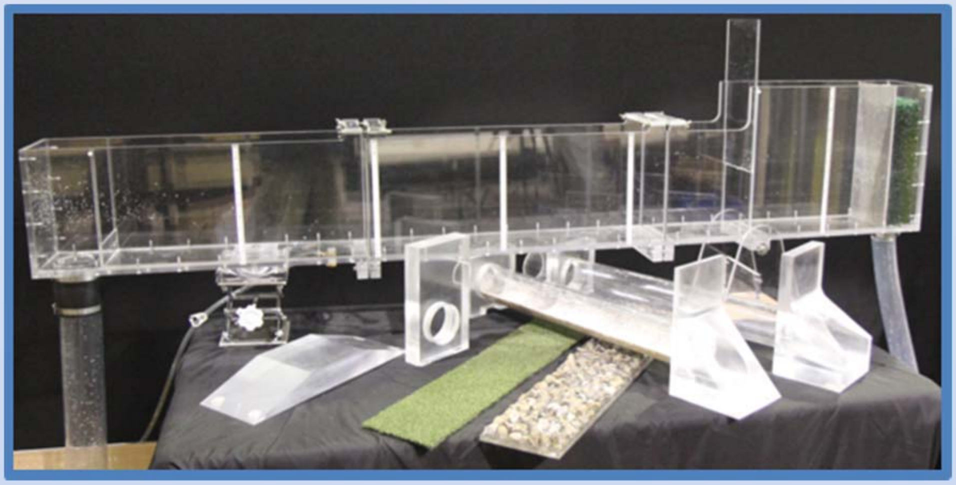
USER'S MANUAL

FLUME MODEL

FDOT Contract No.: BDV29 977-03



Andrew Craig, M.S., P.E. & Marian Muste, Ph.D.

IIHR - Hydroscience & Engineering
The University of Iowa
100 C. Maxwell Stanley Hydraulics Laboratory
Iowa City, IA 52242

M. Emre Bayraktar, Ph.D., Associate Professor

OHL School of Construction
College of Engineering and Computing
Florida International University
10555 West Flagler St.
Miami, FL 33174

Submitted to:

Florida Department of Transportation
Research Center
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Tallahassee, FL 32399

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SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
^{o}F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	^{o}C

TECHNICAL REPORT DOCUMENTATION PAGE

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16. Abstract

The major objective of this project was to develop a custom, easily portable flume model and culvert system to be used by the FDOT Hydraulics Department personnel during the Culvert Design Training Course. The custom portable hydraulic flume model designed and constructed in this project facilitates visual demonstration of different physical characteristics of open channel water flow and numerous hydraulic principles associated with various culvert configurations. In this project, the project team also prepared a user-friendly user's manual for the flume model containing example experiments related to various open-channel flow concepts and flow through selected hydraulic structures.

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EXECUTIVE SUMMARY

The objective of this project was to develop a custom, easily portable flume model and culvert system to be used by the FDOT Hydraulics Department personnel during the Culvert Design Training Course. The desktop flume is designed to facilitate visualization and demonstration of basic open-channel flow concepts and flow through selected hydraulic structures. To ensure the portability of the demonstration unit, a modular design was used with fast assembling components. The flume model is self-contained and allows assembly/disassembly with ease not to take more than 15 minutes with standard tools (i.e. wrench, socket, and screwdriver).

In this project, the project team also prepared a user-friendly user's manual for the flume model containing example experiments related to various open-channel flow concepts and flow through selected hydraulic structures.

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1. SUBCRITICAL AND SUPERCRITICAL FLOW

1.1. Objective

To observe the differences in characteristics between subcritical and supercritical flow states in an open channel, and to understand the properties of each flow condition.

1.2. Definitions

- **Open Channel**: An open channel is a conduit with a free surface that is subjected to atmospheric pressures.
- **Subcritical Flow**: Subcritical flow is the hydraulic condition that occurs when the actual water depth is greater than critical depth. This causes the flow to be dominated by gravitational forces and behave as a stable flow.
- **Supercritical Flow**: Supercritical flow is the hydraulic condition that occurs when the actual water depth is less than critical depth. This causes the flow to be dominated by inertial forces and behave in as an unstable flow.
- **Critical Flow**: Critical flow is the hydraulic condition that possesses the minimum possible energy for that flow rate.
- **Critical Depth**: Critical Depth is the depth at which the flow is at its minimum energy with respect to the bottom of the channel.
- **Velocity:**

$$v = \frac{Q}{y * B} \tag{1}$$

Where Q is the flow rate, y is the water depth and B is the width of the channel.

- **Froude Number**: The Froude number is a convenient index of the flow regime. It is used to determine whether the flow is subcritical or supercritical. The Froude number is less than one for subcritical flow and greater than one for supercritical flow. It is determined using the following equation:

$$Fr = \frac{v}{\sqrt{g * L}} \tag{2}$$

Where *v* is the velocity of the water, *g* is the gravitational force and *L* is some characteristic length of the channel (for the case of a rectangular channel the characteristic length is the depth).

1.3. Experimental Procedures

The following procedures can be interchanged between smooth channel, short vegetation, long vegetation, and rip-rap configurations. Procedures for operation with the smooth rectangular channel are outlined below. Settings and results from model runs with each of the channel inserts are provided in Table 1 through Table 8. The tables are accompanied by photographs showing examples of each flow state with each of the different inserts installed[1].

