PDHonline Course H139 (2 PDH)

Open Channel Hydraulics II – Critical & Non-uniform Flow

Instructor: Harlan H. Bengtson, Ph.D., PE

2020

PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

An Approved Continuing Education Provider

Open Channel Hydraulics II – Critical & Non-uniform Flow

Harlan H. Bengtson, Ph.D., P.E.

COURSE CONTENT

1. Introduction

This course is intended to be taken after the course, H138, "Open Channel Hydraulics I – Uniform Flow." It will be assumed that anyone taking this course is familiar with the major classifications used for open channel flow (steady or unsteady state, laminar or turbulent flow, uniform or non-uniform flow, and critical, subcritical or supercritical flow) and with the use of the Manning equation and the parameters in that equation (e.g. hydraulic radius) for uniform open channel flow.

In this course, the parameter called specific energy will be used to introduce the concepts of critical, subcritical, and supercritical flow. Various calculations related to critical, subcritical and supercritical flow conditions will be presented. The hydraulic jump as an example of rapidly varied non-uniform flow will be discussed. The thirteen possible types of gradually varied non-uniform flow surface profiles will be presented and discussed. Also, the procedure and equations for step-wise calculation of gradually varied non-uniform surface profiles will be presented and illustrated with examples.

2. Specific Energy and Critical Flow in Open Channels

Specifically, Just what is SPECIFIC ENERGY ?

A discussion of specific energy in open channel flow helps to shed some light on the concepts of critical, subcritical and supercritical flow. At any cross-section in an open channel, the specific energy, E, is defined as the sum of the kinetic energy per unit weight of the flowing liquid and potential energy relative to the bottom of the channel. Thus:

$$E = y + V^2/2g \qquad (1)$$

Where: E = specific energy, ft-lb/lb

y = depth of flow above the bottom of the channel, ft

V = average liquid velocity (= Q/A), ft/sec

g = acceleration due to gravity = 32.2 ft/sec^2

Another form of the equation with Q/A replacing V is:

$$E = y + Q^2/2A^2g \qquad (2)$$

In order to show the relationship of specific energy to depth, we will now consider a rectangular cross-section for the open channel, with bottom width, b.

For this channel, A = yb, substituting into equation (2), gives:

$$E = y + Q^2/(2\,y^2b^2g) \qquad (3)$$

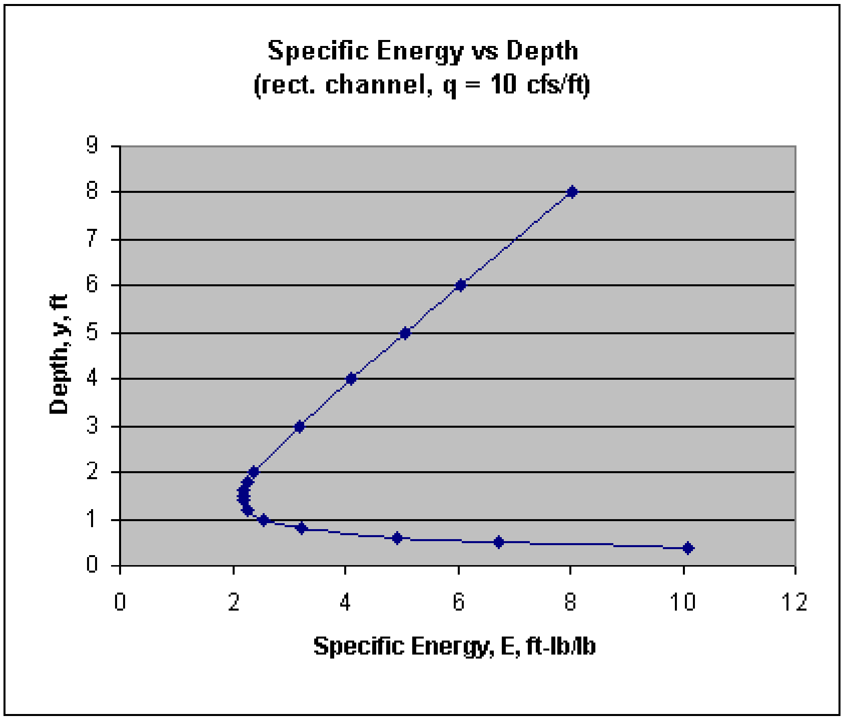
This equation, for a **rectangular channel**, is often expressed in terms of the flow rate per unit channel width, q (q = Q/b). Substituting into equation (3) gives:

$$E = y + q^2/(2\,y^2g) \qquad (4)$$

Using this equation, the specific energy can be plotted as a function of y, for a selected value of q. The table and graph in Figure 1, below illustrate this procedure for q = 10 cfs/ft in a rectangular channel. The values of E in the table were calculated from equation (4) for q = 10, and the indicated values for y. The graph shows that specific energy has high values for large values of y and for small values of y. This does, in fact, make sense. For large values of y, the first term in equation (4) (potential energy) is large. For small values of y with a fixed flow rate per unit channel width, the velocity of flow will become large and the second term in equation (4) (kinetic energy) is large. At some intermediate depth of flow the specific energy has a minimum value. The value of y which gives a minimum specific energy is called the **critical depth**. From the table and graph below, it can be seen that the critical depth is 1.5 ft to 2 significant figures

Figure 1. Specific Energy vs Depth (Rect. channel, q = 10 cfs/ft)

y, ft	E, ft-lb/lb
8	8.024
6	6.043
5	5.062
4	4.097
3	3.173
2	2.388
1.8	2.279
1.6	2.207
1.5	2.190
1.4	2.192
1.2	2.278
1	2.553
0.8	3.226
0.6	4.913
0.5	6.711
0.4	10.105



of accuracy. An equation for the critical depth, which will be represented as y_c , can be derived, with a little application of calculus. The value of y which will give a minimum or maximum value for E can be found by getting an expression for dE/dy from equation (4), setting dE/dy equal to zero, and solving for y. This procedure yields the following equation:

$$y_c = (q^2/g)^{1/3} \qquad (5)$$

Example #1: Calculate the critical depth for a flow rate of 10 ft^3/sec in a rectangular open channel.

