}{8gR_h} \qquad \text{(15.5}$$

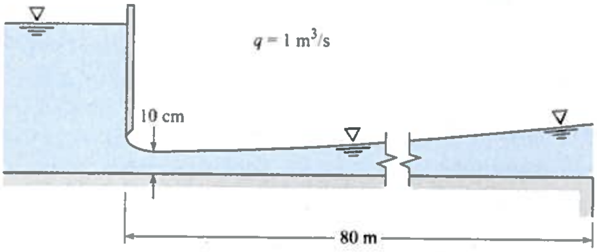
Here V is the mean velocity in the reach, and R_h is the mean hydraulic radius. That $V = (V_1 + V_2)/2$, and $R_h = (R_{h1} + R_{h2})/2$. It is obvious that a numerical approach of this ty is ideally suited for solution by computer.

EXAMPLE 15.13

Classification and Numerical Analysis of a Water-Surface Profile

Problem Statement

Water discharges from under a sluice gate into a horizontal rectangular channel at a rate of 1 m^3/s per meter of width, as shown in the following sketch. What is the classification of the water-surface profile? Quantitatively evaluate the profile downstream of the gate and determine whether it will extend all the way to the abrupt drop 80 m downstream. Make the simplifying assumptions that the resistance factor f is equal to 0.02 and that the hydraulic radius R_h is equal to the depth y.



Define the Situation

Water discharges underneath a sluice gate.

Assumptions:

1. Resistance factor f is equal to 0.02.
2. Hydraulic radius R_h is equal to the depth y.

State the Goal

- Classify of the downstream profile.
- Determine if increasing slope will prevail all the way to a point of interest 80 m downstream.

Generate Ideas and Make a Plan

1. Determine the letter designation of channel using Fig. 15.30.
2. For flow leaving sluice gate, determine critical depth y_c, and compare to actual depth of flow. Use this information to refine the classification.
3. Solve for depth versus distance using Eqs. (15.50) and (15.51).

Take Action (Execute the Plan)

1. Channel is horizontal, so letter designation is H.
2. Determine critical depth y_c using Eq. (15.27).

$$y_c = (q^2/g)^{1/3} = [(1^2\ \text{m}^4/\text{s}^2)/(9.81\ \text{m/s}^2)]^{1/3}$$

$$= \boxed{0.467\ \text{m}}$$

Thus, the depth of flow from sluice gate is less than the critical depth. Therefore the water-surface profile is classified as

type H3.

3. To determine depth versus distance along the channel, apply Eqs. (15.50) and (15.51) using the numerical approach given in Table 15.2. Then, plot the results as shown. From the plot, conclude that the

profile extends to the abrupt drop.

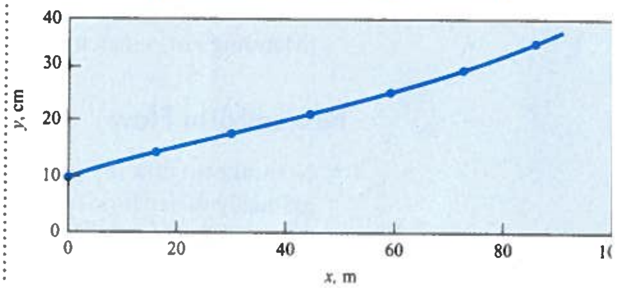


TABLE 15.2 Solution To Example 15.13

Section Number Downstream of Gate	Depth y, m	Velocity at Section V, m/s	Mean Velocity in Reach, $(V_1 + V_2)/2$	V^2	Mean Hydraulic Radius, $R_m = (y_1 + y_2)/2$	$S_f = \frac{f V^2_{mean}}{8gR_m}$	$\Delta x = \frac{(y_1 - y_2) + \frac{(V_1^2 - V_2^2)}{2g}}{(S_f - S_0)}$	Dist fr Ga r
1 (at gate)	0.1	10	...	100	...	...	...	(
	...	...	8.57	73.4	0.12	0.156	15.7	
2	0.14	7.14	...	51.0	...	...	...	15
	...	...	6.35	40.3	0.16	0.064	15.3	
3	0.18	5.56	...	30.9	...	...	...	31
	...	...	5.05	25.5	0.20	0.032	15.1	
4	0.22	4.54	...	20.6	...	...	...	46
	...	...	4.19	17.6	0.24	0.019	13.4	
5	0.26	3.85	...	14.8	...	...	...	59
	...	...	3.59	12.9	0.28	0.012	12.4	
6	0.30	3.33	...	11.1	...	...	...	71
	...	...	3.13	9.8	0.32	0.008	10.9	
7	0.34	2.94	...	8.6	...	...	...	82