1.3.1. Subcritical Flow

1. Level the channel slope by adjusting the screw jack.
2. Install three stop logs at the tailgate and open the sluice gate.
3. Turn on the pump and set the flow rate to 4.5 cubic feet per minute (cfm) using the control valve.
4. Measure the elevation of the water surface at the head box and test sections one through four. This is the water depth, y, from equation 1.
5. Calculate the velocity using equation 1.
6. Calculate the Froude number using equation 2.
7. Create a disturbance in the water and observe how the waves travel upstream in subcritical flow conditions.

1.3.2. Supercritical Flow

1. Set the channel slope to 1.3 degrees using the screw jack.

[1] Not all of the photographs are exact representations of the settings and results provided in Tables 1 through 8 and are provided as visual examples only.

2. Install one stop log at the tailgate and keep the sluice gate open to allow for full flow conditions.
3. Turn on the pump and set the flow rate to 5.0 cfm using the control valve.
4. Measure the elevation of the water surface at the head box, and test sections one through four. This is the water depth, y, from equation 1.
5. Calculate the velocity using equation 1.
6. Calculate the Froude number using equation 2.
7. Create a disturbance in the water and observe how the waves cannot travel upstream in supercritical flow conditions.

1.3.3. Settings & Results

Table 1. Subcritical Flow – Smooth Channel

Settings		
Flow Rate =	7.00	cfm
Channel Slope =	0	degrees
Sluice Gate Opening =	open	
No. Stoplogs =	3	

Results			
Location	Depth (in)	Velocity (ft/s)	Froude Number
Head Box	3.50	0.800	0.261
Test Section 1	3.61	0.776	0.249
Test Section 2	3.68	0.761	0.242
Test Section 3	3.70	0.757	0.240
Test Section 4	3.74	0.749	0.236

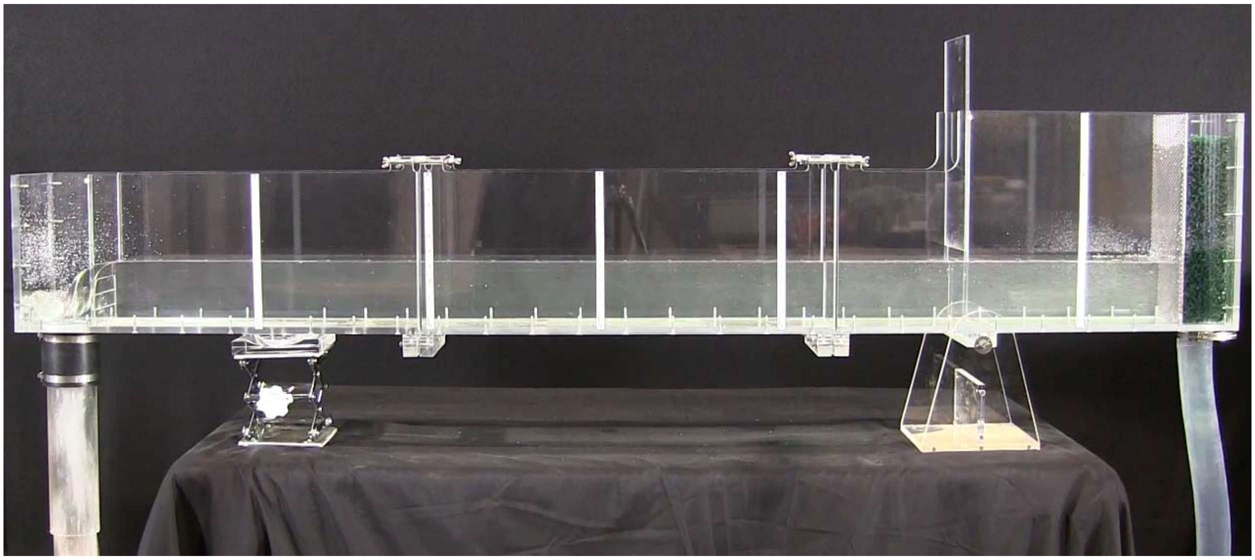

Figure 1. Subcritical flow in a smooth channel

Table 2. Supercritical Flow – Smooth Channel

Settings		
Flow Rate =	8.80	cfm
Channel Slope =	0.8	degrees
Sluice Gate Opening =	open	
No. Stoplogs =	1	

Results			
Location	Depth (in)	Velocity (ft/s)	Froude Number
Head Box	1.45	2.428	1.231
Test Section 1	1.07	3.290	1.942
Test Section 2	1.00	3.520	2.150
Test Section 3	1.90	1.853	0.821
Test Section 4	2.78	1.266	0.464

