Lab #2
Conservation Equations and the Hydraulic Jump
CEE 3310 Fall 2015

Safety
The major safety hazard in this laboratory is a shock hazard. Given that you will be working with water and items running on standard line voltages (the pump and the computer) you should pay attention to the possibility of electric shock. If water spills on the desktop, please clean it up IF there is no risk of shock. If water gets near a 110 Volt electrical connection (i.e. a wall outlet or anything connected to it) DO NOT clean it up. Seek a TA, Cowen, or one of the CEE technicians (Tim Brock, Paul Charles, or Cameron Willkens, who have offices across from the lab) for help.

The lab has many research tools that are potentially dangerous in un-trained hands. We implore you to not touch anything that you have not been invited to use in the CEE 3310 labs.

Particularly important, if you are about to enter the lab and you notice that the “Laser in use” sign is illuminated. DO NOT ENTER. Knock loudly and see what is going on or find a TA, one of the CEE technicians, or Cowen.

If you enter and you see a cyan blue or greenish laser beam light DO NOT LOOK AT IT. Turn away and ask loudly if it is O.K. to enter or leave and seek out a TA, one of the CEE technicians, or Cowen. This should not occur but if it does follow the above procedures.

Always work with a minimum of two people.

Objectives
In this laboratory you will investigate an open-channel flow (flow down a channel with a free-surface, i.e., not confined by a rigid surface as would be the case in pipe flow). You will get a chance to look at this flow analytically using the conservation equations (mass, linear momentum and energy) in Problem Set #6 but for the lab we will focus on the observational evidence. You will be introduced to the hydraulic phenomenon known as the hydraulic jump – the sudden transition from a higher energy state to a lower energy state constrained by the conservation of momentum (analogous to a shock wave in compressible gas flows). This is your chance to get a tangible sense of the conservation equations and concepts such as the energy grade line and the hydraulic grade line. You will also get a chance to think about the energy equation and when the assumptions of the Bernoulli equation are valid and when they are violated.

Theory
The Flow
We will use a sluice gate to convert potential energy to kinetic energy and create what is known as supercritical flow. We will study supercritical flow in some detail in the final weeks of the semester. The concept of supercritical flow is fairly straightforward (and covered in your text in Chapter 10), and simply defined means that waves can only travel downstream. As an example
Consider throwing a rock into a slowly moving river. A circular wave pattern forms initially and propagates radially outward (until the banks are hit at least). If the river flow is slow then a significant portion of the circular wave pattern will propagate upstream – i.e., the waves make progress back against the river current if viewed from the river bank. This state is known as the subcritical state. Now, if the river speed increases eventually it will flow fast enough that none of the circular wave pattern will make progress upstream. When this scenario is true the river flow is said to be supercritical. Another way of thinking about this is that in subcritical flow the information (waves) saying the flow wants to get deeper can propagate both up and downstream so you can influence a flow's depth (in fact you can set it) from downstream. Conversely when the flow is supercritical there is no way from the downstream side to tell the flow that it should get deeper – this information must come from the upstream side.

For waves that have a long wave length in comparison to their flow depth the wave speed \( c \) is simply

\[
c = \sqrt{gh}
\]

where \( h \) is the local flow depth and \( g \) is the acceleration of gravity. Hence we can express the condition that the wave speed is equal to the flow speed as \( V = c \) or

\[
Fr = \frac{V}{\sqrt{gh}} = 1
\]

where \( Fr \) is known as the Froude number and \( V \) is the local flow velocity.

As suggested above a flow can exist in a supercritical \((Fr > 1)\), subcritical \((Fr < 1)\), or critical \((Fr = 1)\) state. For a flow, such as in our case just after the sluice gate, that is locally supercritical, downstream conditions may require the flow to increase its depth, say to get over a sill or weir. Because of the conservation of linear momentum and the conservation of mass there is only one valid supercritical and one valid subcritical depth for a given flow rate, so if the flow must adjust its depth it must transition to the subcritical state, which is slower and hence deeper. Now, normally over short reaches of a river it is reasonable to ignore energy loss and assume energy is constant. However, there is no way for a flow to decelerate smoothly and adjust to a subcritical state (note that it can accelerate smoothly from sub- to supercritical as it did beneath the sluice gate). It accomplishes this transition to deeper flow depth by a feature known as a hydraulic jump (see section 10.6 of your text), which as you will see is a highly turbulent event and dissipates significant energy.

In this lab we have set a weir (an overflow gate as opposed to a sluice gate which is an underflow gate) at the outlet of our teaching flume in the environmental fluid mechanics teaching laboratory that requires that the flow be at minimum 10.5 cm deep to get out of the flume and return to the pumps that supply the flume with water. Hence if we use a sluice gate to deliver a supercritical flow of depth of a bit less than 3 cm to the flume, (the sluice gate opening should be 4.5 cm) it must transition to a deeper state to get over the weir and out of the flume and it does this via a hydraulic jump.
Hydraulic Jump

If the Bernoulli equation were valid across the hydraulic jump we would expect energy to be conserved and hence the energy grade line elevation to be constant across the jump. If this were the case, given the considerably greater flow depth downstream of the hydraulic jump and resultant slower velocities we would expect the actual water depth to approach the depth of the constant head tank. If this were the case water would be pouring over the sides of our flume! Luckily significant energy is dissipated through the hydraulic jump and energy is not conserved. Let’s take a look at how much energy is dissipated – experimentally!