15.8 Summarizing Key Knowledge

Describing Open Channel Flow

- An open channel is one in which a liquid flows with a free surface.
- Steady open-channel flow is classified as either
  - *Uniform* (velocity is constant for all points on each streamline) or
  - *Nonuniform* (velocity is varying for points along a specific streamline)

Steady and Uniform Flow

- The head loss corresponds to the potential energy change associated with the slope of the channel.
- The discharge is given by the Manning equation:

$$Q = \frac{1}{n} A R_h^{2/3} S_0^{1/2}$$

where A is the flow area, S_0 is the slope of the channel, and n is the resistance coefficie (Manning's n), which has been tabulated for different surfaces.

Nonuniform Flow

- Nonuniform flow in open channels is characterized as either rapidly varied flow or gradually varied flow. In rapidly varied flow the channel resistance is negligible, and flow changes (depth and velocity changes) occur over relatively short distances.
- The significant π-group is the Froude number

$$\text{Fr} = \frac{V}{\sqrt{gD_c}}$$

where D_c is the hydraulic depth, A/T. When the Froude number is equal to unity, the flow critical.
- Subcritical flow occurs when the Froude number is less than unity, and supercritical whe the Froude number is greater than unity.

Hydraulic Jump

- A hydraulic jump usually occurs when the flow along the channel changes from supercritical to subcritical.
- The governing equation for hydraulic jump in a horizontal, rectangular channel is

$$y_2 = \frac{y_1}{2}\left(\sqrt{1 + 8\text{Fr}_1^2} - 1\right)$$

- The corresponding head loss in the hydraulic jump is

$$h_L = \frac{(y_2 - y_1)^3}{4 y_1 y_2}$$

- When the flow along the channel changes from subcritical to supercritical flow, the head loss is assumed to be negligible, and the depth and velocity relationship is governed by tl change in elevation of the channel bottom and the specific energy, $y + V^2/2g$. Typical cases of this type of flow are

1. Flow under a sluice gate
2. An upstep in the channel bottom
3. Reduction in width of the channel

Gradually Varied Flow

- For gradually varied flow the governing differential equation is

$$\frac{dy}{dx} = \frac{S_0 - S_f}{1 - \mathrm{Fr}^2}$$

When this equation is integrated along the length of the channel, the depth y is determined as a function of distance x along the channel. This yields the water surface profile for the reach of the channel.

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PROBLEMS

PLUS Problem available in *WileyPLUS* at instructor's discretion.

GO Guided Online (GO) Problem, available in *WileyPLUS* a instructor's discretion.

Describing Open-Channel Flow (§15.1)

15.1 Why is the Reynolds number for onset of turbulence given by Re > 2000 in fully flowing pipes and Re > 500 in partly flowing pipes and other open channels?

15.2 A rectangular open channel has a base of length $2b$, and water is flowing with a depth of b.

a. Sketch this channel.

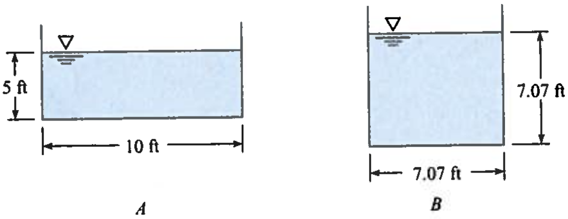
b. What is the hydraulic radius of this channel?

15.3 Two channels have the same cross-sectional area, but different geometry, as shown.

a. Which channel has the largest wetted perimeter?
b. Which channel has more contact between water and channel wall?
c. Which channel will have more energy loss to friction?

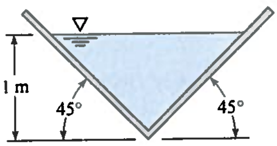
Uniform Open-Channel Flow (§15.3)

15.4 Consider uniform flow of water in the two channels shown. They both have the same slope, the same wall roughness, and the same cross-sectional area. Then one can conclude that (a) $Q_A = Q_B$, (b) $Q_A < Q_B$, or (c) $Q_A > Q_B$.



PROBLEMS 15.3, 15.4

15.5 This wood flume has a slope of 0.0019. What will be the discharge of water in it for a depth of 1 m? The wood is planed.