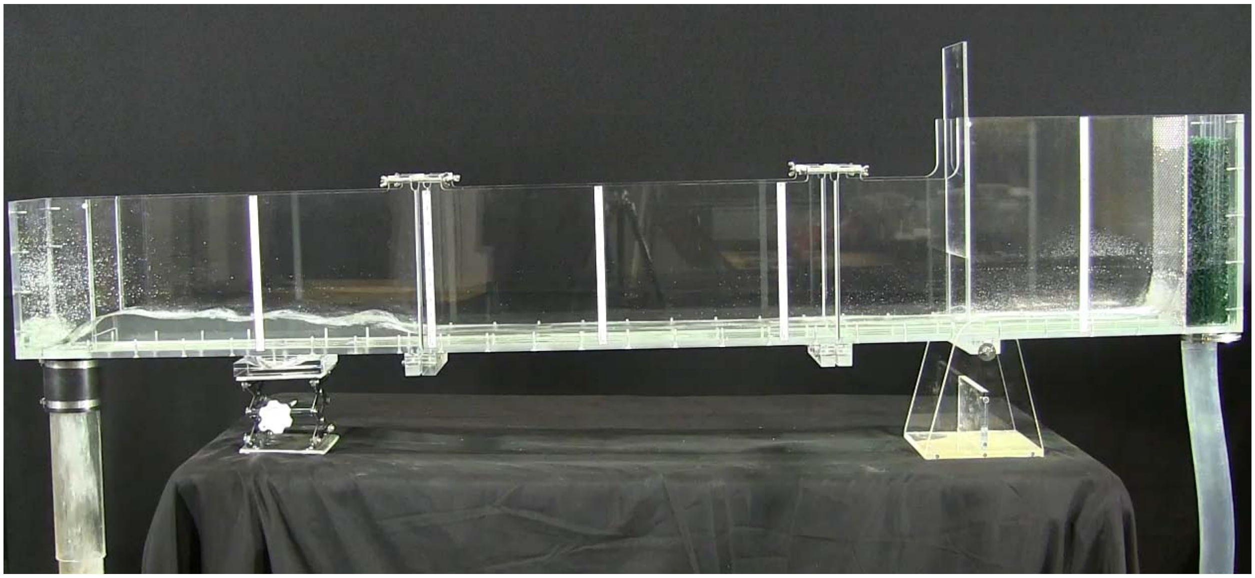

Figure 2. Supercritical flow with hydraulic jump in a smooth channel

Table 3. Subcritical Flow – Short Vegetation

Settings		
Flow Rate =	7.00	cfm
Channel Slope =	0	degrees
Sluice Gate Opening =	open	
No. Stoplogs =	2	

Results			
Location	Depth (in)	Velocity (ft/s)	Froude Number
Head Box	3.50	0.800	0.261
Test Section 1	2.52	1.111	0.427
Test Section 2	2.62	1.069	0.403
Test Section 3	2.68	1.045	0.390
Test Section 4	3.81	0.735	0.230

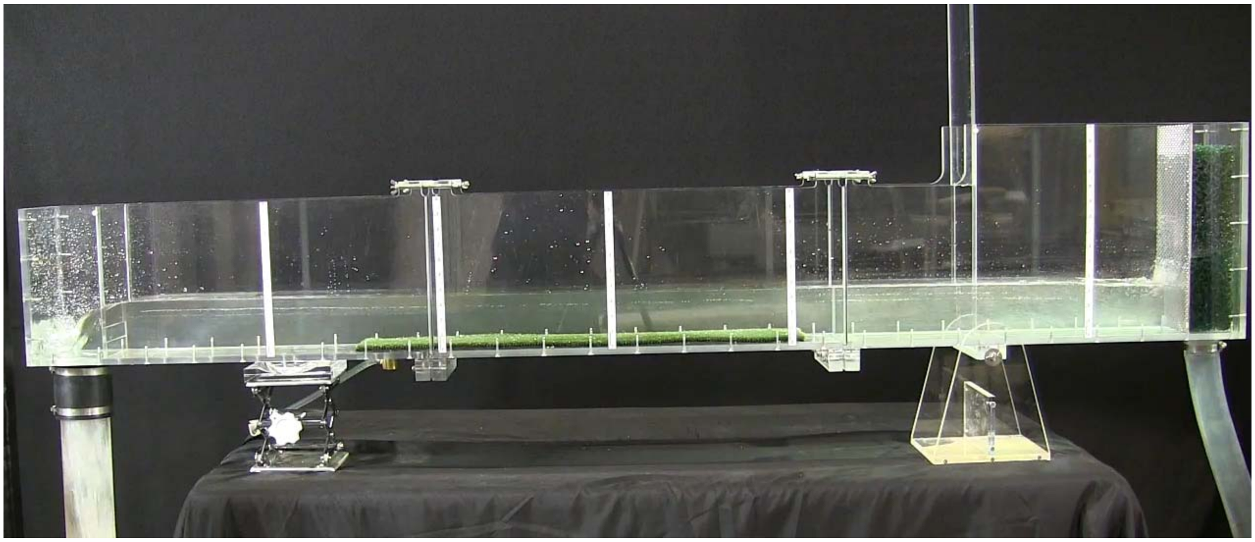

Figure 3. Subcritical flow with short vegetation

Table 4. Supercritical Flow – Short Vegetation

Settings		
Flow Rate =	5.00	cfm
Channel Slope =	1.3	degrees
Sluice Gate Opening =	open	
No. Stoplogs =	1	

Results			
Location	Depth (in)	Velocity (ft/s)	Froude Number
Head Box	1.06	1.882	1.115
Test Section 1	1.50	1.333	0.665
Test Section 2	1.06	1.882	1.115
Test Section 3	1.06	1.882	1.115
Test Section 4	2.06	0.970	0.412

