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## Preliminary investigation of energy dissipation at culvert outlets using a riprap step

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**Preliminary Investigation Of  
Energy Dissipation At Culvert Outlets  
Using A Riprap Step**

**Belinda M. Weikle**

**Thesis submitted to the  
College of Engineering and Mineral Resources  
at West Virginia University  
in partial fulfillment of the requirements  
for the degree of**

**Masters of Science  
in  
Civil Engineering**

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**Morgantown, West Virginia  
2000**

**Keywords: Riprap Step, Energy Dissipation, Hydraulic Jump  
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## **ABSTRACT**

### **Preliminary Investigation Of Energy Dissipation At Culvert Outlets Using A Riprap Step**

**Belinda M. Weikle**

One method used to attenuate high-energy flow at culvert outlets is the construction of a riprap energy dissipator. The current riprap design used by the WVDOH experiences problems with excessive sedimentation and is only applicable at culvert outlets where the flow velocity is low. The purpose of this investigation was to construct a testing device to allow for the testing of physical models and produce a preliminary riprap step design that would perform more effectively than the current design. The new design proposed meets the following criteria. It is:

- Easily constructed on site using available materials
- Economically efficient
- Applicable to various culvert sizes and flowrates
- Self cleaning and requires low maintenance
- Able to re-establish natural flow conditions downstream of the outlet

Several model steps were constructed and tested. This thesis reviews the construction of all experimental equipment and the development of a preliminary design.

## **ACKNOWLEDGEMENTS**

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## **Chapter 1**

### **Introduction**

#### **1.1 Problem Statement**

Energy dissipation is a prime concern at culvert outlets. The methods of attenuating the energy depend on the flow parameters at the culvert outlet, such as velocity, etc. The West Virginia Division of Highways (WVDOH) uses several types of energy dissipators. Their methods of energy dissipation include various baffle block designs and riprap basin designs.

The baffle block designs are generally constructed at culvert outlets with high velocity flows. The baffle blocks consist of reinforced concrete and are expensive and difficult to build. Maintenance costs can be high due to debris and sedimentation occurring on the apron of the dissipator.

Riprap basins, whether grouted or not, are generally placed by the WVDOH at culvert outlets where there is low velocity flow, usually with Froude numbers less than 3 and/or flowrates less than 50 cfs. Riprap is very economical compared to the baffle block designs, but can only be effectively placed at culvert outlets with low velocity flows. It may also require frequent maintenance due to debris and sedimentation on the apron or on the riprap itself. There is a need for an alternative method of energy dissipation at culvert outlets that can withstand higher velocity flows than riprap, yet is more economical than the baffle block design.

The term “riprap”, as used here, refers to rock riprap. In 1989, Hydraulic Engineering Circular 11 (HEC-11) defines riprap as a flexible channel or bank lining or facing consisting of a well graded mixture of rock, broken concrete, or other material, usually dumped or hand-placed, which provides protection from erosion. Dumped riprap is graded stone dumped on a prepared slope in such a manner that segregation will not take place. Hand-placed riprap is stone laid carefully by hand or by derrick following a definite pattern, with the voids between the larger stones filled with smaller stones and surface kept relatively even.

This Thesis will examine the effectiveness of the non-grouted rock riprap energy dissipator used by the WVDOH. The current riprap design problems will be investigated and possible solutions discussed. An alternative riprap step design with adequate energy dissipation, low maintenance and economical feasibility will be presented.

## 1.2 Setting

West Virginia is a densely vegetated, mountainous state, having steep terrain that is drained by channels, streams, and rivers into the low-lying valleys. The natural drainage process involves the balancing of the physical and erosive properties of the drainage channel, stream, or river with the needed energy dissipation of the flow. Whenever a man-made structure is placed in a natural setting, this balance, or equilibrium, is disrupted due to changes in channel roughness, slope, rate of energy dissipation, cross-section and direction of flow. Measures must then be taken to re-establish the balance to avoid damage to the surrounding structures or the downstream channel. When the rate of energy dissipation is changed, whether it is increased or decreased, the degree of erosion and sedimentation also changes, affecting the channel equilibrium. Culvert placement usually decreases energy attenuation, and as a result erosion problems can occur.

The West Virginia Department of Highways (WVDOH) Drainage Manual (1984) specifies the design procedures for the construction of riprap energy dissipators for culvert outlets. Additional guidance for riprap energy dissipators may be found in the Federal Highway Administration (FHWA) HEC-14 (Hydraulic Design of Energy Dissipators for Culverts and Channels, 1983).

## 1.3 Current Design

As previously mentioned, schematics of the current riprap energy dissipator design may be obtained from the WVDOH Drainage Manual or HEC-14. The criteria for design directives of new energy dissipators must provide for sufficient energy dissipation, characterized by **simplicity of design, effectiveness of energy dissipation** and **low construction cost**.

The current WVDOH riprap flowchart, schematic, and construction details are shown in Figures 1.1, 1.2, and 1.3.



