

EmFlume 1.5

Lab Manual

(sample)





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EmFlume 1.5 Specifications

<p>Hydraulic Channel</p> <ul style="list-style-type: none"> Channel dimensions: 1.52m x 93mm x 204mm (60" x 3.66" x 8") Anodized aluminum channel base Ultra scratch-resistant acrylic walls T-slot channel for instrument attachment Magnets at 30cm, 75cm, and 110cm for holding hydraulic models Adjustable slope from -0.6° to 5.7° (-1.0% to 10%) Digital inclinometer with 0.05° resolution 	<p>Lab Cart</p> <ul style="list-style-type: none"> Footprint: 82.5 cm x 157.5 cm (32.5" x 62") Full size with channel in position: 82.5 cm x 247.6 cm (32.5" x 97.5") Leveling casters Heavy duty welded steel construction Storage cabinet with adjustable shelves for all components Hydraulic channel pivots to store vertically within footprint
<p>Pump and Flow</p> <ul style="list-style-type: none"> Silent, brushless, 3-phase synchronous motor Digital control for 0-100% flow Flow capacity: 0-70 L/m (0-18.5 GPM) Unidirectional, oscillating flow capacity Accurate flow measurement from electromagnetic flow meter (no mechanical obstruction or parts) Fluid temperature reading Flange and union fittings for easy setup and maintenance 	<p>Instruments and Models</p> <ul style="list-style-type: none"> Pitot tube Broad-crested weir Ogee-crested weir Sharp-crested weir Point depth gauge V-notch weir set (90°, 60°, 45°) Cylindrical bridge pier Rectangular bridge pier Tapered bridge pier Culvert kit Adjustable sluice gate Tailwater gate Orifice plate Roughness insert
<p>Sediment</p> <ul style="list-style-type: none"> Custom color-coded by size melamine sediment 3 4-gallon buckets for media Custom filters for media catchment and drying 	
<p>Stilling Tank</p> <ul style="list-style-type: none"> Heavy duty acrylic walls for visibility Bottom supply for stilling flow before entering channel 	<p>Catchment Reservoir</p> <ul style="list-style-type: none"> 22-gallon polyethylene tank Drain with ball valve and hose bib Catchment basin with removable 70-micron filter for use with sediment
<p>Electrical Requirements</p> <ul style="list-style-type: none"> 110VAC, Max Load 9A 	<p>Weight</p> <ul style="list-style-type: none"> Dry weight 500 lbs Max weight with water 650 lbs
<p>Optional Items Available Soon</p>	
<ul style="list-style-type: none"> Wave Generator Wind Generator Digital Depth Gauge 	<ul style="list-style-type: none"> UV/LED Light Kit Sediment Feeder



Precautions and Warnings

1. Never run the pump without water in the reservoir.
2. Fluid temperatures in the flume should not exceed 40°C/104°F.
3. Do not freeze.
4. Do not leave water in system for more than two weeks without changing.
5. Never use ammonia-based cleaners on the acrylic walls.
6. Do not leave any non-aluminum metal components in direct contact with the aluminum base in the hydraulic channel. Prolonged contact, especially in the presence of chlorinated water, can cause corrosion.
7. The pump contains a very strong magnet. **Risk of death to people with pacemakers!** Use caution when in close proximity or when servicing.
8. The clear sides of the channel are made with an ultra-scratch-resistant acrylic; however, they can be scratched. Use caution when inserting and removing hydraulic shapes. A sample piece of the acrylic is included with your model to test materials.
9. Avoid pinch hazards when tipping the hydraulic channel into the vertical storage position.
10. Do not add weight (beyond water) to the stilling tank on the upstream end of the hydraulic channel.
11. Do not transport the EmFlume 1.5 with water in the hydraulic channel.
12. All electrical components on the EmFlume 1.5 have GFCI protection through the main power. However, always use caution when handling electrical instruments and water.
13. Always empty the hydraulic channel after use.
14. Do not modify or alter the components of the EmFlume 1.5 without consulting with Emriver. Any functional modification without authorization will void all warranties.



Introduction

The EmFlume 1.5 is a versatile tool for demonstrating open channel hydraulics to students of civil engineering, environmental fluid mechanics, fluvial geomorphology, sedimentology and stratigraphy. The compact and user-friendly design allows instructors and students to quickly set up experiments and visualize outcomes. It is easy to transition from working with sediment to working with a clean channel, and variables such as flow and slope are altered with simple controls.

As with any piece of lab equipment, it is necessary to use and care for the EmFlume 1.5 properly. Please read the EmFlume 1.5 Operating Manual thoroughly before conducting experiments.



The dynamic and interactive quality of the flume will no doubt generate hypotheses and novel experiments not addressed in this manual. This is wonderful and we encourage it! Please consult with the Operating Manual and test any materials and settings to make sure you do not exceed the capacity of the EmFlume 1.5. If you have questions about a specific application, please contact Emriver at 618-529-7423 or info@emriver.com.



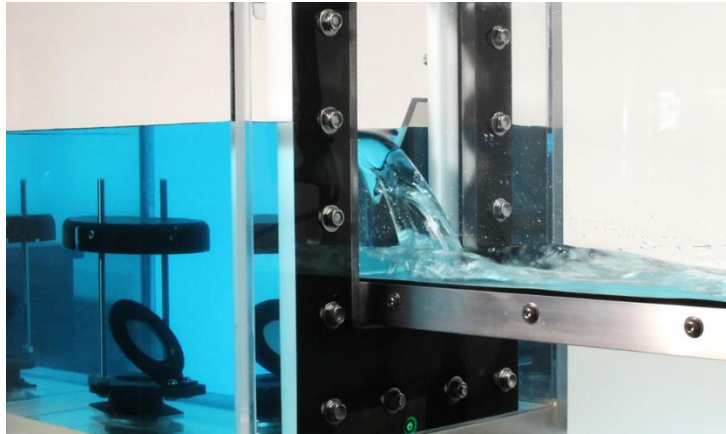
The labs in this collection are tools for teaching the fundamentals of open channel hydraulics, but they are not a substitute for the instruction and curriculum provided by an educator. The labs are somewhat sequential, but you should pick and choose according to your goals. In-depth theoretical explanations are beyond the scope of this manual. While there are plenty of equations in the labs, their full derivations are not included.

Most of the labs also include Excel spreadsheets. The first line includes sample data as well as formulas. If you prefer students to work through the calculations, or generate the formulas on their own, simply delete the first line to clear the data and formulas.

Most of the labs also include Excel spreadsheets. The first line includes sample data as well as formulas. If you prefer students to work through the calculations, or generate the formulas on their own, simply delete the first line to clear the data and formulas.



These labs serve as starting points, and may lead to much deeper exploration of topics in open channel hydraulics. If you develop expanded or novel labs and would like to share them with other users of the EmFlume1.5, please contact Emriver at info@emriver.com.



A Note on Units

All labs included here use SI units. Keep in mind that some textbook examples may assume imperial units. Also keep in mind that some formulas will require conversion; e.g. slope might need to be entered in degrees, percent or rise over run; for example, $1.50^\circ = 2.62\% = 0.0262/1.00$.