Solution: Using equation (5): $\mathbf{y_c} = (10^2/32.2)^{1/3} = (3.1056)^{1/3}$ **= <u>1.459</u>**

Note that this value is consistent with the value of 1.5 from the table below, but with more significant figures.

Any flow condition with depth of flow less than critical depth ($y < y_c$) will be represented by the lower leg of the graph above, and is called supercritical flow. Any flow condition with depth of flow greater than critical depth ($y > y_c$) will be represented by the upper leg of the graph above, and is called subcritical flow. The flow condition with $y = y_c$ is called critical flow.

i) The Froude Number for Rectangular Channels

The Froude Number, Fr, is a dimensionless parameter used for open channel flow. For flow in a rectangular channel, it is defined as: $\mathbf{Fr = V/(gy)^{1/2}}$, where V, y, and g are the average velocity, depth of flow, and acceleration due to gravity, as previously discussed.

Substituting $q = Q/b = VA/b = V(yb)/b = Vy$, into equation (5), simplifying and rearranging the equation yields:

$$V^2/gy_c = 1 \quad \text{or} \quad Fr_c^{\,2} = 1 \quad \text{or} \quad Fr_c = 1$$

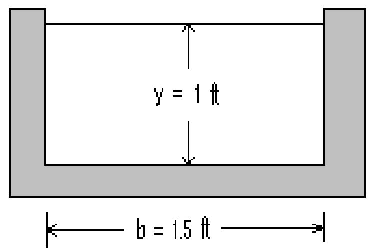
In other words, the Froude number is equal to one at critical flow conditions. Extending this slightly. The Froude number must be greater than one for supercritical flow and less than one for subcritical flow. Summarizing:

$Fr < 1$ for subcritical flow

$Fr = 1$ for critical flow

$Fr > 1$ for supercritical flow

Example #2: A rectangular open channel with bottom width = 1.5 ft, is carrying a flow rate of 9 cfs, with depth of flow = 1 ft. A cross-section of the channel is shown in the figure below. Is this subcritical or supercritical flow?



Solution: There is sufficient information to calculate the Froude Number, as follows:

$$A = by = (1.5)(1)\ ft^2 = 1.5\ ft^2$$

$$V = Q/A = 9/1.5 = 6\ ft/sec$$

$$Fr = V/(gy)^{1/2} = (6)/[(32.2)(1)]^{1/2} = 1.06$$

Since Fr > 1, **this is supercritical flow**.

ii) The Froude Number for Non-rectangular Channels

The Froude Number for flow in a channel with non-rectangular cross-section is defined as $\mathbf{Fr = V/[g(A/B)]^{1/2}}$, where A is the cross-sectional area of flow and B is the surface width for the specified flow conditions. A and B are shown in Figure 2, for a general, non-rectangular cross-section. Note that A/B = y for a rectangular channel, so the definition, $\mathbf{Fr = V/[g(A/B)]^{1/2}}$, is simply a more general definition for the Froude Number. The same criteria given above apply for subcritical, supercritical and critical flow in non-rectangular channels.

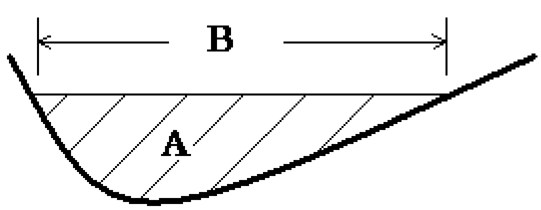
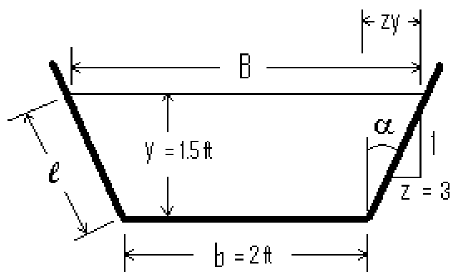


Figure 2. A and B for Non-rectangular Cross-section

Example #3: A trapezoidal open channel, with bottom width = 2 ft and side slope of horiz : vert = 3:1, is carrying a flow rate of 15 cfs, with depth of flow = 1.5 ft. Is this subcritical or supercritical flow? See the diagram below.



Solution: There is sufficient information to calculate the Froude Number, as follows: (recall from "Open Channel Hydraulics I", that $A = by + zy^2$).

$$A = by + zy^2 = (2)(1.5) + (3)(1.5^2)\ ft^2 = 9.75\ ft^2$$

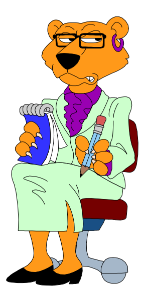
$$V = Q/A = 15/9.75 = 1.538\ ft/sec$$

$$B = b + 2zy = 2 + (2)(3)(1.5) = 11\ ft$$

$$Fr = V/[g(A/B)]^{1/2} = (1.538)/[(32.2)(9.75/11)]^{1/2} = 0.288$$

Since Fr < 1, **<u>this is subcritical flow</u>**.