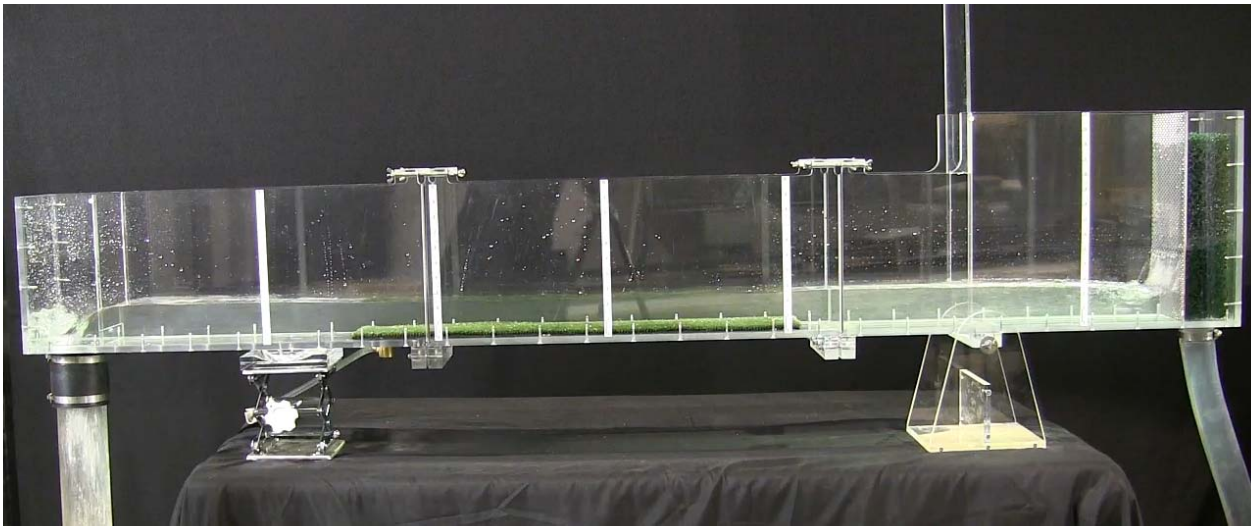

Figure 4. Supercritical flow with short vegetation

Table 5. Subcritical Flow – Long Vegetation

Settings		
Flow Rate =	7.00	cfm
Channel Slope =	0	degrees
Sluice Gate Opening =	open	
No. Stoplogs =	2	

Results			
Location	Depth (in)	Velocity (ft/s)	Froude Number
Head Box	3.68	0.761	0.242
Test Section 1	2.79	1.004	0.367
Test Section 2	2.71	1.033	0.383
Test Section 3	2.68	1.045	0.390
Test Section 4	3.78	0.741	0.233

Figure 5. Subcritical flow with long vegetation

Table 6. Supercritical Flow – Long Vegetation

Settings		
Flow Rate =	5.00	cfm
Channel Slope =	0	degrees
Sluice Gate Opening =	open	
No. Stoplogs =	1	

Results			
Location	Depth (in)	Velocity (ft/s)	Froude Number
Head Box	1.69	1.185	0.557
Test Section 1	1.50	1.333	0.665
Test Section 2	1.25	1.600	0.874
Test Section 3	1.13	1.778	1.024
Test Section 4	2.19	0.914	0.378

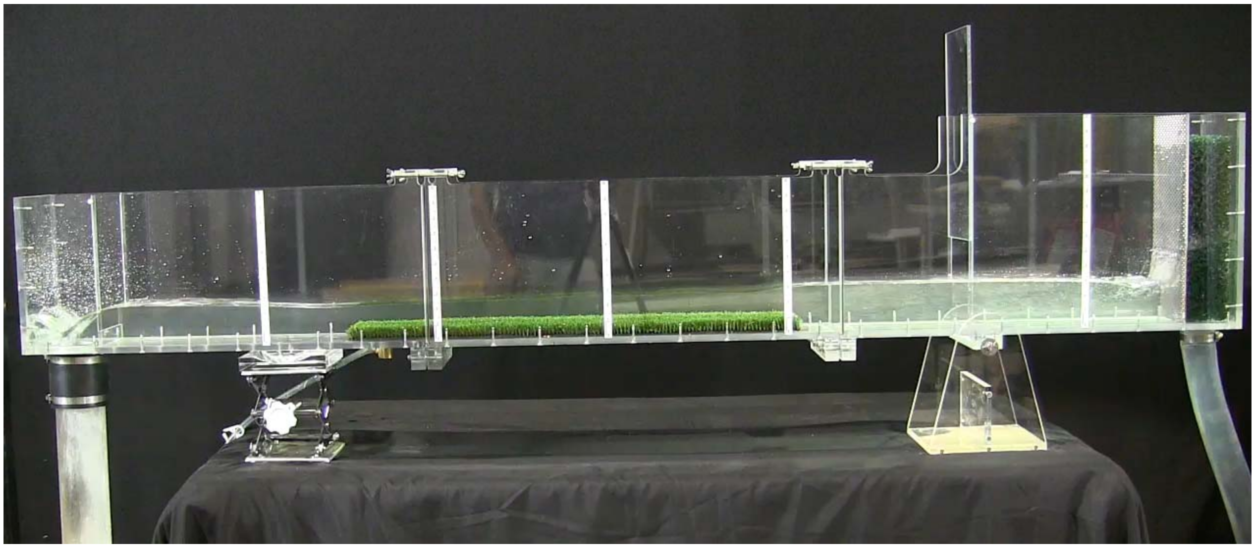

Figure 6. Supercritical flow with long vegetation

Table 7. Subcritical Flow – Rip-Rap

Settings		
Flow Rate =	7.00	cfm
Channel Slope =	0	degrees
Sluice Gate Opening =	open	
No. Stoplogs =	2	

Results			
Location	Depth (in)	Velocity (ft/s)	Froude Number
Head Box	3.68	0.761	0.242
Test Section 1	2.53	1.107	0.425
Test Section 2	2.45	1.143	0.446
Test Section 3	2.45	1.143	0.446
Test Section 4	3.78	0.741	0.233