PROBLEM 15.5

15.6 Estimate the discharge in a rock-bedded stream (d_{84} = 30 cm) that has an average depth of 1.8 m, a slope of 0.0037, and a width of 52 m. Assume $k_s = d_{84}$.

15.7 Estimate the discharge of water ($T = 10°C$) that flows 1.5 m deep in a long rectangular concrete channel that is 3 m wide and is on a slope of 0.001.

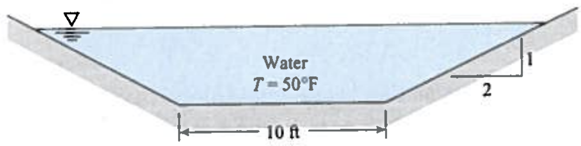
15.8 A rectangular concrete channel is 14 ft wide and has uniform water flow. If the channel drops 6 ft in a length of 8000 ft, what is the discharge? Assume $T = 60°F$. The depth of flow is 4 ft.

15.9 Consider channels of rectangular cross section carrying 100 cfs of water flow. The channels have a slope of 0.001. Determine the cross-sectional areas required for widths of 2 ft, 4 ft, 6 ft, 8 ft, 10 ft, and 15 ft. Plot A versus y/b, and see how the results compare with the accepted result for the best hydraulic section.

15.10 A concrete sewer pipe 2.5 ft in diameter is laid so it has a drop in elevation of 1.0 ft per 800 ft of length. If sewage (assume the properties are the same as those of water) flows at a depth of 1.25 ft in the pipe, what will be the discharge?

15.11 Determine the discharge in a 5-ft-diameter concrete sewer pipe on a slope of 0.001 that is carrying water at a depth of 4 ft.

15.12 Water flows at a depth of 8 ft in the trapezoidal, concrete-lined channel shown. If the channel slope is 1 ft in 1500 ft, what is the average velocity, and what is the discharge?



PROBLEM 15.12

15.13 What will be the depth of flow in a trapezoidal concrete-lined channel that has a water discharge of 1000 cfs? The channe has a slope of 1 ft in 500 ft. The bottom width of the channel is 10 ft, and the side slopes are 1 vertical to 1 horizontal.

15.14 What discharge of water will occur in a trapezoidal channel that has a bottom width of 19 ft and side slopes of 1 vertical to 1 horizontal if the slope of the channel is 2 ft/mile and the depth is 5 ft? The channel is lined with troweled concrete.

15.15 A rectangular concrete channel 4 m wide on a slope of 0.004 is designed to carry a water ($T = 10°C$) discharge of 25 m^3/s. Estimate the uniform flow depth for these conditions. The channel has a rectangular cross section.

15.16 A rectangular troweled concrete channel 8 ft wide with a slope of 10 ft in 3000 ft is designed for a discharge of 400 cfs. For a water temperature of 40°F, estimate the depth of flow.

15.17 A concrete-lined trapezoidal channel having a bottom width of 10 ft and side slopes of 1 vertical to 2 horizontal is designed to carry a flow of 3000 cfs. If the slope of the channel is 0.001, what will be the depth of flow in the channel?

15.18 Design a canal having a trapezoidal cross section to carry a design discharge of irrigation water of 900 cfs. The slope of the canal is to be 0.002. The canal is to be lined with concrete, and it is to have the best hydraulic section for the design flow.

Nonuniform Open-Channel Flow (§15.5)

15.19 How are head loss and slope related for nonuniform flo as compared to uniform flow?

15.20 Is critical flow a desirable or undesirable flow condition Why?

15.21 PLUS Critical flow ______. (Select all of the following that are correct.)

- **a.** occurs when specific energy is a minimum for a given discharge.
- **b.** occurs when the discharge is maximum for a given specific energy.
- **c.** occurs when $Fr < 1$.
- **d.** occurs when $Fr = 1$.

15.22 PLUS Water flows at a depth of 8 in. with a velocity of 35 ft/s in a rectangular channel. (a) Is the flow subcritical or supercritical? (b) What is the alternate depth?

15.23 PLUS The water discharge in a rectangular channel 16 ft wide is 900 cfs. If the depth of water is 3 ft, is the flow subcritical or supercritical?

15.24 PLUS The discharge in a rectangular channel 18 ft wide is 420 cfs. If the water velocity is 9 ft/s, is the flow subcritical or supercritical?