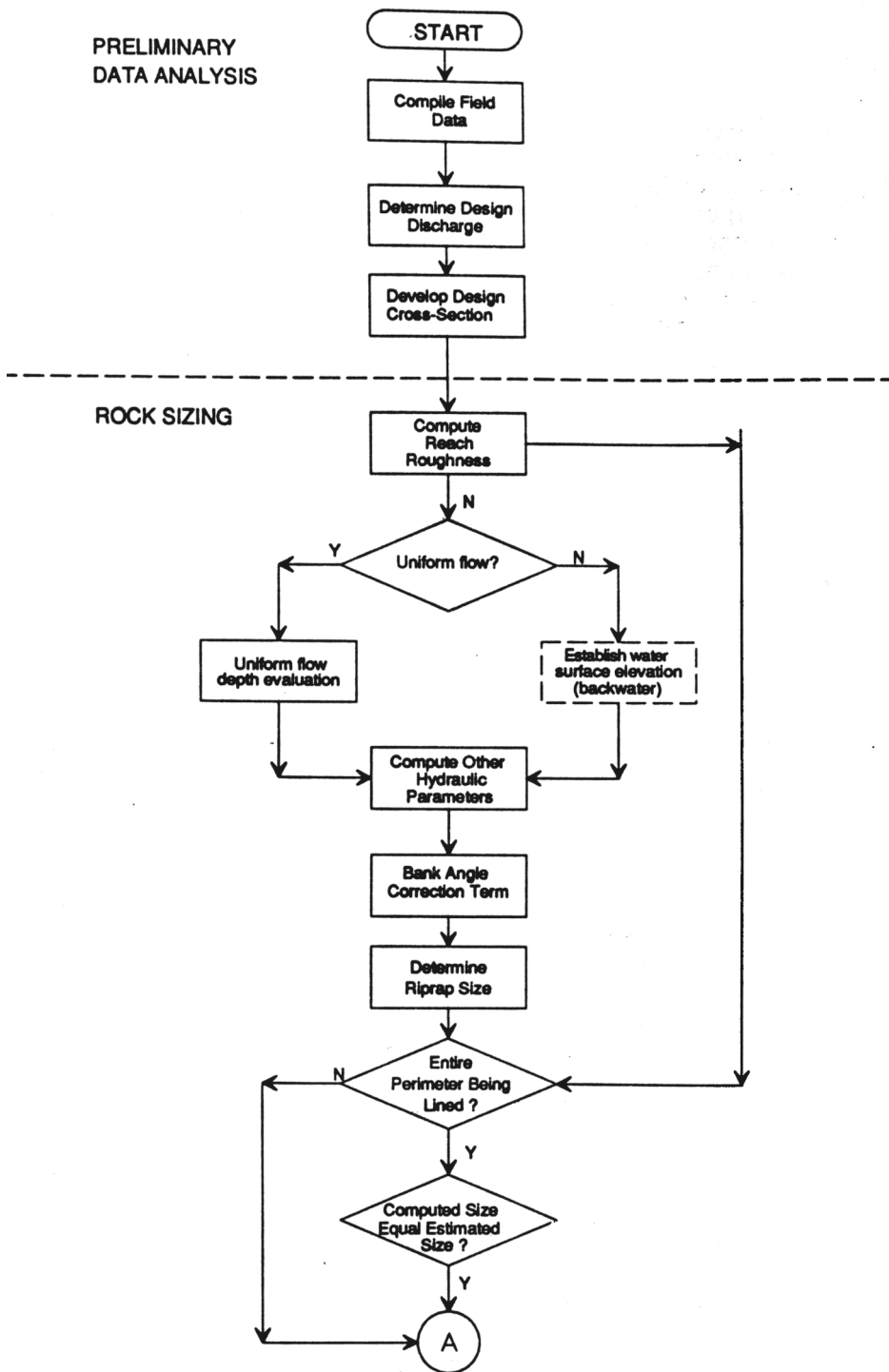


Figure 1.1 Riprap Design Procedure Flow Chart (HEC-11, 1989)