<u>iii) Calculation of Critical Slope</u>



The critical slope, S_c, is the slope that will give critical flow conditions for a specified flow rate in a channel of specified shape, size and Manning roughness. The critical slope can be calculated from the Manning equation for critical flow conditions:

A channel with CRITICAL SLOPE will carry water at CRITICAL FLOW ? I guess that makes sense!

$$\mathbf{Q = (1.49/n)A_c(R_{hc}^{2/3})S_c^{1/2}} \qquad (6)$$

In this equation, Q and n will be specified, S_c is to be calculated, and A_c & R_{hc} will be functions of y_c, along with channel shape and size parameters. The critical depth, y_c, must be calculated first in order to get values for for A_c & R_{hc} . Two examples will be done to illustrate this type of calculation, the first with a rectangular channel and the second with a triangular channel.

Example #4: Find the critical slope for a rectangular channel with bottom width of 3 ft, Manning roughness of 0.011, carrying a flow rate of 15 cfs.

Solution: First calculate the critical depth from: $y_c = (q^2/g)^{1/3}$

Substituting values: $y_c = ((15/3)^2/32.2)^{1/3} = 0.9191$ ft

$A_c = by_c = (3)(0.9191) = 2.757 \text{ ft}^2$

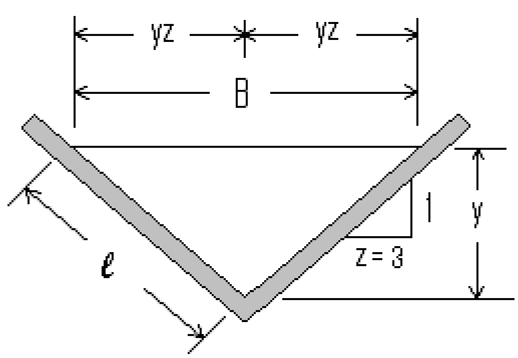
$P_c = b + 2y_c = 3 + (2)(0.9191) = 4.8382$ ft

$R_{hc} = A_c/P_c = 2.757/4.8382 \text{ ft} = 0.5698$ ft

Substituting values into Eqn (6): $15 = (1.49/0.011)(2.757)(0.5698^{2/3})S_c^{1/2}$

Solving for S_c gives: $\underline{\mathbf{S_c = 0.00342}}$

Example #5: Find the critical slope for a triangular channel with side slopes of horiz : vert = 3:1, Manning roughness of 0.011, carrying a flow rate of 15 cfs.



Solution: The critical depth (measured from the triangle vertex) can be calculated from the criterion that $Fr = V/[g(A/B)]^{1/2} = 1$ for critical flow, or $Fr_c = V_c/[g(A_c/B_c)]^{1/2} = 1$.

From the figure above: $B_c = 2y_cz = 6y_c$

$A_c = y_c^2z = 3y_c^2$

$V_c = Q/A_c = 15/(3y_c^2)$

Substituting expressions for V_c, A_c, & B_c into the equation for Fr and setting it equal to 1 gives:

$$(15/(3y_c^2))/[(32.2)(3y_c^2)/ 6y_c)]^{1/2} = 1$$

Believe it or not, this simplifies to $1.246/ y_c^{5/2} = 1$

Solving: $y_c = 1.09$ ft

Now, proceeding as in **Example #4:**

$A_c = 3y_c^2 = (3)(1.09)^2 = 3.564\ ft^2$

$P_c = 2[y_c^2(1 + z^2)]^{1/2} = 2[(1.09^2)(1 + 3^2)]^{1/2} = 6.893$ ft

$R_{hc} = A_c/P_c = 3.564/6.893$ ft $= 0.51709$ ft

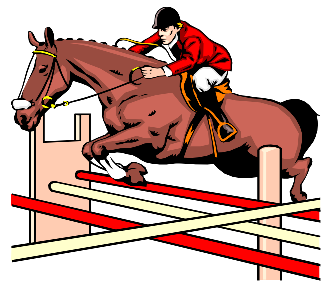
Substituting values into Eqn (6): $15 = (1.49/0.011)(3.564)(0.51709^{2/3})S_c^{1/2}$

Solving for S_c gives: $\underline{\mathbf{S_c = 0.0023}}$

TERMINOLOGY: A bottom slope less than the critical slope for a given channel is called a **mild slope** and a slope greater than critical is called a **steep slope**.

5. Hydraulic Jump (Rapidly Varied Flow)

Whenever a supercritical flow occurs on a slope that cannot maintain a supercritical flow, the transition to sustainable subcritical flow conditions will be through a hydraulic jump. A couple of examples of physical situations, which give rise to a hydraulic jump, are shown in Figure 3 (Hydraulic Jump due to Transition from Steep to Mild Slope) and Figure 4 (Hydraulic Jump due to Flow Under a Sluice Gate). There is no way to have a gradual transition from from supercritical to subcritical flow in an open channel.



Is a HYDRAULIC JUMP really used in a steeplechase ?

Figure 5 shows the upstream (supercritical) parameters and the downstream (subcritical) parameters, which are often used in connection with a hydraulic jump. These parameters are the supercritical velocity, V_1, supercritical depth of flow, y_1, subcritical velocity, V_2, and subcritical depth of flow, y_2.