A Note on Scaling

Accurate scaling with physical models, especially those involving fluids, can become very complex in short order. For example, a civil engineer calculating discharge over a large spillway can reasonably ignore surface tension. However, in a very small model, using water with the same viscosity, surface tension could become a factor. Keep in mind that the equations coming from applied civil engineering necessarily neglect small influences that can appear when working at the scale of the EmFlume1.5.



Characterizing Open Channel Flow

Scientists, engineers and ecologists will often begin a description or analysis of flowing water by characterizing the flow according to the following parameters: *steady vs. unsteady*, *uniform vs. non-uniform*, *laminar vs. turbulent*, and *critical vs. subcritical*. By demonstrating and working with these variables in a controlled environment, such as the EmFlume 1.5, it is easy to isolate variables and understand them in a simplified form. These terms are explored more in-depth in the labs, but a brief overview is provided here.

Steady vs. Unsteady Flow

When flow is consistent over a period of time, it is considered steady. A spring-fed stream is a natural example. In the flume, steady flow can be demonstrated by setting the pump and slope to fixed points and leaving them. The discharge will remain consistent and steady until there is a change made to the settings.

Unsteady flow refers to flow changing over time. A flash flood is an example of unsteady flow, where flow rates rise and fall rapidly over time. A tidal flow is also an example of unsteady flow; the flow oscillates between a lower and higher flow rate. To model unsteady flow in the flume, the pump output can be changed with the controller, the flow can be blocked or released, or an oscillating flow can be created using the controller.

There are examples of unsteady flow in the manual, but whenever formulas are given, steady state is assumed.

Uniform vs. Non-uniform flow

Over a particular reach of a channel, uniform flow will exhibit the same depth and velocity in a channel with a constant cross-sectional shape. Non-uniform flow occurs when there is a change in slope, channel shape, depth, surface roughness or planform shape. The geomorphology of natural streams and rivers means that water moves through a variety of channel shapes, but there can be reaches that are uniform enough to allow for the application of formulas assuming uniform flow.

Non-uniform flow is further described as either *gradually varied flow (GVF)* or *rapidly varied flow (RVF)*. Gradually varied flow is characterized by relatively small changes in velocity, water depth and pressure distributions over a short distance. In the rectangular channel of the EmFlume 1.5, this will be seen as a gradual change in depth over the reach. In GVF, it is assumed that the pressure at any given section is hydrostatic.



Rapidly varied flow, as the name suggests, takes place in a relatively short reach and features very pronounced curvature of the streamlines. It can create high turbulence, with eddies and rollers. There are rapid changes in velocity and depth and the pressure cannot be assumed to be hydrostatic. Because of the turbulence and high variability, it is often necessary to develop empirical solutions to RVF.

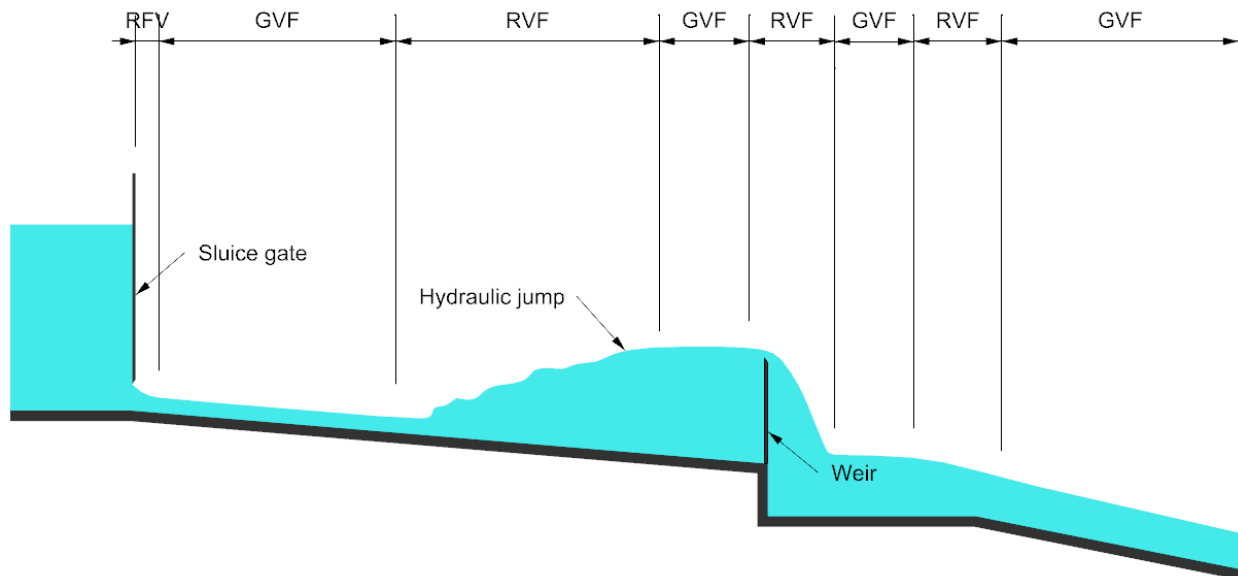


Fig. i.1 Varied flow in open channel

Laminar vs. Turbulent Flow

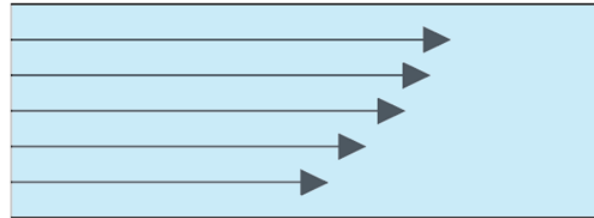
Laminar flow is smooth and streamlined. If the water in a channel is divided into layers, there is parallel movement in the direction of flow, but no mixing between layers. At any given point in the laminar flow, the velocity and direction remain constant. Laminar flow is rare in natural environments, but can exist in sheeting flow, for example, with thin layers of water flowing over impermeable surfaces.

Turbulent flow is characterized by chaotic mixing between layers. At any given point in the flow, the magnitude and direction of flow is highly variable. Turbulent flow is dominant in natural systems.

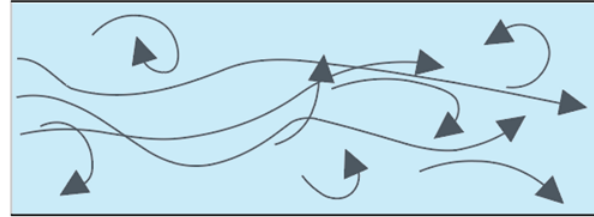


The degree of turbulence in a fluid is dependent on many factors, including velocity, viscosity, depth, channel roughness, presence of obstructions, etc. Reynolds number is used to quantify the degree of turbulence, with very low numbers indicating laminar flow and higher numbers indicating greater degrees of turbulence.

Laminar



Turbulent



Subcritical, Critical and Supercritical Flow

All open channel flow can be categorized as subcritical, critical, or supercritical. These terms are very important in understanding the behavior and effects of water flow based on velocity and depth.

Subcritical flow usually indicates deep, calm water. Sediment transport is minimal and subcritical flow allows for deposition on shores and river beds.

Supercritical flow is characterized by rapid flow that can transport and erode sediment in a river or coastal environment.