15.25 GO Water flows at a rate of 8 m^3/s in a rectangular channel 2 m wide. Determine the Froude number and the type of flow (subcritical, critical, or supercritical) for depths of 30 cm, 1.0 m, and 2.0 m. What is the critical depth?

15.26 For a rectangular channel 3 m wide and discharge of 12 m^3, what is the alternate depth to the 30 cm depth? What is the specific energy for these conditions?

15.27 Water flows at the critical depth with a velocity of 10 m/s. What is the depth of flow?

15.28 PLUS Water flows uniformly at a rate of 320 cfs in a rectangular channel that is 12 ft wide and has a bottom slope of 0.005. If n is 0.014, is the flow subcritical or supercritical?

15.29 GO The discharge in a trapezoidal channel is 10 m^3/s. The bottom width of the channel is 3.0 m, and the side slopes are 1 vertical to 1 horizontal. If the depth of flow is 1.0 m, is the flow supercritical or subcritical?

15.30 For the channel of Prob. 15.29, determine the critical depth for a discharge of 20 m^3/s.

15.31 A rectangular channel is 6 m wide, and the discharge of water in it is 18 m^3/s. Plot depth versus specific energy for these conditions. Let specific energy range from E_{min} to $E = 7$ m. What are the alternate and sequent depths to the 30-cm depth?

15.32 GO A long rectangular channel that is 8 m wide and has a mild slope ends in a free outfall. If the water depth at the brink is 0.55 m, what is the discharge in the channel?

15.33 A rectangular channel that is 15 ft wide and has a mild slope ends in a free outfall. If the water depth at the brink is 1.20 ft, what is the discharge in the channel?

15.34 A horizontal rectangular channel 14 ft wide carries a discharge of water of 500 cfs. If the channel ends with a free outfall, what is the depth at the brink?

15.35 What discharge of water will occur over a 3-ft-high, broad-crested weir that is 10 ft long if the head on the weir is 1.8 ft?

15.36 What discharge of water will occur over a 2-m-high, broad-crested weir that is 5 m long if the head on the weir i[s] 60 cm?

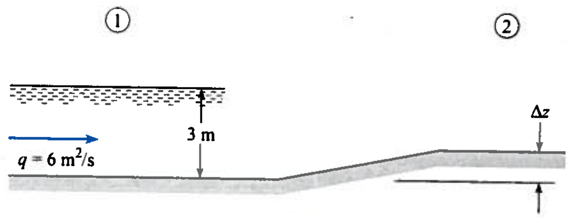
15.37 The crest of a high, broad-crested weir has an elevati[on of] 100 m. If the weir is 10 m long and the discharge of water o[ver] the weir is 25 m^3/s, what is the water-surface elevation in th[e] reservoir upstream?

15.38 The crest of a high, broad-crested weir has an elevati[on of] 300 ft. If the weir is 40 ft long and the discharge of water ove[r the] weir is 1200 cfs, what is the water-surface elevation in the reservoir upstream?

15.39 Water flows with a velocity of 3 m/s and at a depth of in a rectangular channel. What is the change in depth and in water-surface elevation produced by a gradual upward chan[ge in] bottom elevation (upstep) of 30 cm? What would be the dep[th] and elevation changes if there were a gradual downstep of 3[0 cm?] What is the maximum size of upstep that could exist before upstream depth changes would result?

15.40 Water flows with a velocity of 2 m/s and at a depth of in a rectangular channel. What is the change in depth and in water-surface elevation produced by a gradual upward chang[e in] bottom elevation (upstep) of 60 cm? What would be the dept[h] and elevation changes if there were a gradual downstep of 15 What is the maximum size of upstep that could exist before upstream depth changes would result?

15.41 Assuming no energy loss, what is the maximum value Δz that will permit the unit flow rate of 6 m^2/s to pass over th[e] hump without increasing the upstream depth? Sketch careful[ly] the water-surface shape from section 1 to section 2. On the sketch give values for Δz, the depth, and the amount of rise o[r] fall in the water surface from section 1 to section 2.

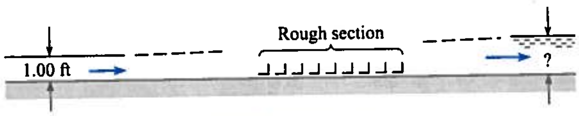


PROBLEM 15.41

15.42 Water flows with a velocity of 3 m/s in a rectangular channel 3 m wide at a depth of 3 m. What is the change in depth and in water-surface elevation produced when a gradua[l] contraction in the channel to a width of 2.6 m takes place? Determine the greatest contraction allowable without altering the specified upstream conditions.