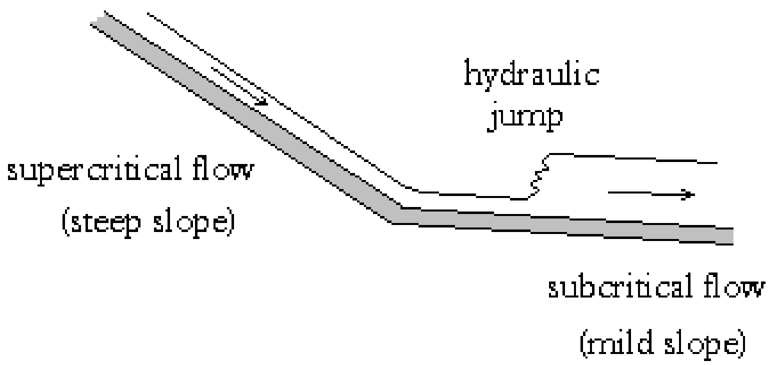


Figure 3. Hydraulic Jump due to Transition from Steep to Mild Slope

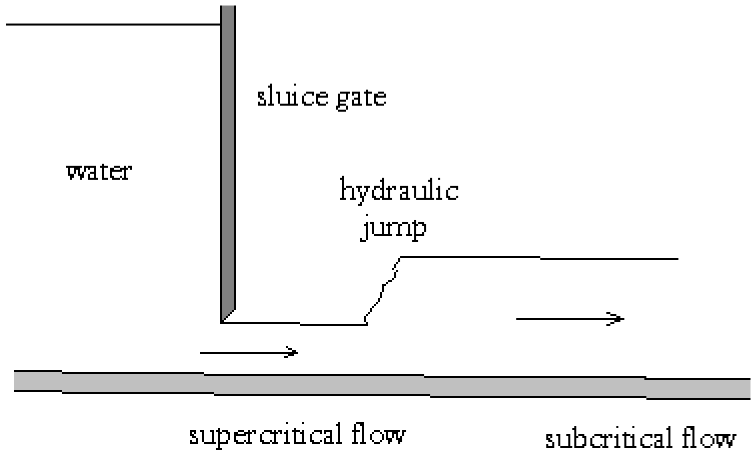


Figure 4. Hydraulic Jump due to Flow Under a Sluice Gate

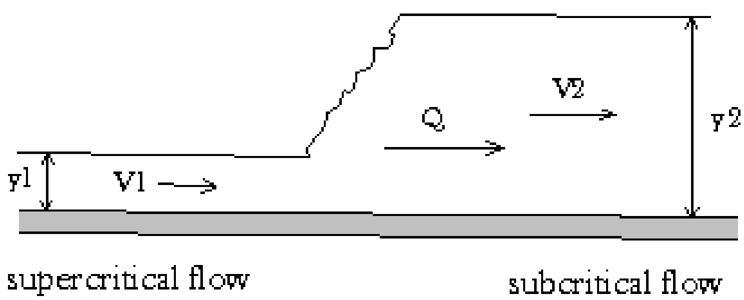


Figure 5. Upstream and Downstream Parameters for a Hydraulic Jump

Through the use of the three conservation equations (the continuity equation, the energy equation and the momentum equation) the following equation can be derived, relating the upstream and downstream conditions for a hydraulic jump in a rectangular channel:

$$y_2/y_1 = (1/2)[-1 + (1 + 8Fr_1^{\,2})^{1/2}] \qquad (7)$$

Where: $Fr_1 = V_1/(gy_1)^{1/2}$

Example #6: The flow rate under a sluice gate in a 10 ft wide rectangular channel is 50 cfs, with a 0.8 ft depth of flow. If the channel slope is mild, will there be a hydraulic jump downstream of the sluice gate?

Solution: From the problem statement: y = 0.8 ft and Q = 50 cfs. Average velocity, V, can be calculated and then Fr can be calculated to determine whether this is subcritical or supercritical flow.

$$V = Q/A = Q/yb = 50/(0.8)(10) = 6.25 \text{ ft/sec}$$

$$Fr = V/(gy)^{1/2} = (6.25)/[(32.2)(0.8)]^{1/2} = 1.23$$

Since Fr > 1, the described flow is supercritical. Since the channel slope is mild, there will be a hydraulic jump to make the transition from supercritical to subcritical flow.

Example #7: What will be the depth of flow and average velocity in the subcritical flow following the hydraulic jump of **Example #6?**

Solution: Equation (7) can be used with $Fr_1 = 1.23$ and $y_1 = 0.8$. Equation (7) becomes:

$$y_2/0.8 = (1/2)[\ -1 + (1 + 8(1.23)^2)^{1/2}\ ] = 1.3099$$

$$\underline{\mathbf{y_2 = 1.05\ ft}}$$

$$V_2 = Q/A_2 = 50/(10)(1.05) = \underline{\mathbf{4.76\ ft/sec = V_2}}$$

6. Gradually Varied, Non-Uniform Open Channel Flow

Gradually varied flow refers to non-uniform flow in which the depth of flow is changing smoothly and gradually. This is in contrast with the abrupt, turbulent transition from supercritical to subcritical flow in a hydraulic jump, which is sometimes called rapidly varied flow.

Classification of Gradually Varied Flow Surface Profiles

Are there really 13 ways to have GRADUALLY VARIED FLOW ?