Critical flow is a transition state between the two other states, and is often unstable. Many engineered structures are designed to force a transition from supercritical to subcritical or vice versa. This can be done to control energy or allow for easy quantification of discharge.



Fig. i.2 Blue Spring, Current River, Missouri



One simple indicator for the determination of subcritical vs critical flow is to try creating a surface wave against the direction of flow in the channel. If it is possible to make a wave that travels *upstream* or *against* the flow, then flow is subcritical. If it is not possible, then the flow is supercritical.

The Froude number is used to quantify this flow characteristic.

Energy in Open Channel Flows

Open channel flow is captivating in many forms, but engineers and fluvial geomorphologists are mostly concerned with a flow's energy. Whether it's carving a Grand Canyon or moving sewage from a city, the quantification of the flow's ability to do work is often the desired outcome of study and analysis. The equations for the conservation of mass and the conservation of energy underlie the measurement of open channel flow.

The conservation of mass means that the amount of fluid entering a channel is the same as the amount leaving. In a natural channel, water can escape a channel through evaporation, seepage into groundwater, or animal (including human) extraction. In many civil engineering applications, including the micro-level of the EmFlume1.5, it is assumed that the mass of water is the same at any given point in the channel.

To get the mass of water we multiply the density of water (ρ) by the velocity of the flow (V) by the cross-sectional area of the water in the channel (A):

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2 \quad (\text{OCi.1})$$

The density of water varies according to temperature, but not much. So, the fluid density is often ignored, and the equation for conservation of mass in a channel is simplified as:

$$V_1 A_1 = Q = V_2 A_2 \quad (\text{OCi.2})$$

Where Q (m^3/s) is the discharge in the channel.

As with mass, energy cannot be created or destroyed. When considering water in open channels, chemical energy is largely ignored. The energy in a flowing fluid can take the form of kinetic energy (energy of motion), potential energy (energy of position/elevation), or molecular energy (energy of pressure). So, the total energy at any given point in a channel is the sum of these three forces.



$$\frac{\rho V^2}{2} + \rho gh + P \quad (\text{OCi.3})$$

↑ Kinetic Energy (velocity head)
 ↑ Potential Energy (elevation head)
 ↑ Molecular Energy (pressure head)

Where g is gravitational acceleration and h is elevation or height above a level datum (could be sea level, or could be the frame of the EmFlume 1.5). Because density and gravity are constants, the terms can be combined as $\rho g = \gamma$.

So, comparing the total energy at two points in a channel can be written as:

$$\frac{V_1^2}{2g} + h_1 + \frac{P_1}{\gamma} = \frac{V_2^2}{2g} + h_2 + \frac{P_2}{\gamma} \quad (\text{OCi.4})$$

This is the famous Bernoulli equation.

In open channel flow, by definition, there is a free surface open to the sky. This means that there is no significant pressure difference from one location to another. So, the pressure variable can be removed from the Bernoulli equation:

$$\frac{V_1^2}{2g} + h_1 = \frac{V_2^2}{2g} + h_2 \quad (\text{OCi.5})$$

The potential energy, or elevation head is a combination of the elevation above a datum (z), and the elevation above a channel bottom, water depth (d), so $z + d = h$.

$$\frac{V_1^2}{2g} + z_1 + d_1 = \frac{V_2^2}{2g} + z_2 + d_2 \quad (\text{OCi.6})$$

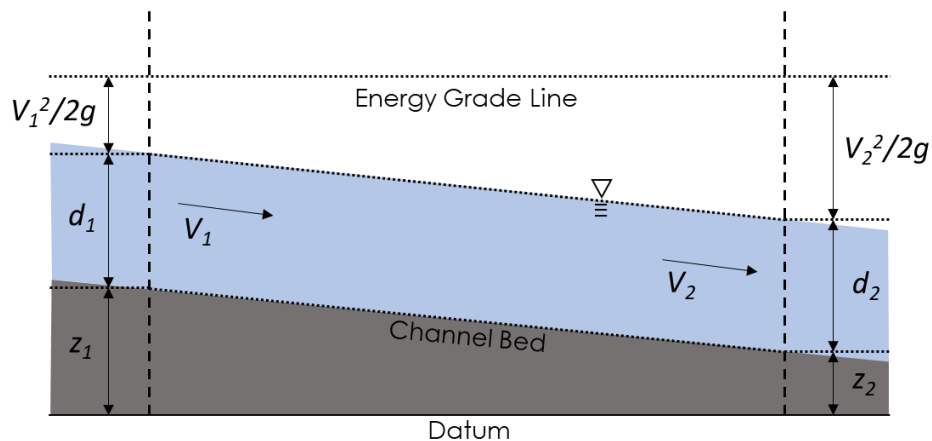


Fig. i.3 Conservation of energy along open channel



The equation OCi.6 and Figure i.3 demonstrate the conservation of energy, but assuming no friction loss. Many equations in open channel hydraulics will do the same, as the friction loss is assumed to be minimal.

Adding friction loss, often called *head loss*, (h_f) to the equation and the graphic, results in the following:

$$\frac{V_1^2}{2g} + z_1 + d_1 = \frac{V_2^2}{2g} + z_2 + d_2 + h_f \quad (\text{OCi.7})$$

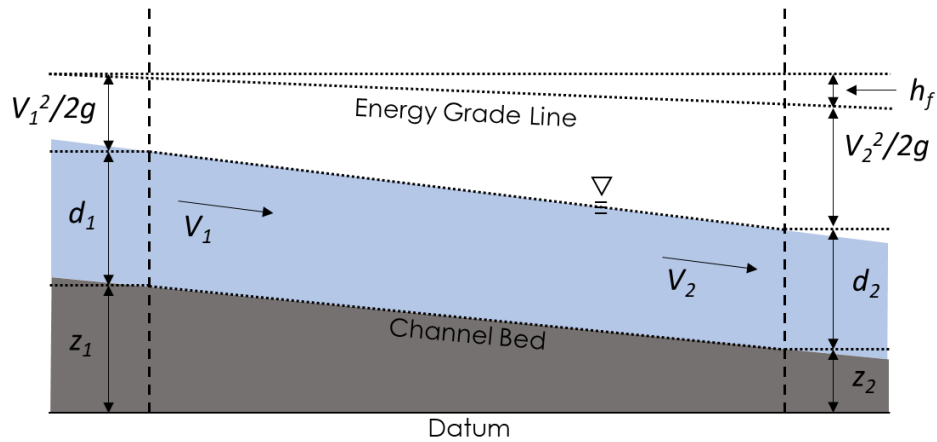


Fig. i.4 Conservation of energy with frictional head loss along open channel

It is very helpful to consider open channel flows as energy systems. The amount of energy in an open channel, as well as its form (i.e. potential v. kinetic), affects its impact on engineered structures such as weirs and armored embankments. In natural streams and rivers, the energy affects its ability to erode or deposit sediment.



Glossary of Terms

Alternate depth For a given flow rate and channel geometry the water depth can be at critical depth or one of two alternate depths corresponding to supercritical and subcritical flow.

Apron The area on the downstream end of a weir to protect it against scour by the force of water.