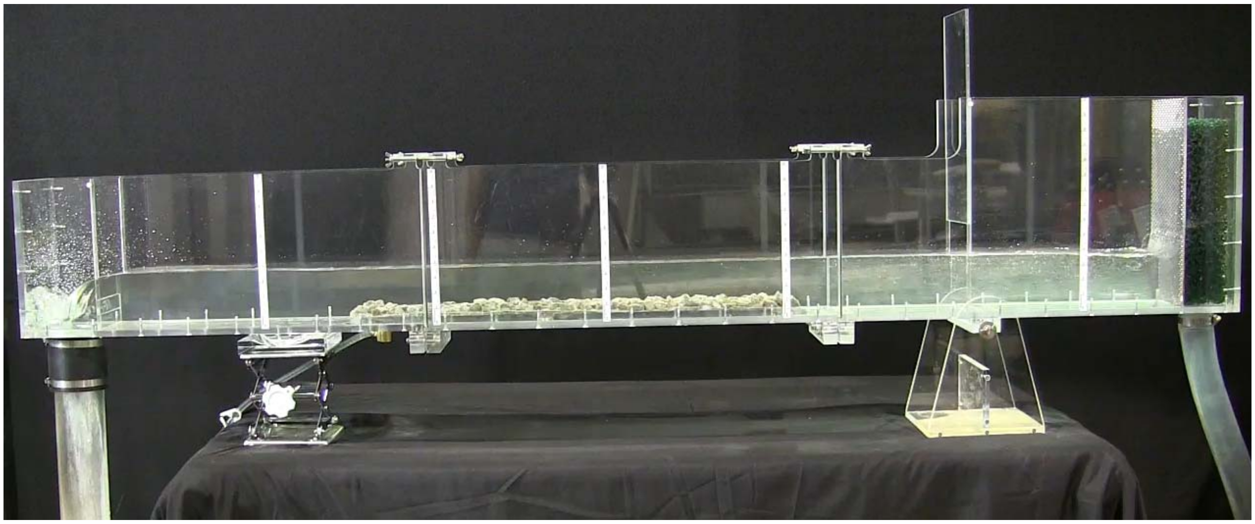

Figure 7. Subcritical flow with Rip-Rap

Table 8. Supercritical Flow – Rip-Rap

Settings		
Flow Rate =	7.00	cfm
Channel Slope =	0	degrees
Sluice Gate Opening =	open	
No. Stoplogs =	1	

Results			
Location	Depth (in)	Velocity (ft/s)	Froude Number
Head Box	3.20	0.875	0.299
Test Section 1	1.84	1.522	0.685
Test Section 2	1.58	1.772	0.861
Test Section 3	1.24	2.258	1.238
Test Section 4	2.60	1.077	0.408

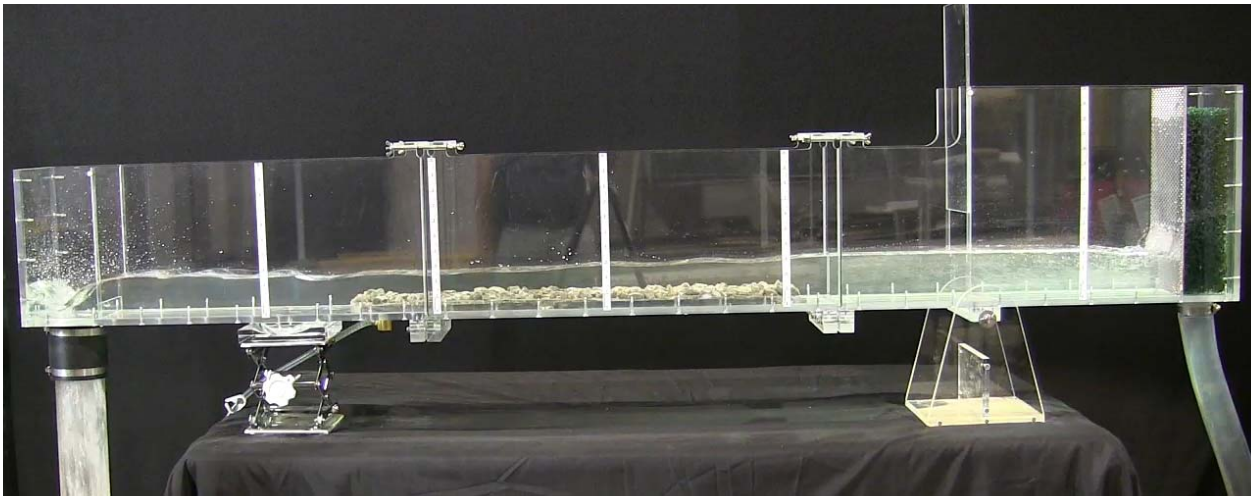

Figure 8. Supercritical flow with Rip-Rap

2. HYDRAULIC JUMP IN SMOOTH CHANNEL

2.1. Objective

To observe the characteristics of a strong hydraulic jump that is induced by a sluice gate.

2.2. Definitions

- **Hydraulic Jump**: Hydraulic jump is the rapid transition from below the critical depth to above the critical depth. It occurs where supercritical flow interacts with a section of subcritical flow.

2.3. Experimental Procedures

1. Set the channel slope to 2.3 degrees using the screw jack.
2. Install two stop logs at the tailgate and open the sluice gate 0.7 inches.
3. Turn on the pump and set the flow rate to 5.0 cfm using the control valve.
4. Measure the elevation of the water surface at the head box, and test sections one through four.
5. Observe how the section of supercritical flow rapidly transitions to subcritical flow through a hydraulic jump near test section 3.