**ROCK SIZING  
(CONTINUED)**

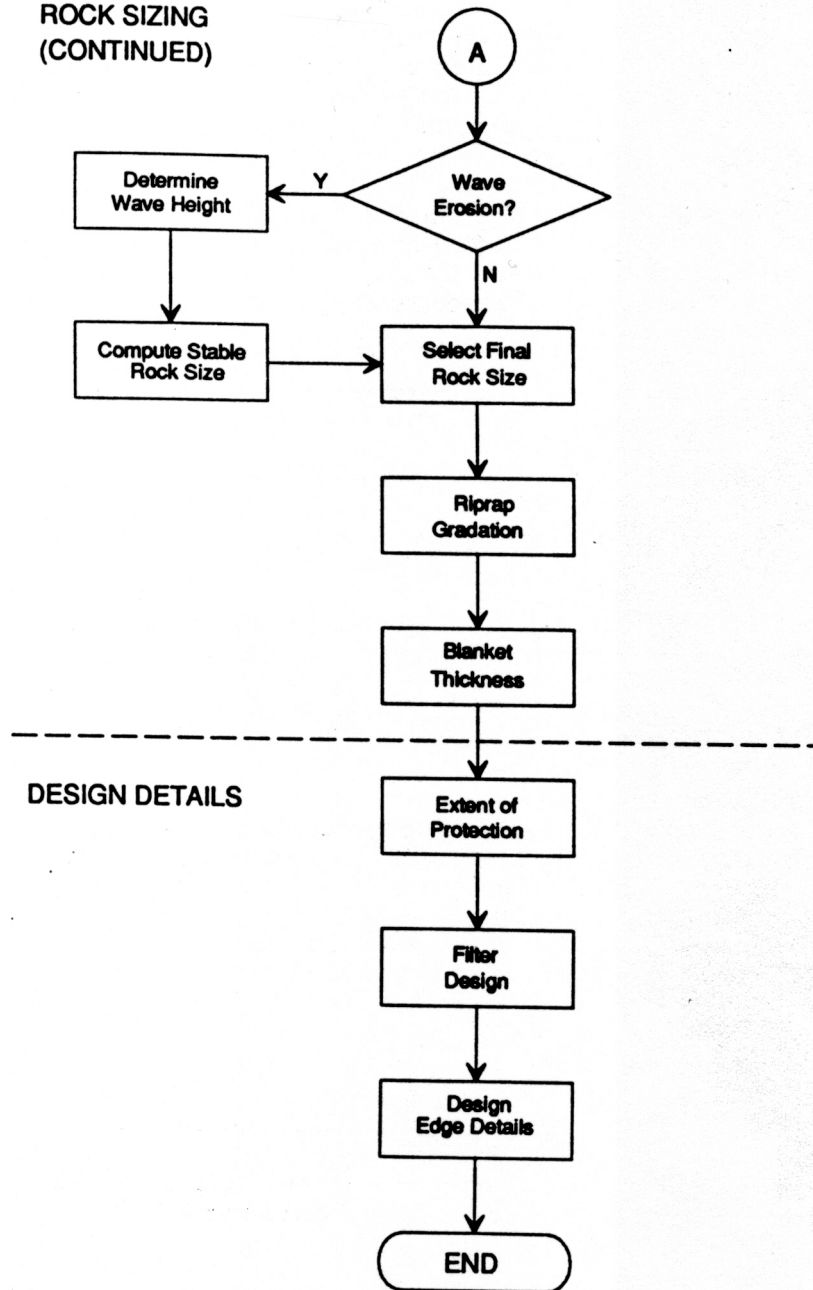
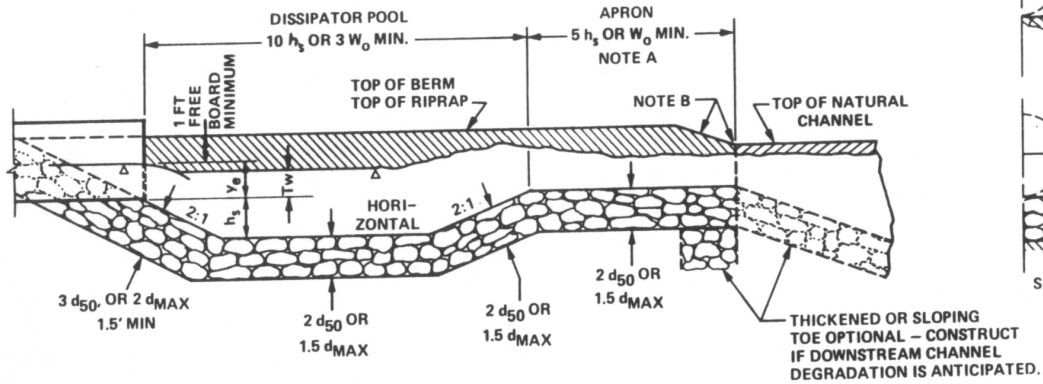


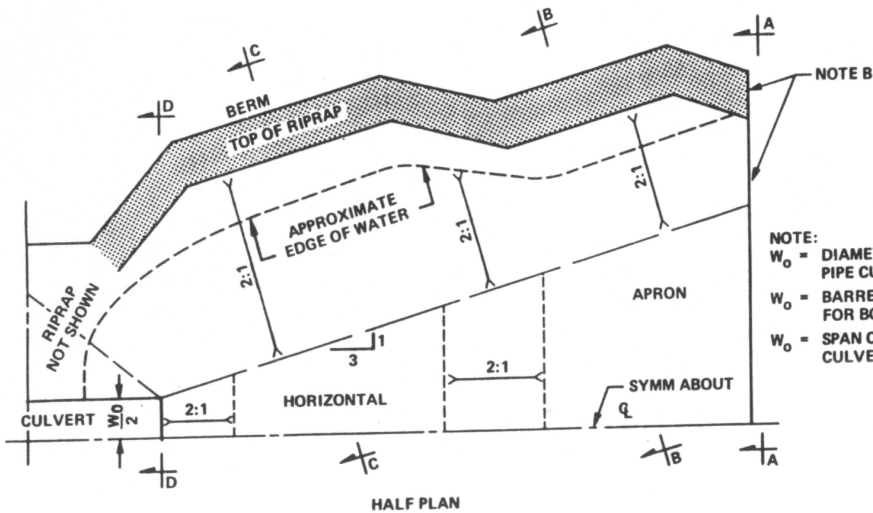
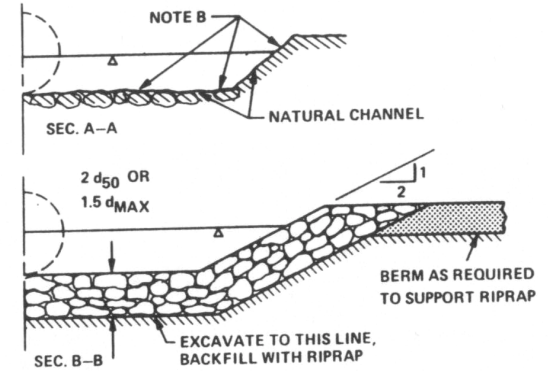
Figure 1.2 (Continued) Riprap Design Procedure Flow Chart (HEC-11, 1989)