15.43 Because of the increased size of ships, the phenomen[on] called "ship squat" has produced serious problems in harbor[s] where the draft of vessels approaches the depth of the ship channel. When a ship steams up a channel, the resulting flov[w] situation is analogous to open-channel flow in which a constricting flow section exists (the ship reduces the cross-sectional area of the channel). The problem may be analyzed by referencing the water velocity to the ship and applying the energy equation. Thus, at the section of the channel where the ship is located, the relative water velocity in the channel will be greatest, and the water level in the channel will be reduced as dictated by the energy equation. Consequently, the ship itself will be at a lower elevation than if it were stationary; this lowering is referred to as "ship squat." Estimate the squat of the fully loaded supertanker *Bellamya* when it is steaming at 5 kt (1 kt = 0.515 m/s) in a channel that is 35 m deep and 200 m wide. The draft of the *Bellamya* when fully loaded is 29 m. Its width and length are 63 m and 414 m, respectively.

15.44 A rectangular channel that is 10 ft wide is very smooth except for a small reach that is roughened with angle irons attached to the bottom. Water flows in the channel at a rate of 200 cfs and at a depth of 1.0 ft upstream of the rough section. Assume frictionless flow except over the roughened part, where the total drag of all roughness (all of the angle irons) is assumed to be 2000 lbf. Determine the depth downstream of the roughness for the assumed conditions.



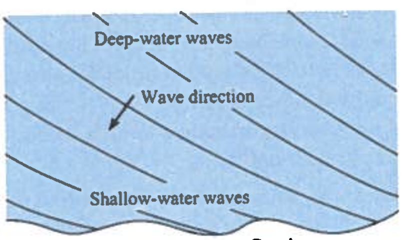
PROBLEM 15.44

15.45 Water flows from a reservoir into a steep rectangular channel that is 4 m wide. The reservoir water surface is 3 m above the channel bottom at the channel entrance. What discharge will occur in the channel?

15.46 A small wave is produced in a pond that is 6 in. deep. What is the speed of the wave in the pond?

15.47 WILEY PLUS A small wave in a pool of water having constant depth travels at a speed of 1.5 m/s. How deep is the water?

15.48 As waves in the ocean approach a sloping beach, they curve so that they are nearly parallel to the beach when they finally break (see accompanying figure). Explain why the waves curve like this. *Hint*: With a sloping beach, where is the water most shallow?



Aerial view of waves

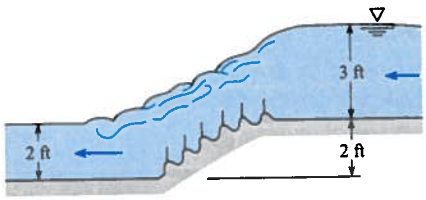
PROBLEM 15.48

Hydraulic Jumps (§15.6)

15.49 WILEY PLUS For a hydraulic jump, __________. (Select all of the following that are correct.)

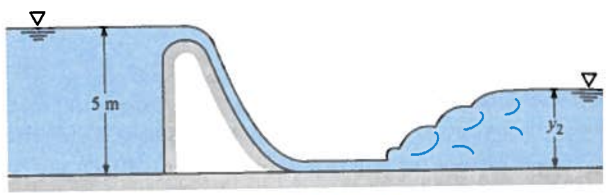
- **a.** the flow changes from subcritical to supercritical.
- **b.** the flow changes from supercritical to subcritical.
- **c.** significant energy is lost.
- **d.** the height of the water abruptly increases from the upstream to the downstream cross-section.
- **e.** the downstream and upstream depth are related quantitatively in terms of the upstream Fr.
- **f.** the energy equation is a better tool for analysis than the momentum equation.

15.50 The baffled ramp shown is used as an energy dissipator in a two-dimensional open channel. For a discharge of 18 cfs per foot of width, calculate the head lost, the power dissipated, and the horizontal component of force exerted by the ramp on the water.



PROBLEM 15.50

15.51 WILEY PLUS The spillway shown has a discharge of 2.9 m^3/s per meter of width occurring over it. What depth y_2 will exist downstream of the hydraulic jump? Assume negligible energy loss over the spillway.