Figure 6, on the next page shows the thirteen possible gradually varied flow surface profiles with a commonly used classification scheme. There are five possible types of channel bottom slope:

i) mild (M): $(S < S_c)$,

ii) Steep (S): $(S > S_c)$,

iii) critical (C): $(S = S_c)$,

iv) horizontal (H): $(S = 0)$, and

v) adverse (A): (upward slope).

y > yo & y > yc | y is between yo & yc | y < yo & y < yc

Mild Slope

S < Sc

Steep Slope

S > Sc

Critical Slope

S = Sc

Horizontal

Channel

S = 0

Adverse Slope

S = upward

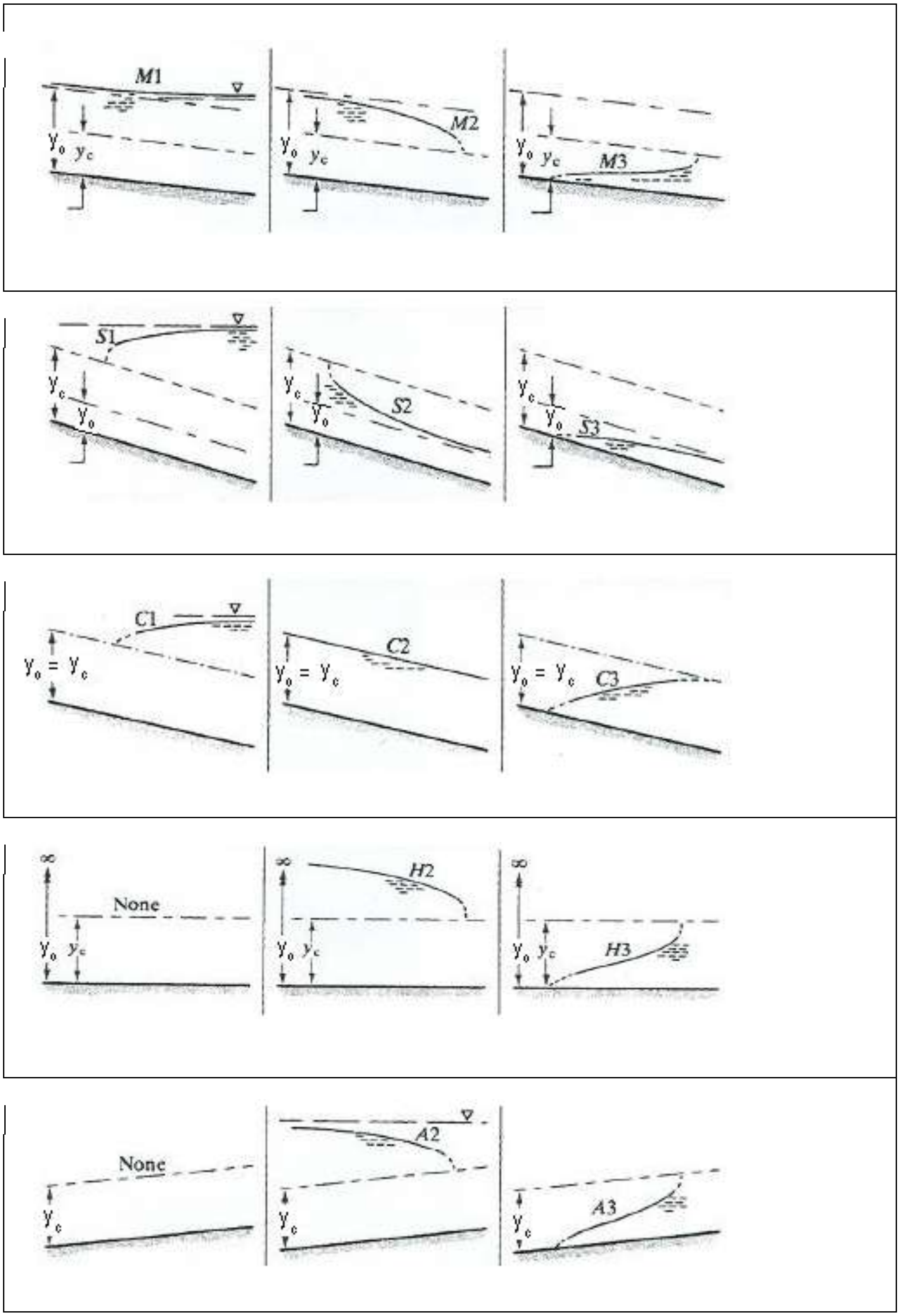


Figure 6. The Possible Gradually Varied Flow Profiles

The relative values of depth of flow, y, normal depth, y_o, and critical depth, y_c, can be classified into three categories as follows:

i) category 1: $y > y_c$ & $y > y_o$;

ii) category 2: y is between y_c & y_o ;

iii) category 3: $y < y_c$ & $y < y_o$.

For example, a non-uniform surface profile with a mild slope and $y > y_o > y_c$ is called an M_1 profile, and a non-uniform surface profile with a steep slope and $y_o < y < y_c$ is called an S_2 profile. The entire classification and terminology is shown in Figure 6, on the previous page.

Note that there is no possible surface profile H_1 or A_1, because neither a horizontal nor adverse slope can sustain uniform flow and hence neither has a normal depth.