NOTE A - IF EXIT VELOCITY OF BASIN IS SPECIFIED, EXTEND BASIN AS REQUIRED TO OBTAIN SUFFICIENT CROSS-SECTIONAL AREA AT SECTION A-A SUCH THAT  $Q_{des}/(CROSS\ SECTION\ AREA\ AT\ SEC.\ A-A) = SPECIFIED\ EXIT\ VELOCITY$ .

NOTE B - WARP BASIN TO CONFORM TO NATURAL STREAM CHANNEL. TOP OF RIPRAP IN FLOOR OF BASIN SHOULD BE AT THE SAME ELEVATION OR LOWER THAN NATURAL CHANNEL BOTTOM AT SEC. A-A

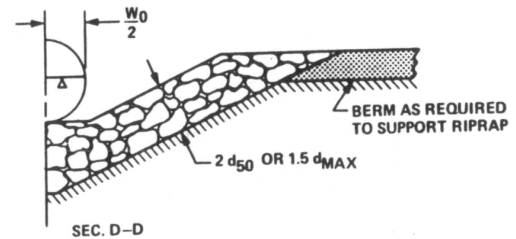
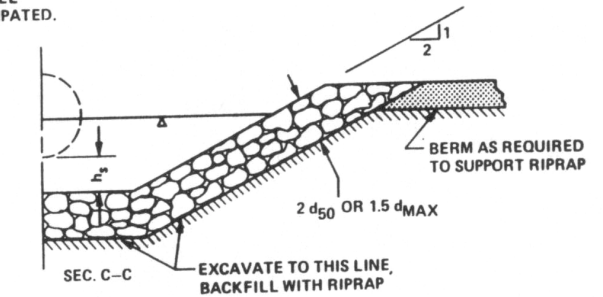


SECTION



HALF PLAN

NOTE:  
 $W_0$  = DIAMETER FOR PIPE CULVERT  
 $W_0$  = BARREL WIDTH FOR BOX CULVERT  
 $W_0$  = SPAN OF PIPE-ARCH CULVERT



The research project's experimental test runs will be conducted on a scale model. In order to construct a scale model of the wingwall and apron used in conjunction with the current riprap energy dissipator design, the various dimensions were taken from the appropriate WVDOH drawings, and placed in Microstation for ease of interpretation and manipulation. The dimensions of the wingwall and apron are all a function of pipe diameter with the exception of thickness, T, and cutoff wall height, W, which are determined by the standard construction specifications. A schematic of the WVDOH wingwall and apron is shown in Figures 1.4, 1.5, and 1.6. The dimensions are shown as a multiple of culvert diameter in Table 1.1.