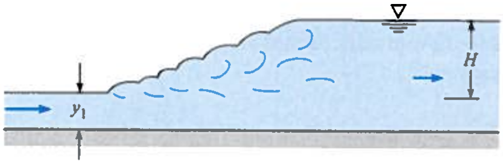


PROBLEM 15.51

15.52 WILEY GO The flow of water downstream from a sluice gate in a horizontal channel has a depth of 32 cm and a flow rate of 5.2 m^3/s per meter of width. The sluice gate is 2 m wide.

- **a.** Could a hydraulic jump be caused to form downstream of this section?
- **b.** If so, what would be the depth downstream of the jump?

15.53 It is known that the discharge per unit width is 65 cfs/ft and that the height (H) of the hydraulic jump is 14 ft. What is the depth y_1?



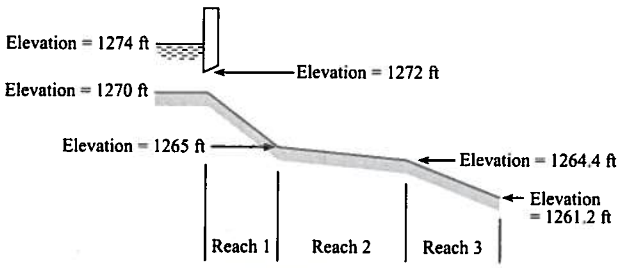
PROBLEM 15.53

15.54 Water flows in a channel at a depth of 40 cm and with a velocity of 8 m/s. An obstruction causes a hydraulic jump to be formed. What is the depth of flow downstream of the jump?

15.55 Water flows in a trapezoidal channel at a depth of 40 cm and with a velocity of 10 m/s. An obstruction causes a hydraulic jump to be formed. What is the depth of flow downstream of the jump? The bottom width of the channel is 5 m, and the side slopes are 1 vertical to 1 horizontal.

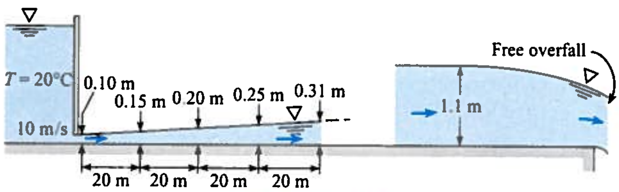
15.56 WILEY PLUS A hydraulic jump occurs in a wide rectangular channel. If the depths upstream and downstream are 0.50 ft and 10 ft, respectively, what is the discharge per foot of width of channel?

15.57 The 20-ft-wide rectangular channel shown has three different reaches. $S_{0,1} = 0.01$; $S_{0,2} = 0.0004$; $S_{0,3} = 0.00317$; $Q = 500$ cfs; $n_1 = 0.015$; normal depth for reach 2 is 5.4 ft and that for reach 3 is 2.7 ft. Determine the critical depth and normal depth for reach 1 (use Manning's equation from §15.3). Then classify the flow in each reach (supercritical, subcritical, critical), and determine whether a hydraulic jump could occur. In which reach(es) might it occur if it does occur?



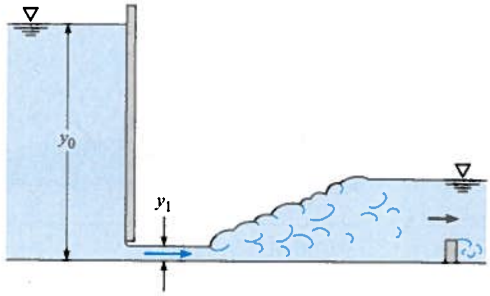
PROBLEM 15.57

15.58 Water flows from under the sluice gate as shown and continues on to a free overfall (also shown). Upstream from the overfall the flow soon reaches a normal depth of 1.1 m. The profile immediately downstream of the sluice gate is as it would be if there were no influence from the part nearer the overfall. Will a hydraulic jump form for these conditions? If so, locate its position. If not, sketch the full profile and label each part. Draw the energy grade line for the system.



PROBLEM 15.58

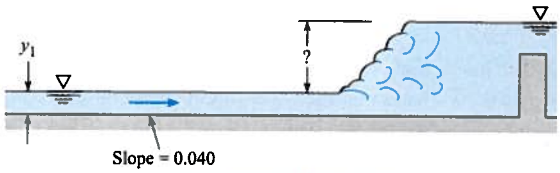
15.59 WILEY PLUS Water is flowing as shown under the sluice gate in a horizontal rectangular channel that is 5 ft wide. The depths of y_0 and y_1 are 65 ft and 1 ft, respectively. What will be the horsepower lost in the hydraulic jump?