2.3.1. Settings & Results

Table 9. Hydraulic Jump in Smooth Channel

Settings		
Flow Rate =	5.00	cfm
Channel Slope =	2.3	degrees
Sluice Gate Opening =	0.7	inches
No. Stoplogs =	2	

Results			
Location	Depth (in)	Velocity (ft/s)	Froude Number
Head Box	4.88	0.410	0.113
Test Section 1	0.50	4.000	3.455
Test Section 2	0.50	4.000	3.455
Test Section 3	2.50	0.800	0.309
Test Section 4	3.13	0.640	0.221

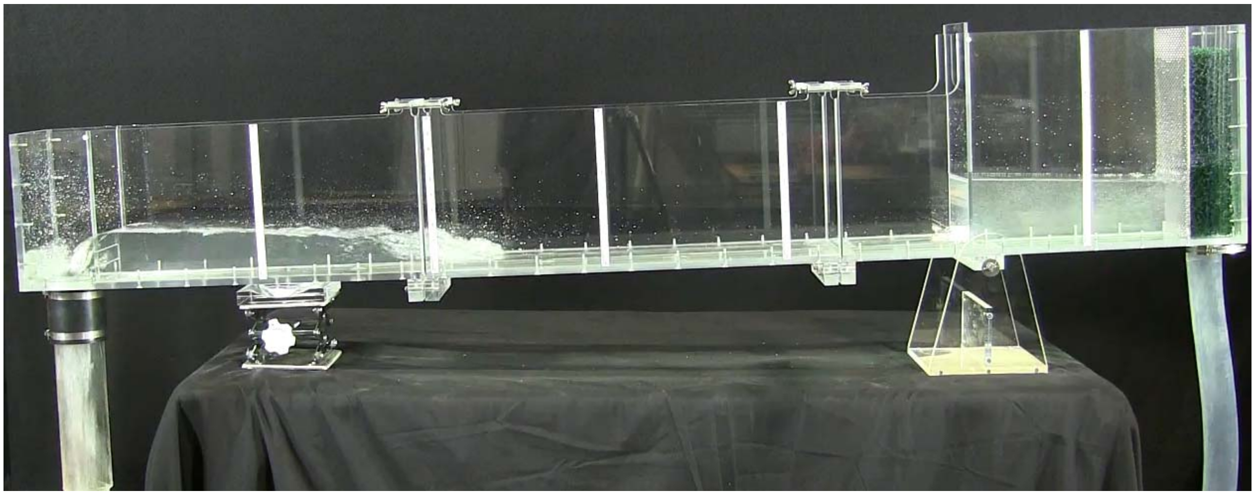

Figure 9. Hydraulic jump in smooth channel

3. VARIED FLOW

3.1. Objective

To understand the flow patterns over a broad-crested weir in order to demonstrate varied flow in the model.

3.2. Definitions

- **Varied Flow**: The depth of flow changes along the length of the channel.
- **Broad-Crested Weir**: A broad crested weir is a flat topped weir that is typically used to measure open channel flow rate. The weir is long enough that parallel flow occurs over it, and that the flow over the weir is critical.

3.3. Experimental Procedures

1. Set the channel slope to 1.3 degrees by adjusting the screw jack.
2. Install one stop log at the tailgate and open the sluice gate to allow for full flow conditions.
3. Install the broad-crested weir.
4. Turn on the pump and set the flow rate to 4.0 cfm using the control valve.

5. Observe how flow over the broad-crested weir transitions through subcritical, critical, supercritical, and then back to subcritical via a hydraulic jump near test section 4.

3.3.1. <u>Settings & Results</u>

Table 10. Varied Flow

Settings		
Flow Rate =	4.00	cfm
Channel Slope =	1.3	degrees
Sluice Gate Opening =	open	
No. Stoplogs =	1	

Results			
Location	Depth (in)	Velocity (ft/s)	Froude Number
Head Box	2.90	0.552	0.198
Test Section 1	3.38	0.473	0.157
Test Section 2	0.81	1.975	1.340
Test Section 3	0.50	3.200	2.764
Test Section 4	0.94	1.702	1.072

Figure 10. Gradually Varied Flow

4. Flow Conditions in a Culvert

4.1. Objective

Observe the flow types associated with four flow conditions:

- Inlet control, low tailwater
- Inlet control, hydraulic jump in culvert
- Outlet control, partial full flow
- Outlet control, full flow

4.2. Definitions

- **Culvert**: A culvert is a pipe that carries water under or through some feature that would otherwise block the flow. Culverts are classified according to which of their ends controls the discharge capacity.
- **Inlet control**: Inlet control is where the flow can travel through and out of the culvert faster than it can enter the culvert.
- **Outlet control**: Outlet control is where the flow cannot exit the culvert as fast as it can enter the culvert.
- **Energy equation:**

$$HW_0 + \frac{v_{up}}{2g} = TW + \frac{v_{down}}{2g} + H_L \qquad (3)$$

Where HW_0 is the water depth at the headbox, v_{up} is the velocity of the water upstream of the culvert, TW is the water depth at test section 4, v_{down} is the velocity of the water downstream of the culvert, and H_L is the head loss.

4.3. Experimental Procedures – Flared Entrance Treatment

4.3.1. Inlet Control – Low Tailwater

1. Set the channel slope to 3.2 degrees using the screw jack.
2. Do not install any stop logs at the tailgate and open the sluice gate to allow for full flow conditions.
3. Install the smooth single barrel culvert with the flared entrance treatment.
4. Turn on the pump and set the flow rate to 4.9 cfm using the control valve.
5. Observe how the flow is restricted into the inlet, causing the water to build up at the entrance to the culvert, and that the full capacity of the culvert is not being utilized to handle the flow.