Backwater The longitudinal profile of water upstream of a constriction or control structure, such as a bridge or weir.

Bed form The irregular shape of a channel bed related to flow conditions, including ripples, dunes and anti-dunes.

Bed load Sediment transported in a channel by rolling, sliding, or skipping along the bed or very close to it; considered to be within the bed layer (contact load).

Bélanger equation Momentum equation applied across a hydraulic jump in a horizontal channel.

Bernoulli equation Foundational equation describing the conservation of energy in fluid mechanics.

Boundary layer The flow region next to a solid boundary where the flow velocity and streamlines are affected by friction.

Chezy coefficient Resistance coefficient for open channel flows.

Constriction Natural or artificial control section, such as a bridge crossing, channel reach or dam, with limited flow capacity in which the upstream water surface elevation is related to discharge.

Control section The cross-section in open channel flow where critical flow conditions take place.

Critical depth The flow depth for which the mean specific energy is at its minimum.

Critical flow conditions The flow conditions with a Froude number equal to 1, and specific energy at its minimum. Critical flow conditions are not stable over a long reach in an open channel.

Critical shear stress Minimum amount of shear stress required to initiate soil particle motion.

Discharge Volume of water passing through a channel during a given time.



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Darcy-Weisbach friction factor Dimensionless parameter characterizing the friction loss in a flow.

Free surface The contact surface between a liquid and a gas. A free surface is a defining characteristic of open channel flow where the water surface is exposed to atmosphere.

Froude number Dimensionless number that represents the ratio of inertial to gravitational forces in open channel flow.

Gate A plate, valve or system for controlling the passage and volume of flow.

Gradually varied flow Flow characterized by relatively small changes in velocity and pressure distributions over a short reach.

Headwater The water surface elevation on the upstream side of a culvert providing the energy to force water through the culvert.

Hydraulic jump The rapid transition from supercritical to subcritical flow.

Hydraulic radius Cross-sectional area of a stream divided by its wetted perimeter.

Inlet control One of two basic types of flow control in culvert hydraulics where the culvert barrel is capable of conveying more flow than the inlet will accept.

Invert Lowest point in the channel cross section or at flow control devices such as weirs, culverts, or dams.

Laminar flow Flow characterized by particles moving in parallel laminas or layers.

Longitudinal profile Profile of a stream or channel drawn along the length of its centerline. In drawing the profile, elevations of the water surface or the thalweg are plotted against distance as measured from the mouth or from an arbitrary initial point.

Manning's equation An empirical equation that applies to uniform flow in open channels and is a function of the channel velocity, flow area and channel slope.

Navier-Stokes equation A momentum equation applied to a small control volume of incompressible fluid to determine velocity.

Normal depth Flow depth when flow is uniform and steady in an open channel.

Outlet control One of two types of flow control in culvert hydraulics where the barrel is not capable of conveying as much flow as the inlet opening will accept.



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Performance curve A plot of the headwater depth or elevation versus flow rate for a given culvert.

Pitot tube Device for measuring flow velocity by contrasting flow pressure with atmospheric pressure.

Rapidly varied flow Flow characterized by large changes in velocity or depth over a short distance.

Reach Segment of channel length that is arbitrarily bounded for purposes of study.

Reynolds number Dimensionless number proportional to the ratio of inertial force over the viscous force, used to characterize the degree of turbulence in a flow.

Roller A large-scale eddy in an open channel flow. For example, in a hydraulic jump.

Roughness coefficient Numerical measure of the frictional resistance to flow in a channel, as in the Manning's or Chezy's formulas.

Sediment load Amount of sediment being moved by a stream.

Sediment transport The transport of sediment within a fluid flow.

Sediment transport capacity The volume of sediment material that can be carried by a specific flow per unit time.

Sequent depth The water depths before and after a hydraulic jump.

Shear stress The force that acts on a fluid parallel to a surface element, per unit area. It is caused by the friction between fluid particles, and a function of the fluid's viscosity and velocity.

Slope Fall per unit length along the channel centerline or thalweg.

Sluice gate A flow control gate that constricts flow from the top of the channel. Also called an undershot weir.

Steady flow Flow in which velocity, depth, and pressure do not change over a given period of time.

Subcritical flow When flow depth is greater than critical depth. It is generally calm and deep. Subcritical flow is controlled by downstream conditions.

Supercritical flow When flow depth is less than critical depth. It is generally fast and shallow flow and is controlled by upstream conditions.

Surface tension The property of a liquid surface to act as if it were a stretched elastic membrane.



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Suspended load Any transported sediment that is maintained in suspension.

Tailwater The depth of water on the downstream side of a culvert measured from the outlet invert, and an important factor in outlet control culvert hydraulics.

Thalweg Line extending down a channel that follows the lowest elevation of the bed.

Total head The sum of a fluid's elevation head, kinetic head, and pressure head. It is expressed in meters (or feet) of water.

Turbulence Motion of fluids in which local velocities and pressures fluctuate irregularly in a random manner as opposed to laminar flow where all particles of the fluid move in distinct and separate lines.

Uniform flow Flow of constant cross section and velocity through a reach of channel at a given time. Both the energy slope and the water slope are equal to the bed slope under conditions of uniform flow.

Unsteady flow Flow of variable discharge and velocity through a cross section with respect to time.

Velocity Time rate of flow usually expressed in m/s (ft/sec). Average velocity is the velocity at a given cross section determined by dividing discharge by cross-sectional area.

Vena contracta Minimum cross-sectional area of a flow discharging through an orifice or gate.

Viscosity Fluid property characterizing the resistance to shear; i.e. resistance to a change in shape or movement.

Weber number A dimensionless number used to characterize the ratio of inertial forces over surface tension forces. It is applied to problems involving the interface between liquids and between liquids and gases.

Weir Low dam used to raise the upstream water level and measure discharge.

Wetted perimeter In a channel's cross-section, it is the length of the wetted contact between the flowing stream and the solid channel boundaries.



List of Symbols

A	Cross-sectional Area (m^2)
b	Channel Width (m)
C	Constant Coefficient
E	Specific Energy (m)
Fr	Froude Number (dimensionless)
g	Gravitational acceleration ($9.81 m/s^2$)
L	Length (m)
n	Manning's Roughness Number (dimensionless)
P	Wetted Perimeter (m)
Q	Total volume discharge (m^3/s)
q	Discharge per meter width (m^2/s)
R_h	Hydraulic Radius (m)
Re	Reynolds Number (dimensionless)
S_o	Channel slope (m/m)
V	Velocity (m/s)
y	Water depth (m)
ρ	Fluid Density (kg/m^3)
μ	Viscosity (Pascal-second or $Pa \cdot s$)
τ	Shear stress (N/m^2 or Pa)



References & Recommended Reading

Chanson, H. (2004) *Environmental Hydraulics of Open Channel Flows*. Elsevier Butterworth-Heinemann, Burlington, MA, 2004.

Chow, V.T. (1959) *Open Channel Hydraulics*. McGraw-Hill, Boston, 1988.

Das, M.M., (2013) *Hydraulics and Hydraulic Machines*. PHI Learning, New Delhi, 2013.