PROBLEM 15.59

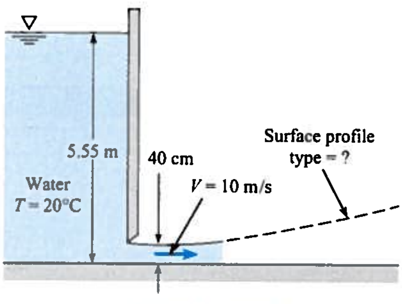
15.60 Water flows uniformly at a depth $y_1 = 32$ cm in the concrete channel shown, which is 8 m wide. Estimate the height of the hydraulic jump that will form when a sill is installed to force it to form. Assume Manning's n value is $n = 0.012$.

15.61 For the derivation of Eq. (15.28) on p. 571 of §15.5 it is assumed that the bottom shearing force is negligible. For water flowing uniformly at a depth $y_1 = 40$ cm in the concrete channel shown, which is 10 m wide, a sill is installed to force a hydraulic jump to form. Estimate the magnitude of the shearing force F_s associated with the hydraulic jump and then determine F_s/F_H, where F_H is the net hydrostatic force on the hydraulic jump. Assume Manning's n value is $n = 0.012$.



PROBLEMS 15.60, 15.61

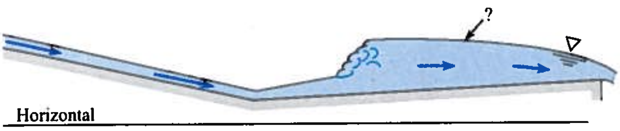
15.62 The normal depth in the channel downstream of the sluice gate shown is 1 m. What type of water-surface profile occurs downstream of the sluice gate? Also, estimate the shear stress on the smooth bottom at a distance 0.5 m downstream of the sluice gate.



PROBLEM 15.62

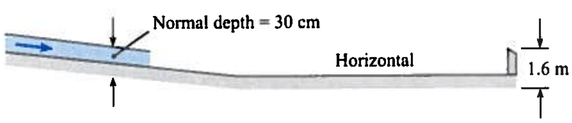
15.63 WILEY PLUS Water flows at a rate of 100 ft^3/s in a rectangular channel 10 ft wide. The normal depth in that channel is 2 ft. The actual depth of flow in the channel is 4 ft. The water-surface profile in the channel for these conditions would be classified as (a) S1, (b) S2, (c) M1, or (d) M2.

15.64 WILEY PLUS The water-surface profile labeled with a question mark is (a) M2, (b) S2, (c) H2, or (d) A2.



PROBLEM 15.64

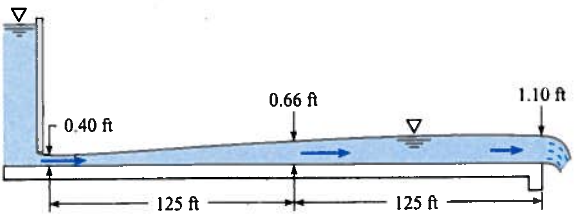
15.65 The partial water-surface profile shown is for a rectangular channel that is 3 m wide and has water flowing in it at a rate of 5 m^3/s. Sketch in the missing part of the water-surface profile and identify the type(s).



PROBLEM 15.65

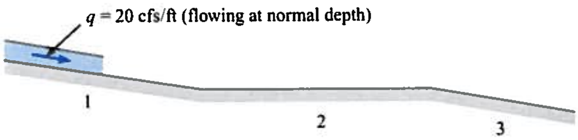
15.66 A very long 10-ft-wide concrete rectangular channel with a slope of 0.0001 ends with a free overfall. The discharge in the channel is 120 cfs. One mile upstream the flow is uniform. What kind (classification) of water surface occurs upstream of the brink?

15.67 The horizontal rectangular channel downstream of the sluice gate is 10 ft wide, and the water discharge therein is 108 cfs. The water-surface profile was computed by the direct step method. If a 2-ft-high sharp-crested weir is installed at the end of the channel, do you think a hydraulic jump would develop in the channel? If so, approximately where would it be located? Justify your answers by appropriate calculations. Label any water-surface profiles that can be classified.