4.3.2. Inlet Control – Hydraulic Jump in Pipe

1. Set the channel slope to 3.2 degrees using the screw jack.
2. Install four stop logs at the tailgate and open the sluice gate to allow for full flow conditions.
3. Install the smooth single barrel culvert with the flared entrance treatment, and free exit.
4. Turn on the pump and set the flow rate to 2.5 cfm using the control valve.
5. Measure the elevation of the water surface at test sections one and four. These can be taken as the headwater depth (Hw_0) and tailwater depth (TW) respectively.
6. The head losses (H_L) can be calculated using equation 3.

4.3.3. Outlet Control – Full Flow

1. Level the channel slope using the screw jack.
2. Install four stop logs at the tailgate and open the sluice gate to allow for full flow conditions.
3. Install the smooth single barrel culvert with the flared entrance treatment, and free exit.
4. Turn on the pump and set the flow rate to 6.6 cfm using the control valve.

5. Measure the elevation of the water surface at test sections one and four. These can be taken as the headwater depth (Hw_0) and tailwater depth (TW) respectively.
6. The head losses (H_L) can be calculated using equation 3.

4.3.4. <u>Outlet Control – Partial Full</u>

1. Set the channel slope to 0.7 degrees using the screw jack.
2. Install two stop logs at the tailgate and open the sluice gate to allow for full flow conditions.
3. Install the smooth single barrel culvert with the flared entrance treatment, and free exit.
4. Turn on the pump and set the flow rate to 5.65 cfm using the control valve.
5. Measure the elevation of the water surface at the test sections one and four. These can be taken as the headwater depth (Hw_0) and tailwater depth (TW) respectively.
6. The head losses (H_L) can be calculated using equation 3.

4.3.5. Settings & Results

Table 11. Flow through the smooth single barrel culvert

Inlet Control-Low Tailwater	Flared Entrance
Flow Rate	4.90
Channel Slope	3.2
Inlet Water Depth	4.39
Outlet Water Depth	Free
Sluice Gate	Open
Number of Stop Logs	0

Inlet Control-Hydraulic Jump in Pipe	Flared Entrance
Flow Rate	2.50
Channel Slope	3.2
Inlet Water Depth	3.13
Outlet Water Depth	4.44
Sluice Gate	Open
Number of Stop Logs	4

Outlet Control-Full Flow	Flared Entrance
Flow Rate	6.60
Channel Slope	0
Inlet Water Depth	7.21
Outlet Water Depth	5.89
Sluice Gate	Open
Number of Stop Logs	4

Outlet Control-Partial Full	Flared Entrance
Flow Rate	5.65
Channel Slope	0.7
Inlet Water Depth	5.00
Outlet Water Depth	3.21
Sluice Gate	Open
Number of Stop Logs	2

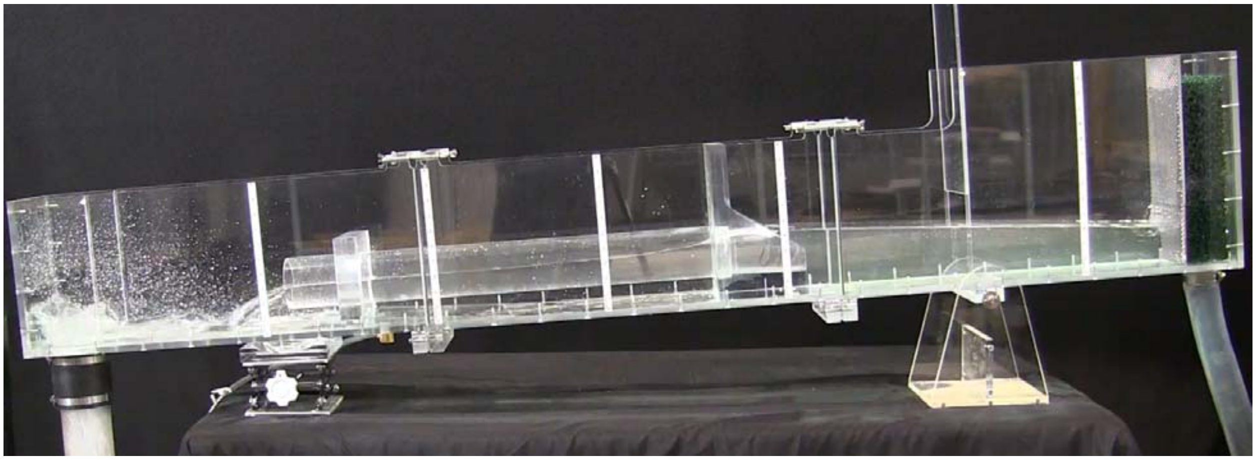

Figure 11. Inlet Control – Low Tailwater (Flared Inlet-Smooth Pipe)