Pitot Tube

The Pitot tube used in this lab is a simple air-tight plastic tube with a 90 degree elbow with a tip with very small diameter opening mounted in it. As discussed in class a Pitot tube converts the kinetic energy of the flow to potential energy so you will be interested in the height the water \((H)\) rises within the Pitot tube, which by definition is the EGL. From Pitot tube theory, recall that we can calculate the velocity as \(V = \sqrt{2g(H - h)}\)

Experimental Method

1. Check that the water level in the flume (with the pumps turned off) is just below the red tape on the piezometer at the flume outlet end. If the water level needs adjusting check with the TA.

2. Turn on the pumps by first turning on the master power switch (whiteboard side of the flume) and then hitting “run” on the three pumps (opposite side of the flume). The pumps should spin up to a reading of about 40Hz, which means 2/3 (40/60) of full speed. Please do not adjust any of the pumps – the TAs and I have them set where we want them.

3. The hydraulic jump should position itself around mid-flume. If after a minute or two it does not, the TA will help you position it.

4. Take measurements listed below in the “Data Collection/Analysis” section (hint: Use the Appendix to record your data).

5. Observe the velocity as monitored by the acoustic Doppler Velocimeter (ADV) only in the subcritical section of the flow. This instrument measures the Doppler shift of sound to measure all three components of the velocity. Record the average \(u, v\) and \(w\) components of velocity (the 30 second average is reported in the table on the screen) and notice how turbulent the flow is (how much the velocity varies about its mean).

*Note: the ADV measures 15 cm below the head of the instrument, and the head must be submerged when it is recording data; do NOT mount the ADV closer than 15 cm from the bed (ideally, the ADV head should be ~20 cm above the bed). The ADV cannot be used in the supercritical section of the flow because the flow is too shallow.
6. Before you turn off the flume, make waves in the supercritical and subcritical regions of the flow. Can you get the waves to propagate upstream in each region? Now try to make waves just after the weir. Is the flow over the weir is subcritical or supercritical?

7. After you have taken all of your measurements, hit “stop” on the pump controllers (all three) and then turn off the master power switch.

**Data Collection and Analysis**

Your first goal is to plot the energy grade line and hydraulic grade line for the flow you establish. You can find the energy grade line by measuring stagnation pressure head (the elevation of the water within the Pitot tube) with the Pitot (you want the elevation above the bed, your datum). Measure the energy grade line (EGL) at a minimum of:

- Just under the sluice gate (stick the tube under the gate as far as you can get it to go).
- At the beginning (where the free surface first becomes horizontal), middle, and end of the supercritical flow region (3 points). Make measurements as high up in the water as possible without exposing the tip of the Pitot tube to air while you are taking the measurement. It may help to start at the bed and raise the Pitot tube and watch the head rise. Since friction is slowing the velocity down near the bed you want to raise the tube to get the maximum velocity (total pressure head) so basically you want to raise the Pitot tube until the pressure just starts to drop so you can find the maximum.
- Two different horizontal points within the hydraulic jump more than mid-way up in the water column. These won’t be at the same height. Again, make sure that the Pitot tube is always submerged.
- At the beginning, middle, and end of the subcritical flow region (3 points minimum), again, just enough below the free surface to ensure that the Pitot tube is always submerged. Make sure that all three measurements are at the same elevation.
- Record the hydraulic grade line (HGL) at each of the above sections as well. Note the head box (inlet section) is clear so you can measure the water depth inside the head box to get the initial elevation of the HGL.

**Checkout**

1. Use the results found in class to predict the downstream depth and velocity based on your measured upstream depth and velocity (class notes page 64).
2. Show a plot (in Matlab, Excel, or on the graph paper provided) of the energy and hydraulic grade lines vs. the distance from the sluice gate. Label your axes (don't forget units), and label the EGL and HGL. Mark the location of the hydraulic jump on the plot (beginning and end).
3. For each measurement station, write the Froude number value on your plot. If your EGL/HGL plot is in Excel, make a separate plot of Froude number vs. distance from the sluice gate.
4. Calculate the head loss through the hydraulic jump.
5. Can you detect any head loss in the supercritical and/or subcritical reaches from your measurements? Can you detect any head loss through the sluice gate? What would be the possible sources of this head loss?

6. In which regions is the Bernoulli equation valid for this flow?

7. Why do you think we use the ADV to measure velocity in the subcritical section and not the Pitot tube (hint: calculate the stagnation head for the measured subcritical velocity)?

8. Describe your attempts to make waves in the supercritical region, the subcritical region, and over the weir.

Appendix

EGL/HGL Measurement Worksheet

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