PROBLEM 15.67

15.68 The discharge per foot of width in this rectangular channel is 20 cfs. The normal depths for parts 1 and 3 are 0.5 ft and 1.00 ft, respectively. The slope for part 2 is 0.001 (sloping upward in the direction of flow). Sketch all possible water-surface profiles for flow in this channel, and label each part with its classification.

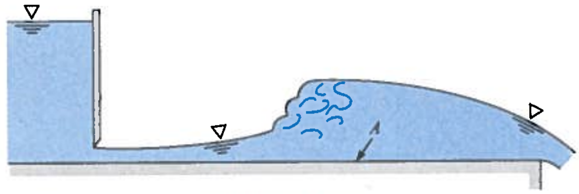


PROBLEM 15.68

15.69 Water flows from under a sluice gate into a horizontal rectangular channel at a rate of 3 m^3/s per meter of width. The channel is concrete, and the initial depth is 20 cm. Apply Eq. (15.42) on p. 579 of §15.6 to construct the water-surface profile up to a depth of 60 cm. In your solution, compute reaches for adjacent pairs of depths given in the following sequence: d = 20 cm, 30 cm, 40 cm, 50 cm, and 60 cm. Assume that f is constant with a value of 0.02. Plot your results.

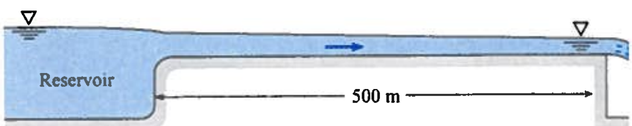
15.70 A horizontal rectangular concrete channel terminates in a free outfall. The channel is 4 m wide and carries a discharge of water of 12 m^3/s. What is the water depth 300 m upstream from the outfall?

15.71 Consider the hydraulic jump shown for the long horizontal rectangular channel. What kind of water-surface profile (classification) is located upstream of the jump? What kind of water-surface profile is located downstream of the jump? If baffle blocks are put on the bottom of the channel in the vicinity of A to increase the bottom resistance, what changes are likely to occur given the same gate opening? Explain and/or sketch the changes.



PROBLEM 15.71

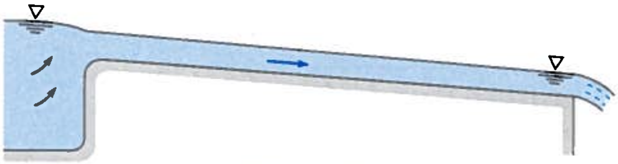
15.72 The steep rectangular concrete spillway shown is 4 m wide and 500 m long. It conveys water from a reservoir and delivers it to a free outfall. The channel entrance is rounded and smooth (negligible head loss at the entrance). If the water-surface elevation in the reservoir is 2 m above the channel bottom, what will the discharge in the channel be?



PROBLEM 15.72

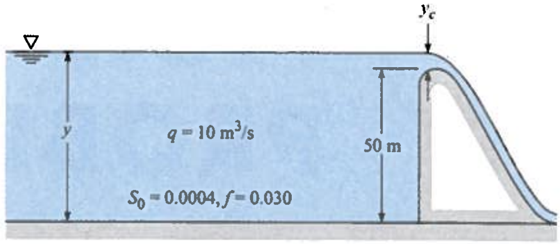
15.73 The concrete rectangular channel shown is 3.5 m wide and has a bottom slope of 0.001. The channel entrance is rounded and smooth (negligible head loss at the entrance), and the reservoir water surface is 2.5 m above the bed of the channel at the entrance.

- **a.** Estimate the discharge in it if the channel is 3000 m long.
- **b.** Tell how you would solve for the discharge in it if the channel were only 100 m long.



PROBLEM 15.73

15.74 A dam 50 m high backs up water in a river valley as shown. During flood flow, the discharge per meter of width, q, is equal to 10 m^3/s. Making the simplifying assumptions that $R = y$ and $f = 0.030$, determine the water-surface profile upstream from the dam to a depth of 6 m. In your numerical calculation, let the first increment of depth change be y_c; use increments of depth change of 10 m until a depth of 10 m is reached; and tl use 2 m increments until the desired limit is reached.



PROBLEM 15.74

15.75 Water flows at a steady rate of 12 cfs per foot of width (q = 12 cfs) in the wide rectangular concrete channel shown. Determine the water-surface profile from section 1 to sectior

PROBLEM 15.75