Subramanya, K. (2015) *Flow in Open Channels*. McGraw Hill, New Delhi, 2015.

US Federal Highway Administration, *Hydraulic Design of Culverts*, Hydraulic Design Series 5, US Department of Transportation, 2005.



Lab OC6: Subcritical, Critical and Supercritical Flow – Froude Number and Specific Energy Curve

Open channel flow can be characterized as subcritical, critical or supercritical. In subcritical flow, surface disturbances, i.e. waves, can be perpetuated upstream. This kind of flow is typical in deep, tranquil sections of rivers, or upstream of a dam or weir. In supercritical flow, waves cannot be perpetuated upstream because the kinetic forces in the flow are dominant. Think of rapids or shallow water falling over a low-head dam. Critical flow is a transitional state between the other two.

Objective

1. Gain an intuitive feel for the characteristics of subcritical, critical and supercritical flow.
2. Calculate the Froude number and plot a Specific Energy Curve for four different flow rates.
3. Determine critical depth for each of the four flow rates.
4. Confirm the characteristics of subcritical and supercritical qualitatively by disturbing the surface and observing the travel of surface waves.

Background

The dimensionless Froude number, **Fr**, is used to quantify subcritical, critical and supercritical flow. It is widely used in open channel hydraulics.

$$Fr = \frac{v}{\sqrt{gh}} \quad (\text{OC6.1})$$

Where

h = Depth of water in m

v = Water velocity in m/s

g = Gravitational acceleration (9.81 m/s)

The critical depth for a particular flow rate indicates the minimum energy for that flow. Critical depth is not stable, however, and most often occurs in transition between the other two states.

Fr < 1 Subcritical Flow



$Fr = 1$ Critical Depth d_c

$Fr > 1$ Supercritical Flow

Understanding critical depth is useful because all weirs used for measuring discharge are designed to position the critical depth in a controlled location for measurement.

The formula for critical depth, d_c , is written:

$$d_c = \sqrt[3]{\frac{Q^2}{gb^2}} \quad (\text{OC6.2})$$

Where

Q = Discharge in m^3/s

g = Gravitational acceleration (9.81 m/s^2)

b = Width of rectangular channel in m

Familiarity with the Froude number and its applications will also become relevant when considering sediment transport, bedload scour, and control of hydraulic jump.

Specific Energy in a channel is defined as the energy measured above the channel bottom at the section.

$$E = h + \frac{Q^2}{2gA^2} \quad (\text{OC6.3})$$

Where

h = Depth of water in m

Q = Discharge in m^3/s

g = Gravitational acceleration (9.81 m/s^2)

A = Cross-sectional area of water channel ($h \times b$ (width)) in m^2

For a given discharge **Q** , the specific energy is a function of the depth of water only. A plot of depth, **h** , vs. **E** is called the **Specific Energy Curve**.

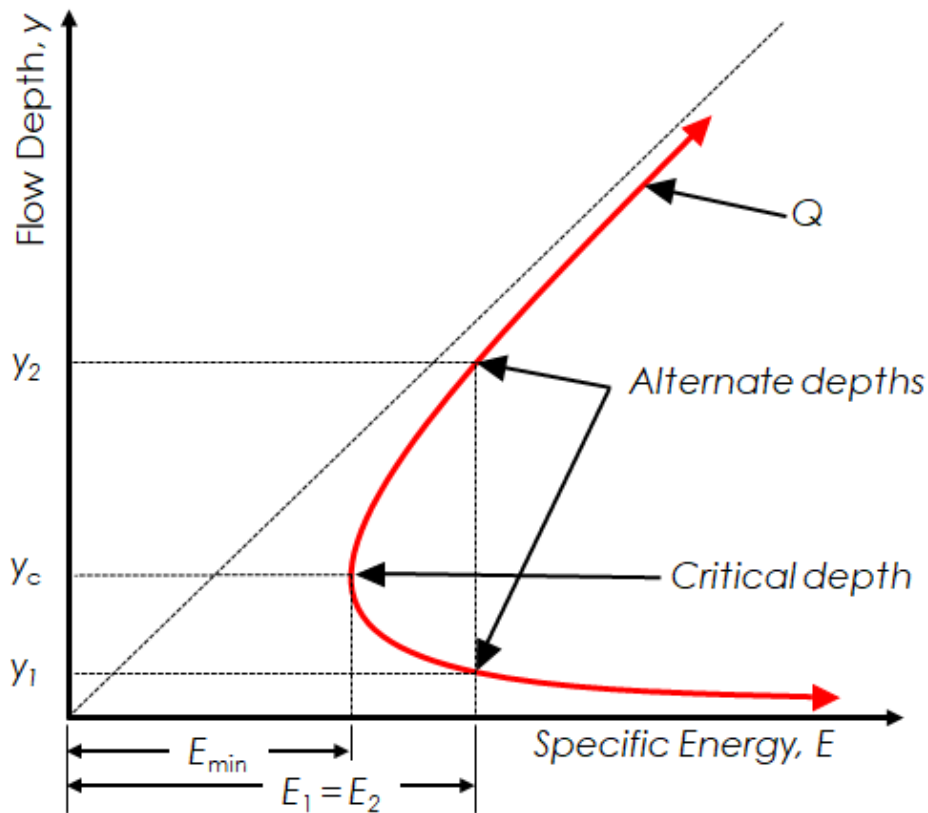


Fig OC6.1 Specific Energy curve

Note:

1. For a given value of E , there are two depths, called **alternate depths**. For the low depth, the bulk of the energy is in the form of kinetic energy whereas for the greater depth, most of the energy is in the form of potential energy.
2. There is a minimum specific energy with only a single depth of flow. The flow at this point is called **critical flow**.
3. The upper part of the curve (upper limb) is asymptotic to a 45° line that passes through the origin. The lower part (lower limb) is asymptotic to the horizontal axis. (For channels with a very steep slope, the asymptotic line is different from 45°.)
4. The existence of the two alternate depths means that it is possible to convey a given discharge with a shallow depth and high velocity or to convey the same discharge with a larger depth and low velocity. The shallow flow receives the name of supercritical flow whereas the flow with larger depth receives the name of sub-critical flow.



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- The **critical** depth, d_c , is associated with the point of minimum energy in the associated control volume and is an unstable depth that occurs within the jump.

Equipment and Materials

- Depth gauge (Manual Vernier or digital)
- Tailwater gate

Spreadsheet **Lab OC 6 Froude**

NOTE: The first line in the spreadsheet contains sample data and formulas. The instructor should choose whether to extend the formulas or delete them.

Procedures

- Fill the reservoir and make sure the channel is clean.
- Press the power buttons for both the pump and the flow meter.
- Start the flow. Experiment with different flow rates, slopes and water depths (using the tailwater gate). For the different configurations, use your hand or a paddle to attempt to create a surface wave against the direction of flow. This will provide you with a sense of what conditions will create representative flows.
- Create 20 different flow rates in the flume, with at least 8 you believe to be supercritical and 8 you believe to be subcritical. For each setting record the following in the spreadsheet:
 - Discharge (Q) as measured by the flow meter
 - Water depth at center of channel

UNIT REMINDERS	
Q	Discharge in m^3/s
S_o	Slope in $m(\text{rise})/m(\text{run})$
A	Area in m^2
V	Velocity in m/s
H	Depth & all distances in m
g	Gravitational acceleration = $9.81 m/s^2$
b	Channel width in m
Fr	Froude number
E	Specific Energy in m
C_d	Critical Depth in m

(NOTE TO INSTRUCTOR: If you would like students to go through the process, you can have them calculate cross-sectional area (A), velocity (V), critical depth (d_c) and specific energy (E) for each setting instead of using the pre-entered formulas in the spreadsheet.)