Table 1.1 Design Dimensions as Multiple of Culvert Diameter

Dimension	Multiple of Diameter
L	1.2
M	0.6
N	1.2
O	1.3
P	3.9
Q	1.8

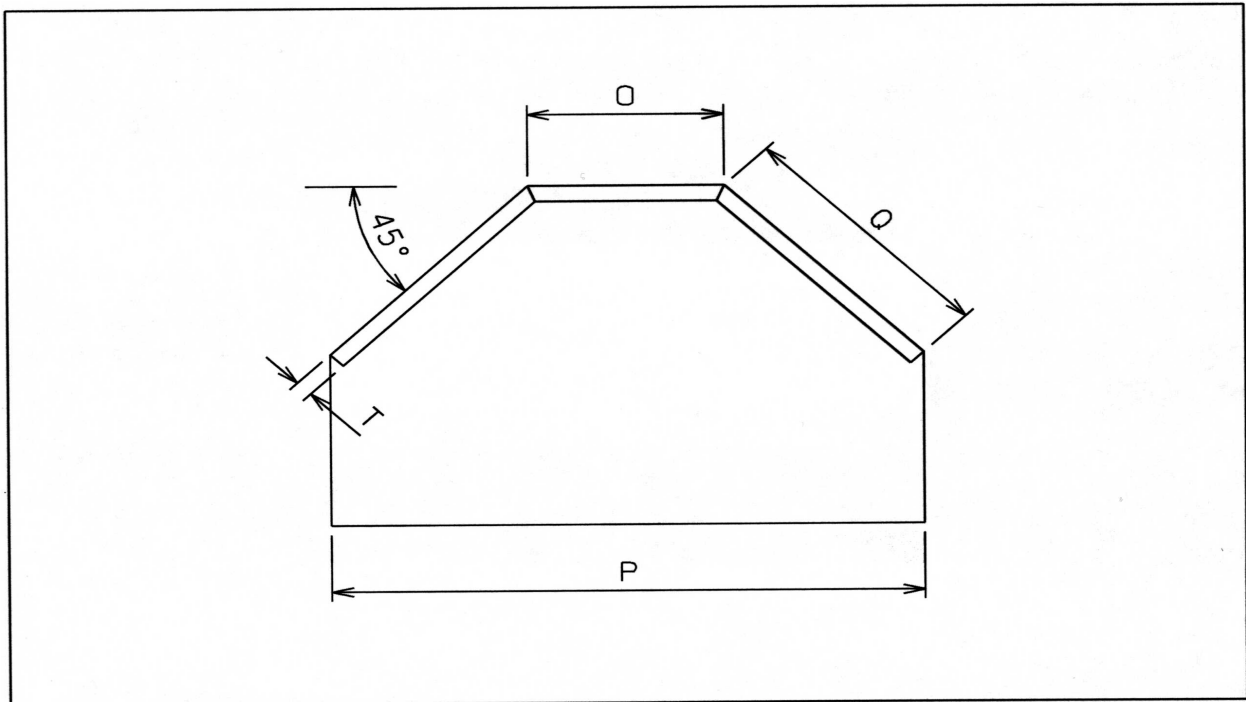


Figure 1.4 Plan of Current WVDOH Headwall, Wingwall and Apron

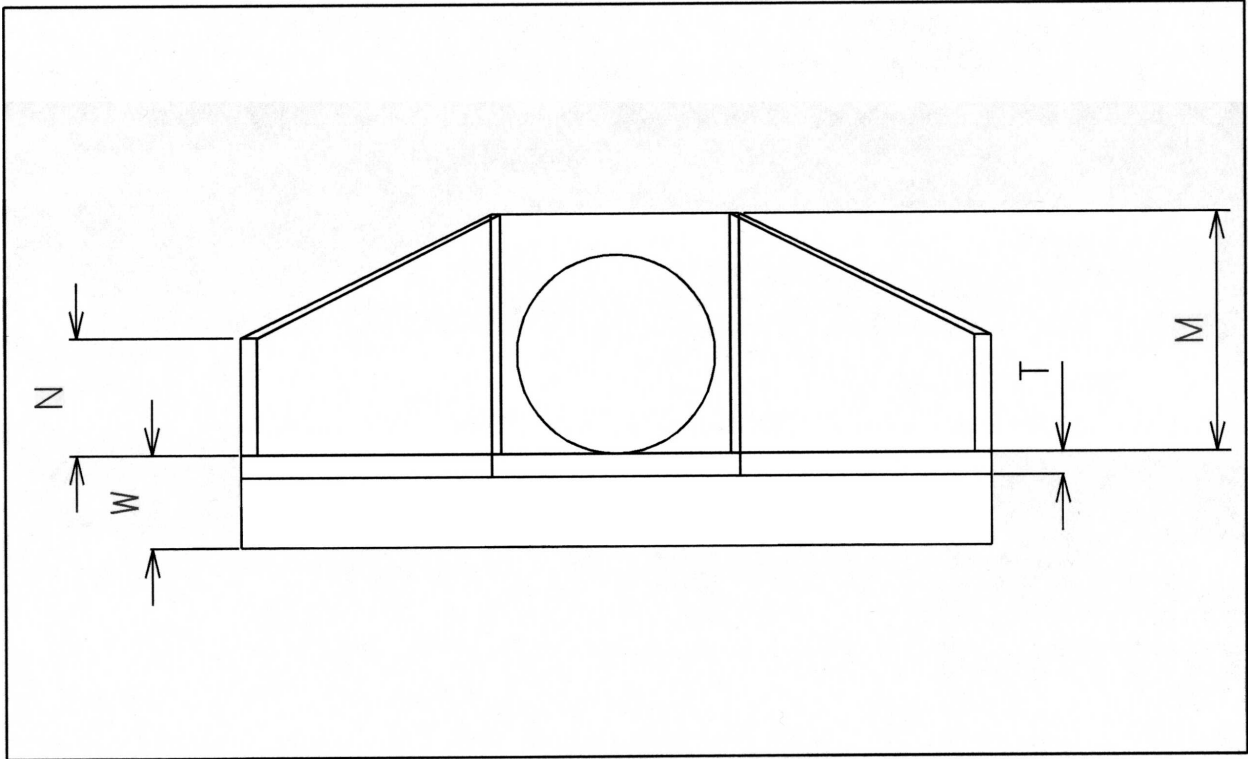


Figure 1.5 Front View of Current WVDOH Headwall, Wingwall and Apron

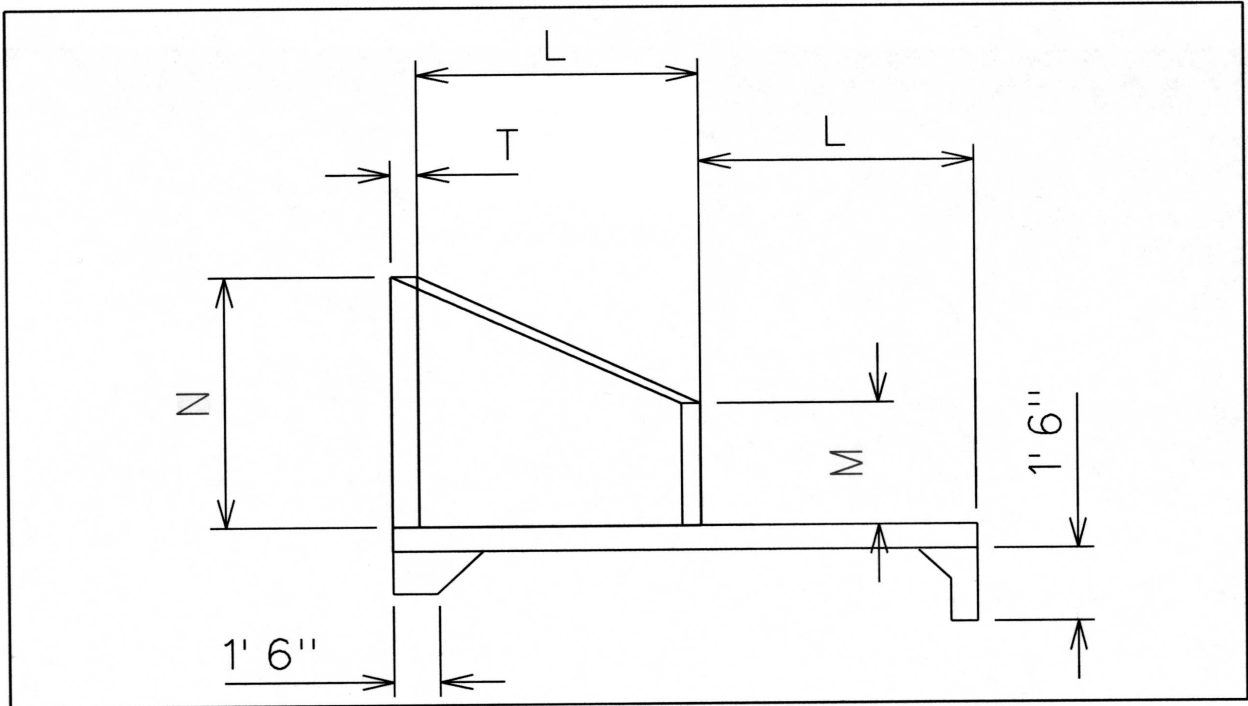


Figure 1.6 Profile of Current WVDOH Headwall, Wingwall and Apron

As with current WVDOH riprap designs, the proposed alternative riprap step energy dissipator design will be preceded by the same wingwall and apron geometry design as shown in Figures 1.4, 1.5, and 1.6.

#### **1.4 Field Experiences With the Current Riprap Energy Dissipator**

Current riprap design used by the WVDOH has both advantages and disadvantages. The advantages were ease of placement, whether hand placed or dropped, without a need for skilled laborers, and low cost. The disadvantages of the current design were scouring, either local or gully, ineffective attenuation of energy at high flow velocities, and sediment accumulation resulting in low to no energy dissipation. A new riprap design must be developed and implemented as an alternative design to the current riprap design, that will eliminate or reduce existing problems.

## Chapter 2

### Background and Literature Review

Considerable effort and time was initially spent in exploring a variety of riprap designs that held promise of providing an acceptable solution to the energy dissipation problem. Once an acceptable design approach was developed, time constraints imposed on the project limited the number of additional alternatives that could be explored. Because no riprap step design could be found in the literature, there was no related research data available that could provide direct support to this investigation.