Figure 12. Inlet Control – Hydraulic Jump in Pipe (Flared Inlet-Smooth Pipe

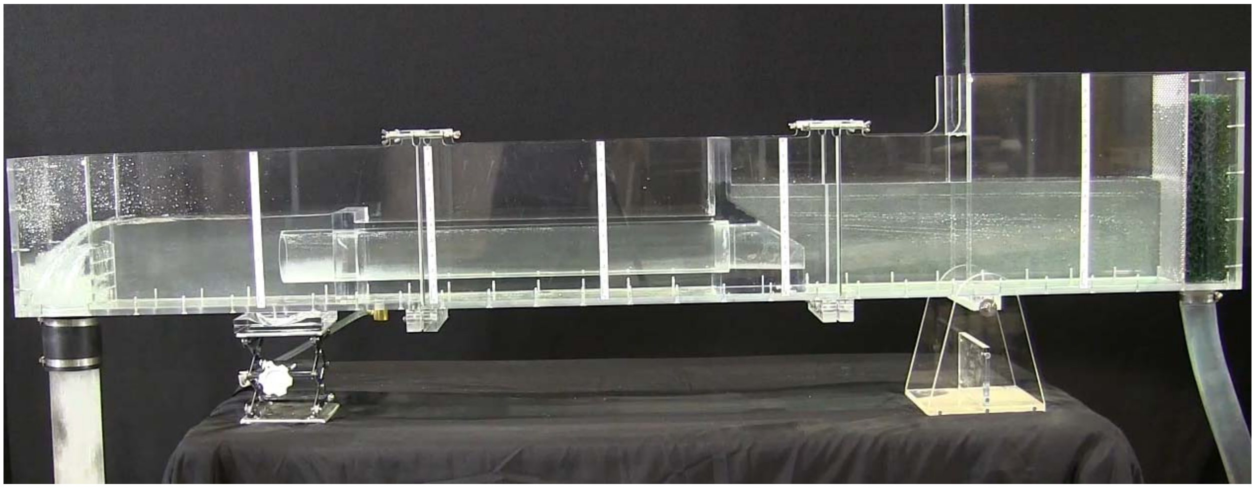

Figure 13. Outlet Control – Full Flow (Flared Inlet-Smooth Pipe)

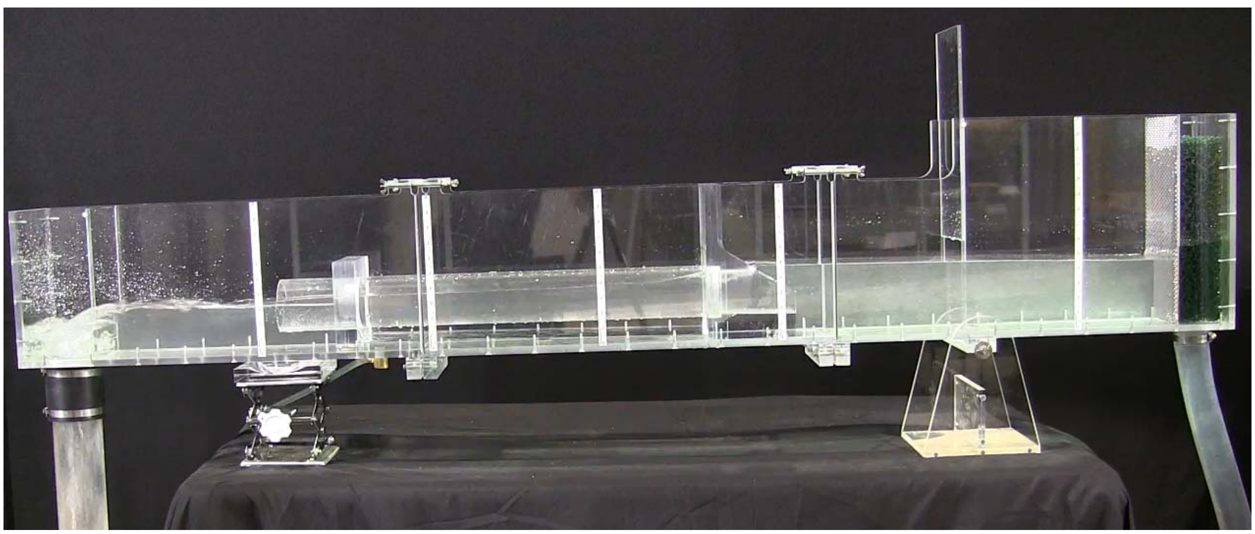

Figure 14. Outlet Control – Partial Full (Flared Inlet-Smooth Pipe)

4.4. Experimental Procedures – Entrance Treatments

There are three entrance treatments that can be used interchangeably: flared, mitered and strait end wall treatments. The effects that the entrance treatments have on the flow through the culvert can be observed by changing the entrance treatments sequentially in the model. The settings for the different flow conditions are similar to those for the flared entrance (Table 11). There may be minor adjustments that need to be made to the flow rate and/or channel slope to account for the differences in the entrance treatments. Any changes that need to be made can be done by adjusting the control valve and screw jack until the desired flow condition is achieved.

Example settings for the various entrance treatments and rough single barrel culvert are provided in Appendix A.

4.5. Experimental Procedures – Pipe Roughness

The smooth single barrel pipe can be used interchangeably with the rough single barrel pipe. To show the effect that energy losses have on the system, set up the model with the rough pipe and the settings that are used for the smooth pipe (Table 11), and then compare the results to those obtained using the smooth pipe. Example settings for the rough single barrel culvert are provided in Appendix A.

5. MANHOLE

5.1. Description

In addition to the culvert inserts, there is also a culvert equipped with a manhole that can be used interchangeably with any of the entrance treatments. A photograph of the flume with the manhole insert installed is provided in Figure 15. No specific setup parameters were established for the manhole demonstration. Therefore, it is up to the user to establish the flow characteristics desired by varying the pump flow rate, water depth and channel slope.

Figure 15. Teaching flume shown with manhole insert