- Generate a specific energy curve using the data set you created with the 20 different settings.



Closing Procedures

1. Stop the flow at the controller.
2. Turn off power to the flume.
3. Remove the downstream tailwater gate.
4. Allow water to drain from the channel.

Results/Discussion

1. Describe the settings and configurations that generated subcritical and supercritical flows in the flume.
2. How well did your specific energy curve match the theoretical curve in Figure OC6.1? How would you describe or explain the differences?



Lab OC8: Hydraulic Jump

Hydraulic jump is a phenomenon in open channel flow where fast-moving flow changes suddenly into a slow-moving flow. This abrupt change of flow velocity is usually accompanied by violent turbulence called a hydraulic jump.

For a nice video introduction, see Practical Engineering:
<https://www.youtube.com/watch?v=7tjf8HWiR3Y>

Objective

The objective of this experiment is to create and observe a hydraulic jump and validate some of the important momentum and specific energy equations in a laboratory-scale open channel flow.

Background

Hydraulic jump is usually observed in open channel flow such as rivers and downstream of spillways or sluice gates where velocity of the water is high. This phenomenon can be used, for example, as an energy dissipater so that scouring of the alluvial fan at the river bottom can be prevented. Hydraulic jump can also be induced as a mixing device in water or sewage treatment designs. Engineers are usually concerned mainly with the possible occurrence, size, and location of the jump.

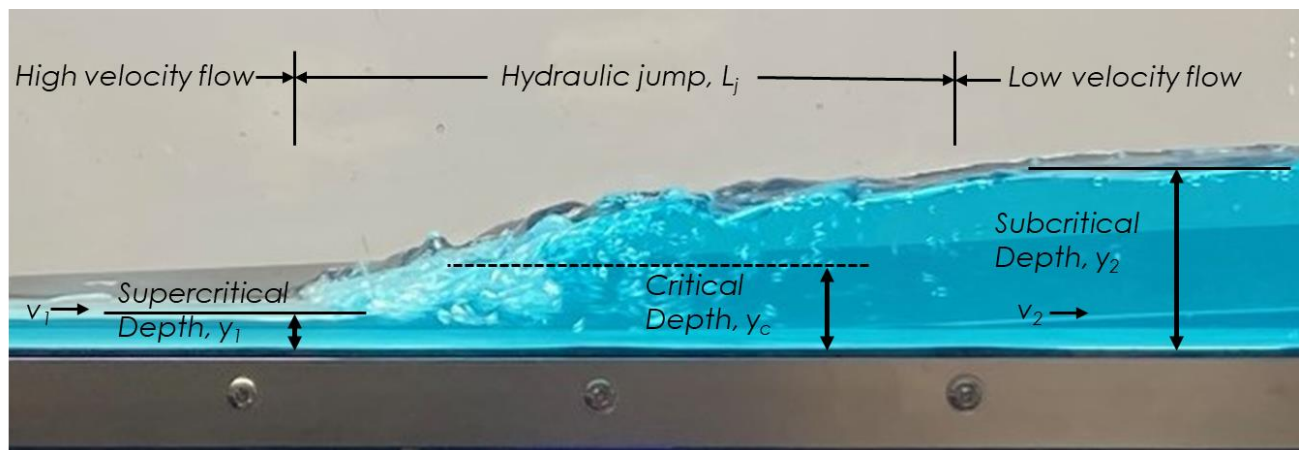


Fig. OC8.1 Hydraulic jump

Consider the hydraulic jump shown in the image above. The high velocity flow upstream of the hydraulic jump is known as supercritical flow and the low velocity flow downstream of the jump is known as subcritical flow.

A parameter that can be used to characterize these flow regimes (subcritical or supercritical) is the Froude number, **Fr**, (See Lab OC6). This is expressed as:



$$Fr = \frac{V}{\sqrt{gD}} \quad (\text{OC8.1})$$

where, V is the flow velocity, g is the gravitational acceleration, and D is the hydraulic depth. The Froude number, Fr , is < 1 for subcritical flow, > 1 for supercritical flow and $= 1$ for critical flow.

For a rectangular channel such as the EmFlume 1.5, $D = y$, and the Froude number (Fr) can be rewritten as follows:

$$Fr = \frac{V}{\sqrt{gD}} = \frac{Q}{by\sqrt{gy}} \quad (\text{OC8.2})$$

where, Q is discharge, b is the width of the channel, and y is the flow depth.

For supercritical flow in a rectangular channel (Figure 1), the energy of the flow is dissipated through frictional resistance due to channel boundary or any other structures along the channel, resulting in a decrease in velocity and an increase in depth in the direction of flow. A hydraulic jump occurs if the Froude number F_1 of the upstream flow, the upstream flow depth y_1 , and a downstream flow depth (sequent depth) y_2 satisfy the equation

$$\frac{y_2}{y_1} = 1/2 \left(-1 + \sqrt{1 + 8Fr_1^2} \right) \quad (\text{OC8.3})$$

This is the Belanger momentum equation, derived from the conservation of linear momentum equation. The equation can be used to predict the upstream or downstream depths when the other depth and Froude number are known.

$$y_2 = \frac{y_1}{2} \left(-1 + \sqrt{1 + 8Fr_1^2} \right) \quad (\text{OC8.4})$$

$$y_1 = \frac{y_2}{2} \left(-1 + \sqrt{1 + 8Fr_2^2} \right) \quad (\text{OC8.5})$$

Specific Energy (E)

Specific energy in open channel is defined as the energy per unit weight of water at any section of a channel measured with respect to the channel bottom. Hence,



$$E = y + \frac{V^2}{2g} \quad (\text{OC8.6})$$

This equation indicates that specific energy is equal to the sum of the depth of water and velocity head. For a rectangular channel of width **b**, this equation can be written as

$$E = y + \frac{Q^2}{y^2(2gb^2)} \quad (\text{OC8.7})$$

This equation indicates that for a given discharge, **Q**, the relationship between **E** and **y** can be plotted as shown in Figure 2 below.