#### 2.1 Riprap

The definition of riprap varies according to the source. The simplest definition of riprap is a natural rock dumped or hand-placed to prevent erosion (Streambank Protection Guidelines, 1983). Generally, riprap is used to minimize erosion at the toe of a soil bank, to prevent erosion by placing a riprap blanket over a slope of a bank, to prevent erosion by piling riprap in windrows at the top or within an eroding bank, or to dissipate energy at culvert outlets. Riprap is one of the most common and economical methods of dealing with the problem of scouring at the end of culverts or pipe outlets (Shafai-Bajestan and Albertson, 1993). Some advantages of using riprap are: it is a speedy method of construction, skilled labor is not required, and usually, local sources of rock may be used (Streambank Protection Guidelines, 1983). Graded riprap is cheaper and more stable while uniform riprap has more voids and is less stable. The use of graded riprap is advantageous due to its healing process; one rock tumbling downstream due to erosion activity may fill a void further downstream, thus promoting stabilization.

#### 2.2 Hydraulic Jumps

Hydraulic jumps are usually an inherent part of energy dissipator design. There are two different types of hydraulic jumps, a natural hydraulic jump and a forced hydraulic jump (HEC-14, 1983). The natural hydraulic jump occurs when there is a change from supercritical ( $Fr > 1$ ) to subcritical ( $Fr < 1$ ) flow conditions on a uniform bed (no

local blockage or artificial roughness). The forced hydraulic jump is a tool utilized by energy dissipators, and is forced by blocks, sills, and riprap, or other artificial roughness elements. The roughness elements can be used inside culvert barrels, at culvert exits, or in the open channels downstream of the exit (HEC-14, 1983).

### 2.2.1 Hydraulic Jump Forms

Hydraulic jumps are usually referenced to the approach Froude number in order to categorize them appropriately. The physical characteristics of the hydraulic jump change with increasing Froude number. Energy absorption characteristics vary for each of the hydraulic jump forms, as seen below in Figure 2.1.