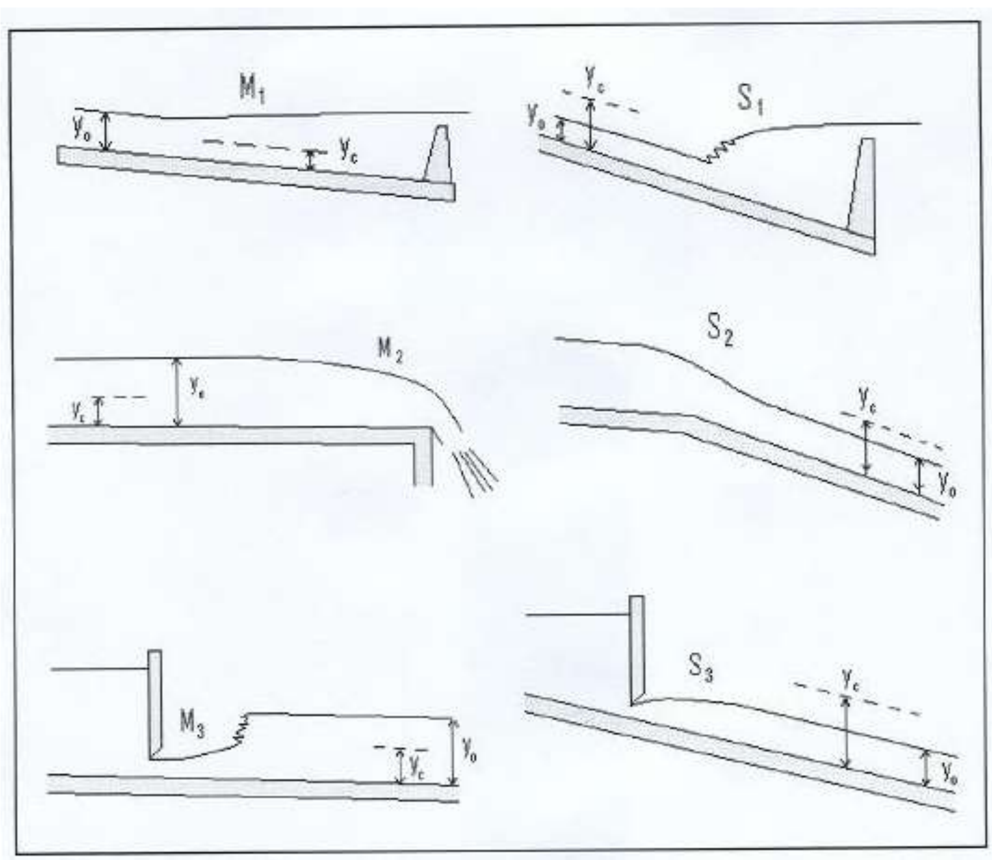


Figure 7. Physical Situations for M & S Non-Uniform Surface Profiles

Figure 7 shows physical situations which give rise to the six classifications of gradually varied flow surface profiles for mild and steep slopes.

ii) Stepwise Calculation of Non-uniform Flow Surface Profiles

An important distinction between uniform flow and gradually varied non-uniform flow in open channels has to do with the relationship between the channel bottom slope and the slope of the liquid surface. For uniform flow, these two slopes are equal (because the depth of flow is constant). For gradually varied non-uniform flow, the depth of flow is changing, so the surface slope is not the same as the channel bottom slope. Either the surface slope is greater than the bottom slope (if the depth of flow is increasing in the direction of flow), or the surface slope is less than the bottom slope (if the depth of flow is decreasing in the direction of flow). This is illustrated in Figure 8, below.

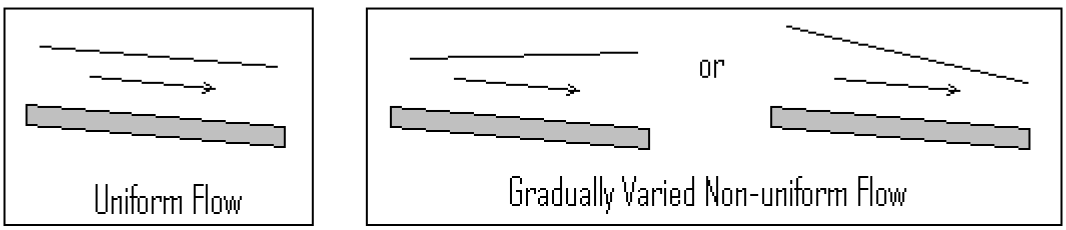


Figure 8. Uniform Flow and Gradually Varied Non-uniform Flow

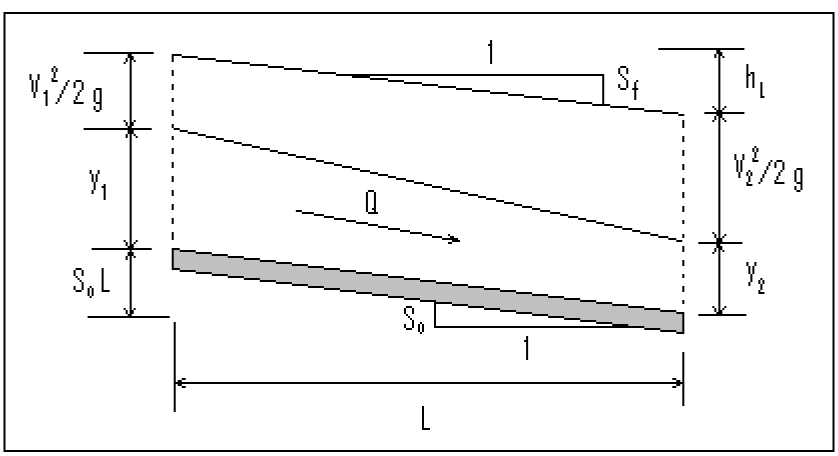


Figure 9. Reach of Open Channel with Gradually Varied Non-uniform Flow

Figure 9, which shows a reach (longitudinal section) of open channel with gradually varied non-uniform flow, will be used to develop an equation to be used for stepwise calculation of the surface profile (depth of flow vs length in direction of flow) for such a flow. The parameters shown in the diagram at the inlet and outlet ends of the channel reach are components of the Energy Equation as applied to the reach of channel. These components are summarized here:

Potential energy per lb of flowing water in = $y_1 + S_oL$

Kinetic energy per lb of flowing water in = $V_1^2/2g$

Potential energy per lb of flowing water out = y_2

Kinetic energy per lb of flowing water out = $V_2^2/2g$

Frictional head loss over length of flow L = h_L

The Energy Equation (First Law of Thermodynamics) applied to the reach of channel in Figure 9 can be stated as:

Energy per lb of flowing water into reach = Energy per lb of flowing water out of reach + Frictional head loss over the reach of channel

Substituting the parameters from above the Energy Equation becomes:

$$y_1 + S_oL + V_1^2/2g = y_2 + V_2^2/2g + h_L \qquad (8)$$

As can be seen in the diagram in Figure 9, the frictional head loss over the length of channel, L, is simply the decrease in elevation of the water surface. This decrease in elevation can be expressed as the slope of the water surface times the length of the reach, or:

$$h_L = S_fL$$

Substituting into equation (8) and solving for $y_1 - y_2$, gives the following:

$$y_1 - y_2 = (V_2^2 - V_1^2)/2g + (S_f - S_o)L \qquad (9)$$

Equation (9) can now be used to make a stepwise determination of the non-uniform surface profile for a reach of channel such as that shown in Figure 9. The bottom slope, S_o, the length of the channel reach, L, and the flow rate through the reach of channel, Q, should be known. Also, g is, of course, the known acceleration due to gravity, 32.2 ft/sec^2. If values can be determined for V_1, V_2, & S_f (which of course they can), then the downstream depth of flow, y_2, can be calculated for a specified upstream depth of flow, y_1, and vice versa. Also, the length of reach, L, can be the unknown. That is the length of channel required for the depth of flow to change from a specified value y_1 to another specified value, y_2, can be determined.

With known values for the Manning roughness factor and the size and shape of the channel, estimation of V_1, V_2, & S_f can proceed as follows. A value for S_f can be estimated from the Manning Equation:

$$S_f = [nQ/(1.49A_mR_{hm}^{2/3})]^2$$

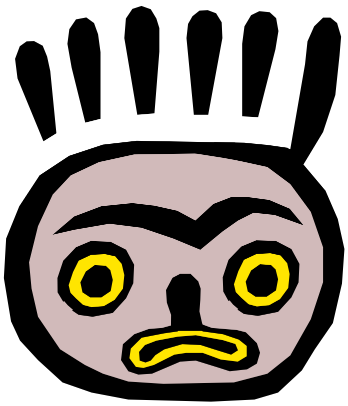
NOTE: The slope used in the above equation is the slope of the water surface, not the bottom slope as we are accustomed to using in the Manning equation. The slope to be used in the Manning equation is actually the water surface slope, but for uniform flow, the surface slope and bottom slope are the same, so either can be used.

A_m and R_{hm} are mean values across the reach of channel, that is:

$$A_m = (A_1 + A_2)/2 \quad \text{and} \quad R_{hm} = (R_{h1} + R_{h2})/2$$

Values of V_1 & V_2 can be estimated from the definition of average velocity, $V = Q/A$, as follows:

$$V_1 = Q/A_1 \quad \text{and} \quad V_2 = Q/A_2$$



Watch out here ! This isn't hard, but there are a lot of steps and it can get tedious !!

Example #8: A rectangular flume of planed timber (n = 0.012) is 5 ft wide and carries 60 cfs of water. The bed slope is 0.0006, and at a certain section the depth is 2.8 ft. Find the distance to the section where the depth is 2.5 ft.

Solution: This will be done using a single step calculation for the 0.3 ft change in depth. From the problem statement: Q = 60 cfs, n = 0.012, S_o = 0.0006, b = 5 ft, y_1 = 2.8 ft, and y_2 = 2.5 ft.

The other necessary parameters are calculated as follows:

$$V_1 = Q/A_1 = 60 \text{ ft}^3/\text{sec}/(5)(2.8)\text{ft}^2 = 4.286 \text{ ft/sec}$$

$$V_2 = Q/A_2 = 60 \text{ ft}^3/\text{sec}/(5)(2.5)\text{ft}^2 = 4.8 \text{ ft/sec}$$

$$A_m = (A_1 + A_2)/2 = [(5)(2.8) + (5)(2.5)]/2 = 13.25 \text{ ft}^2$$

$$R_{h1} = A_1/P_1 = (5)(2.8)/[5 + (2)(2.8)] = 1.32 \text{ ft}$$

$$R_{h2} = A_2/P_2 = (5)(2.5)/[5 + (2)(2.5)] = 1.25 \text{ ft}$$

$$R_{hm} = (R_{h1} + R_{h2})/2 = (1.32 + 1.25)/2 = 1.285 \text{ ft}$$

$$S_f = [nQ/(1.49A_mR_{hm}^{2/3})]^2 = [(0.012)(60)/(1.49(13.25)(1.285^{2/3})]^2$$

$$= 0.0009520$$

Substituting all of these values into equation (9) gives:

$$2.8 - 2.5 = (4.8^2 - 4.286^2)/(2)(32.2) + (0.000950 - 0.0006)L$$

Solving for L**:** **L = 647 ft**

Example #9: In **Example #8,** is the 2.5 ft depth upstream or downstream of the 2.8 ft depth?