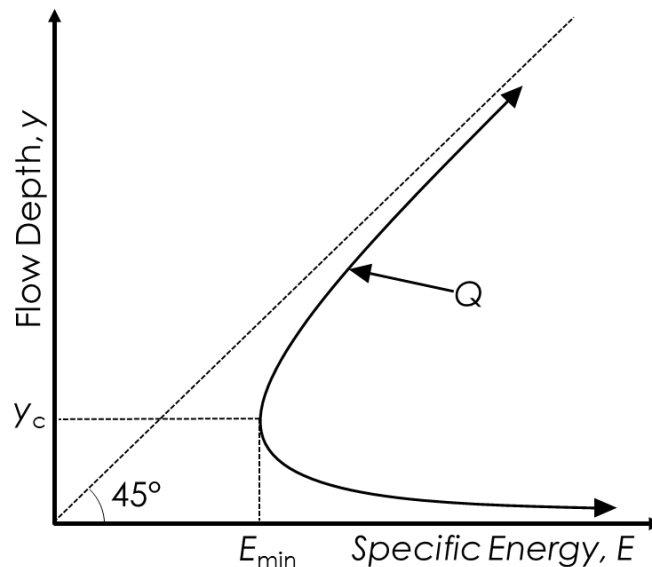


Fig. OC8.2 Specific Energy curve

The flow depth associated with the zone of minimum specific energy (Figure 2) is called **critical depth, y_c** . This depth is the unstable depth of a hydraulic jump. For rectangular open channel flow, the critical depth equation in terms of discharge, **Q**, and channel width, **b**, is:

$$y_c = \left(\frac{Q^2}{b^2 g} \right)^{1/3} \quad (\text{OC8.8})$$

On the specific energy curve (Figure OC8.2), the limb above the critical depth point shows a subcritical flow condition and below shows a supercritical flow condition. Therefore, for a given discharge, **Q**, subcritical flow occurs at a depth greater than critical depth and supercritical flow occurs at a depth below critical depth.



Characteristics of a hydraulic jump

The two characteristics commonly used in the evaluation or planning of a hydraulic jump are energy loss and efficiency.

Energy Loss, ΔE , is the loss of energy in the jump which is equal to the difference in specific energies before and after jump. It can be shown that the loss is

$$\Delta E = E_1 - E_2 = \frac{(y_2 - y_1)^3}{4y_1y_2} \quad (\text{OC8.9})$$

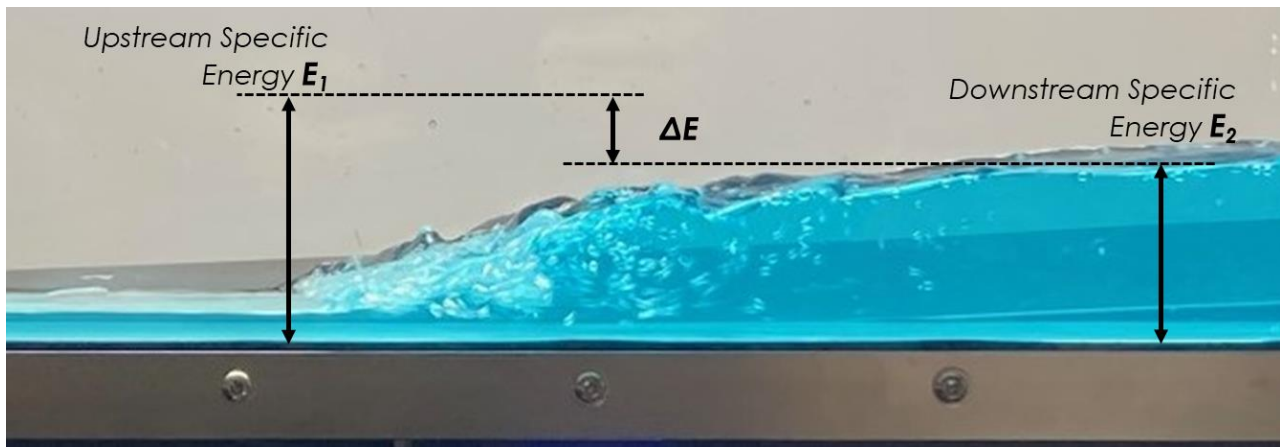


Fig. OC8.2 Energy loss in hydraulic jump

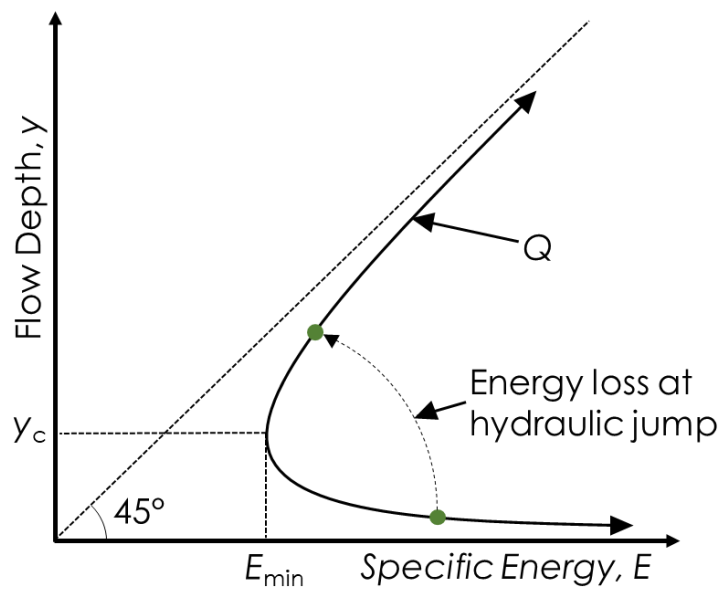


Fig. OC8.3 Energy loss in hydraulic jump, as shown on Specific Energy curve



In the Froude number lab, the idea of alternate depths was introduced; for a given Specific Energy, the two limbs of the curve above intersect with a vertical line, indicating one supercritical and one subcritical flow. In the graph above, note that the hydraulic jump involves energy loss, so the point on the upper limb (subcritical), will be to the left, indicating a lower energy.

Efficiency, E_2 / E_1 , is the ratio of the specific energy after the jump to that before the jump. It can be shown that efficiency is

$$\frac{E_2}{E_1} = \frac{(8Fr_1^2 + 1)^{3/2} - 4Fr_1^2 + 1}{8Fr_1^2(2 + F_1^2)} \quad (\text{OC8.10})$$

The above two characteristics of a hydraulic jump quantify the amount of energy lost due to the hydraulic jump in absolute or relative terms, respectively.

Hydraulic jumps can be predicted and classified according to the upstream Froude number.

Fr 1.0 – 1.7 = Undular jump

Fr 1.7 – 2.5 = Weak jump

Fr 2.5 – 4.5 = Oscillating jump

Fr 4.5 – 9.0 = Steady jump

$Fr > 9.0$ = Strong jump

Equipment and Materials

1. Tailwater gate
2. Depth gauge or side scale for measuring water depth
3. Sluice gate

Spreadsheet **Lab OC8 Hydraulic Jump**

NOTE: The first line in the spreadsheet contains sample data and formulas. The instructor should choose whether to extend the formulas or delete them.