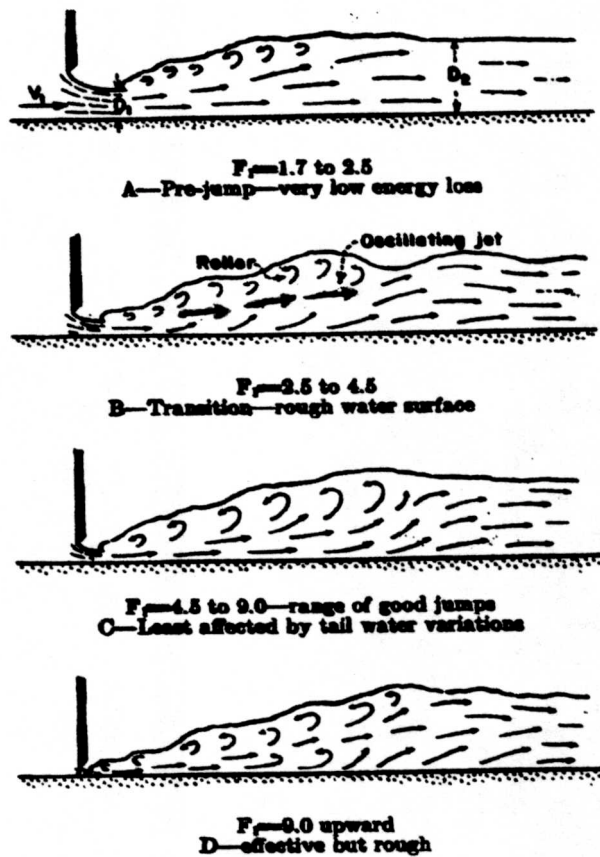


Figure 2.1 Hydraulic Jump Forms (Peterka, 1958)



**Weak Jump ( $1 < Fr_1 < 2.5$ )**

For  $1 < Fr_1 < 1.7$ ,  $y_1$  and  $y_2$  are approximately equal to each other, and only a slight ruffle is formed on the surface. This undulation results in very little energy dissipation. As  $Fr_1$  approaches 1.7, a number of small rollers are formed on the water surface, although the downstream water surface remains smooth. The energy loss is low in this jump.

**Oscillating Jump ( $2.5 < Fr_1 < 4.5$ )**

The jet at the entrance to the jump oscillates from the bottom to the top at an irregular period. Turbulence may be near the channel bottom at one instant and at the water surface the next. These oscillations result in the formation of irregular waves, which may persist for long distances downstream of the jump. These waves may cause considerable damage to the channel banks. This range of  $Fr_1$  should be avoided when designing an energy dissipator.

**Steady Jump ( $4.5 < Fr_1 < 9$ )**

The jump forms steadily at the same location, and the position of the jump is least sensitive to the downstream flow conditions. The jump is well balanced and energy dissipation is considerable. The jump is stable with the fluid turbulence confined to the jump. The water surface downstream will usually appear to be smooth and an energy loss ranging from 45 to 70 percent can be expected.

**Strong Jump ( $Fr_1 > 9$ )**

The difference between the conjugate depths is large, slugs of water roll down the front of the jump face into the high velocity jet and generates additional waves. The jump action is very rough and the dissipation rate is high, but the turbulence can cause downstream erosion.

(Chaudhry, 1993, and HEC-14, 1983)

**2.2.2 Governing Equations**

Past studies of similar nature utilize the principles of momentum, energy, and Froude number equations.

The momentum equation is the sum of the forces equal to the change in the momentum flux, or

$$\Sigma F = \Delta(QV\rho) = \Delta[Q(V_2 - V_1)\rho] \quad (2.1)$$

Where:

$F$  = Force

$V$  = Average flow velocity

$V_1$  = Upstream average flow velocity

$V_2$  = Downstream average flow velocity

$Q$  = Flowrate

$\rho$  = Density of water

the energy, and head loss for a horizontal, rectangular channel, through the jump equations are listed below,

$$\frac{V_1^2}{2g} + y_1 = \frac{V_2^2}{2g} + y_2 + h_L \quad (2.2)$$

$$h_L = \frac{(y_1 - y_2)^3}{4y_1y_2} \quad (2.3)$$

Where:

$y_1$  = Upstream water depth

$y_2$  = Downstream water depth

$g$  = Acceleration due to gravity

$V_1$  = Upstream velocity

$V_2$  = Downstream velocity

$Fr_1$  = Upstream Froude number

The Froude number,  $Fr$ , is a dimensionless parameter and is important in establishing similitude between the model prototype (Roberson et al, 1995). Froude number is given by:

$$Fr = \frac{V}{\sqrt{gy}} \quad (2.4)$$

Where:

$Fr$  = Froude number

$V$  = Flow velocity

$y$  = hydraulic depth

The Froude number is proportional to the inertial force and the body force (Peterka, 1958).

$$Fr^2 = \frac{V^2}{gy} = \frac{\rho V^2 y^2}{\rho g y^2} \cong \frac{InertialForce}{BodyForce} \quad (2.5)$$