Solution: Since L as calculated from equation (9) is positive, **the 2.5 ft depth is downstream of the 2.8 ft depth.**

NOTE: Equation (9) is written with L being positive for y_1 being the upstream depth and y_2 being the downstream depth. In the solution to **Example #8**, y_1 was set to be 2.8 ft and y_2 was set to be 2.5 ft. Since L came out positive in the calculation, this confirmed that the assumed direction of flow was correct. If L had come out negative, that would have meant that the flow was in the opposite direction.

Example #10: A rectangular channel is 30 ft wide, has a slope of 1/3000, and Manning roughness of 0.018. The normal depth for this channel is 12 ft. Due to an obstruction, the depth of flow at one point in the channel is 18 ft. Determine the length of channel required for the transition from the 18 ft depth to a depth of 12.5 ft. Use step-wise calculations with one foot increments of depth.

Solution: A set of calculations like those of **Example #8** will be done six times (for 18 to 17 ft; for 17 to 16 ft; etc, down to 13 to 12.5 ft). For repetitive calculations like this it is convenient to use a spreadsheet such as Excel.

First the flow rate, Q, must be calculated for the normal depth of 12 ft.

The Manning equation: $Q = (1.49/n)A(R_h^{2/3})S^{1/2}$

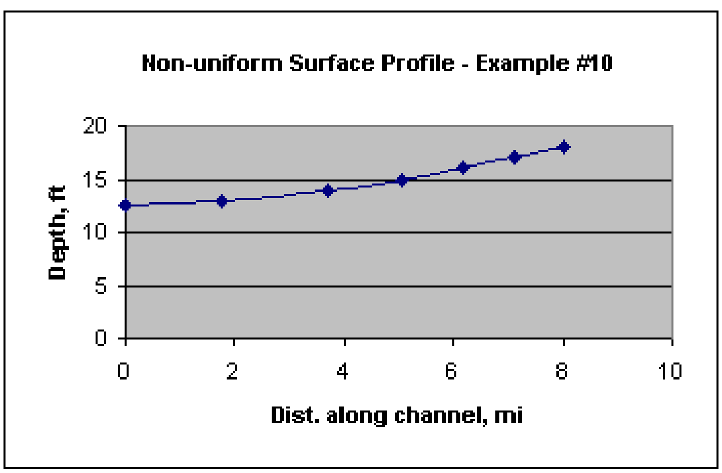
$$= (1.49/0.018)[(30)(12)][(30)(12)/(30 + 24)]^{2/3}(1/3000)^{1/2} = 1927.2 \text{ cfs}$$

The table below is copied from the Excel spreadsheet in which the calculations were made. In each column, calculations are made as shown above for **Example #8.** It can be seen that the distance for the transition from a depth of 12.5 ft to a depth of 18 ft is **42,260 feet or 8.004 miles**. The negative sign for L shows that the flow is from the 12.5 ft depth to the 18 ft depth, which confirms what we already knew from the problem statement.

Q, cfs	1927.2	1927.2	1927.2	1927.2	1927.2	1927.2
y_1, ft	18	17	16	15	14	13
y_2, ft	17	16	15	14	13	12.5
A_1, ft^2	540	510	480	450	420	390
A_2, ft^2	510	480	450	420	390	375
A_m, ft^2	525	495	465	435	405	382.5
V_1, ft/s	3.569	3.779	4.015	4.283	4.589	4.942
V_2, ft/s	3.779	4.015	4.283	4.589	4.942	5.139
R_{h1}, ft	8.182	7.969	7.742	7.500	7.241	6.964
R_{h2}, ft	7.969	7.742	7.500	7.241	6.964	6.818
R_{hm}, ft	8.075	7.855	7.621	7.371	7.103	6.891
S_f	0.0001214	0.0001417	0.0001672	0.0001997	0.0002420	0.0002825
ΔL, ft	-4605.0	-5068.1	-5809.8	-7167.4	-10380.4	-9229.0
Cumul. L, ft	-4605.0	-9673.1	-15482.9	-22650.3	-33030.6	**-42259.6**
Cumul. L, mi	-0.872	-1.832	-2.932	-4.290	-6.256	**-8.004**

The graph below shows a plot of the non-uniform surface profile calculated in the table above for **Example #10**. Based on the problem statement this physical situation is like that for the M_1 profile in Figure 7. Also, the shape of the surface profile is like that for the M_1 profiles in Figures 6 and 7.

L, mi	y, ft
0	12.5
1.748	13
3.714	14
5.071	15
6.171	16
7.131	17
8.003	18



8. Summary

Through the use of the Froude number, it is possible to determine whether a specified example of open channel flow is subcritical or supercritical flow. When supercritical flow occurs on a mild slope, which cannot maintain the supercritical velocity, there will be an abrupt transition to subcritical flow in the form of a hydraulic jump. Non-uniform flow, which occurs as a smooth transition from one flow condition to another, is often called gradually varied flow. Any gradually varied flow example will be one of 13 possible classifications, based on the slope of the channel and the relationships among y, y_c, & y_o. A specified gradually varied flow profile can be calculated as depth versus distance along the channel using a step-wise calculation, which was discussed and illustrated with examples in this course.