Procedures

1. Fill the reservoir and make sure the channel is clean.
2. Set the EmFlume1.5 channel to 0° slope.
3. Install the sluice gate near the upstream end of the channel, around the 20cm mark. (Remember to wet the gate before lowering into the channel. See further instructions in the EmFlume1.5 Operating Manual.)
4. Start the flow and allow it to stabilize. Lower the sluice gate, being careful not to restrict the flow so much that you get an overflow.
5. Install a tailwater gate on the downstream end. Adjust gates and flow until you get a stable jump. Your initial setup should look something like this:

UNIT REMINDERS	
Q	Discharge in m^3/s
S_0	Slope in $\text{m}(\text{rise})/\text{m}(\text{run})$
A	Area in m^2
H	Depth & all distances in m
g	Gravitational acceleration = 9.81 m/s^2
B	Channel width in m
y_c	Critical depth in m

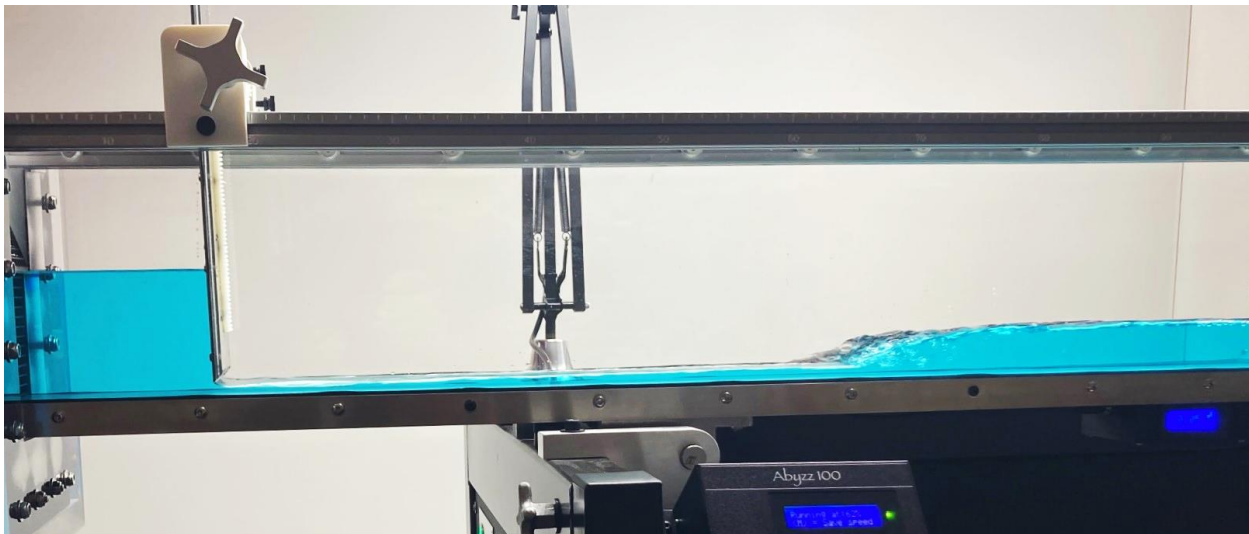


Fig. OC8.4 Sluice gate and hydraulic jump

6. Take measurements (y_1 , y_2 , etc.) using a depth gauge or a side scale and record in the spreadsheet, **Lab OC8 Hydraulic Jump**.
7. Calculate the Froude number for before and after the jump.
8. Calculate the critical depth for flow rate.
9. Calculate energy loss at jump.
10. Repeat the process using velocity as measured by the pitot tube rather than Q as measured by the magnetic flow meter. (You will need to create a new spreadsheet.)



11. Change the flowrate and repeat the calculations.
12. Change the slope and position of the sluice gate to generate upstream Froude numbers to create hydraulic jumps that would be classified as *undular, weak, oscillating and steady*.

Fr 1.0 – 1.7 = Undular jump

Fr 1.7 – 2.5 = Weak jump

Fr 2.5 – 4.5 = Oscillating jump

Fr 4.5 – 9.0 = Steady jump

$Fr > 9.0$ = Strong jump

(You will likely not be able to get a Froude number over 9.0 for a *strong* jump.)

13. As an additional experiment, add a roughness insert and repeat procedures to see the effects.

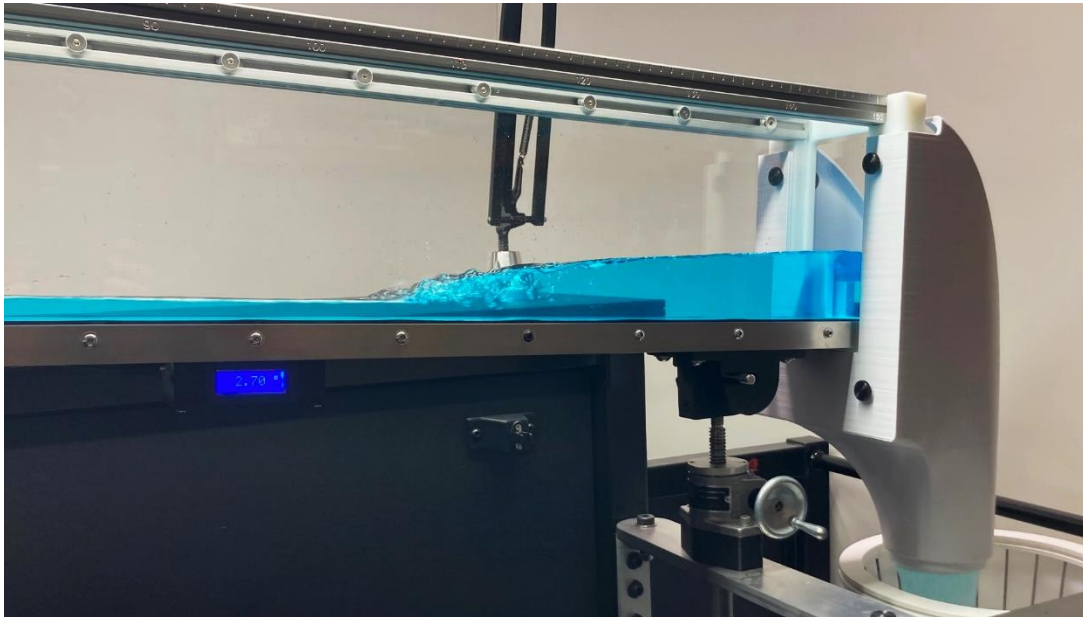


Fig. OC8.5 Hydraulic jump with steep slope and tailgate.

Closing Procedures

1. Stop the flow at the controller.
2. Remove the depth gauge and store.
3. Remove the sluice gate and store.
4. Remove the roughness insert if it was used.



EmFlume 1.5 Lab Manual



5. Allow the channel to drain and wipe it clean.
6. Turn off all power.

Results/Discussion

1. With respect to the upstream Froude number, F_1 , how do you characterize the hydraulic jumps in terms of strength and stability?
2. How do the tailwater depth, y'_2 , and the sequent depth, y_2 , compare? Was it the result you expected? If not, what do you think happened? If yes, explain your expectation using the experiment results.
3. "Supercritical flow occurs at a depth below critical depth and subcritical flow occurs at a depth greater than critical depth." Validate this statement in your results.
4. What is the relationship between upstream Froude number, F_1 , and the energy loss, ΔE , and hydraulic jump efficiency, E_2/E_1 ? You can plot F_1 versus energy loss, and F_1 versus efficiency curves. Discuss these relationships.
5. What kind of energy loss, ΔE , and hydraulic jump efficiency, E_2/E_1 , values do you expect when designing a hydraulic jump to act as a good energy dissipater? What do those values imply for the upstream Froude number, F_1 ?