The Federal Highway Administration, in 1987, produced a video, Hydraulics of Energy Dissipators outlining the procedure for analyzing the hydraulic jump in stilling basins. Since density is unchanging in open channels and culverts, the term can be eliminated from the continuity equation, leaving the volume rate of flow, or discharge, equal to the area times the velocity or  $Q = A_1V_1 = A_2V_2$ . The momentum flux at one end of the hydraulic jump does not equal the momentum flux at the other end of the hydraulic jump. The momentum equation relates change in momentum flux across the control volume to the forces produced by hydrostatic pressure and boundary, or shear forces. The shear forces or boundary forces are small and considered insignificant, therefore neglected. The hydrostatic forces on the control volume are balanced by a change in the momentum across the control volume. The hydraulic jump equation combines the momentum equation with the continuity equation and introduces the Froude number defined above. This yielding,

$$\frac{y_2}{y_1} = \frac{1}{2} \left( \sqrt{1 + 8Fr_1^2} - 1 \right) \quad (2.6)$$

which can be used to give the tailwater depth that is necessary to produce a hydraulic jump assuming that the depth and velocity of the flow upstream of the jump for a rectangular channel is known (HEC-14, 1983).

### 2.2.3 Specific Head and Energy Loss

Using the governing equations presented above one can calculate the energy lost in the jump on a level bed by taking the difference between the specific head upstream and downstream. This difference is the loss of energy, expressed in units of head, due to the dissipation of energy in the jump. The upstream depth,  $y_1$ , and the downstream depth,  $y_2$ , are called conjugate depths and  $y_2$  is said to be sequent to  $y_1$  (Gray, 2000). Figure 2.2 shows the relationship between specific head and depth of the hydraulic jump. It is essential to know the magnitude of energy loss produced by the jump so that efficiencies of the dissipator design can be fully evaluated.

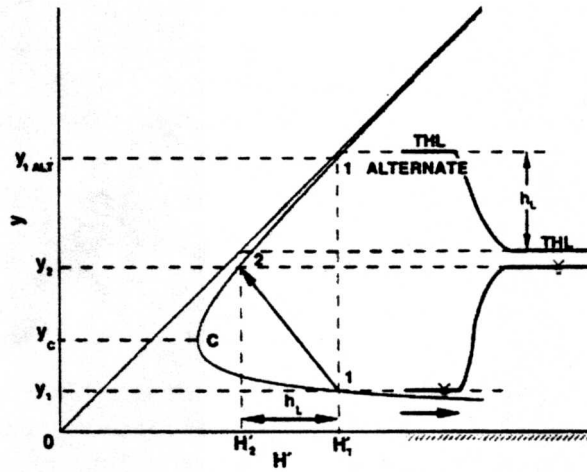


Figure 2.2 Specific Head. NOTE:  $H'$  represents specific head and  $H_1'$  and  $H_2'$  are specific heads upstream and downstream

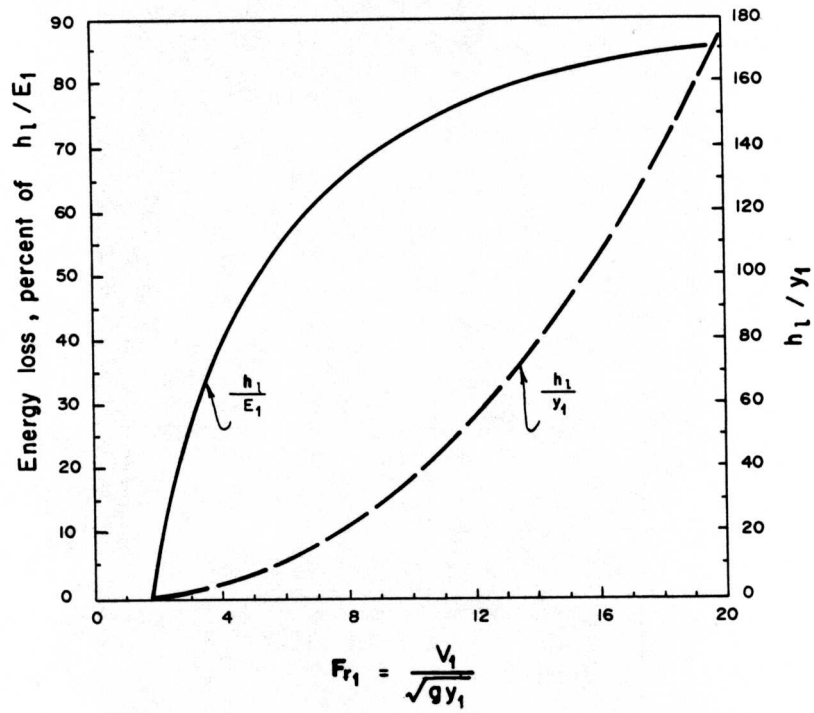


Figure 2.3 Energy Dissipation in Jump (Chaudhry, 1993)

## 2.2.4 Jump Length

It is difficult to determine the length of the hydraulic jump due to its complex and random flow patterns. The formation of rollers, eddies, air entrainment, and a highly turbulent flow surface make the beginning and end of the jump more difficult to locate. If the jump is controlled by an abrupt rise, the jump is formed at a distance  $x$  upstream of the rise.

$$x = 5(h + y_3) \quad (2.7)$$

Where:

$x$  = Horizontal distance in channel preceding the abrupt rise

$h$  = Abrupt rise (step) height

$y_3$  = Downstream water depth

See Figure 2.4 below.

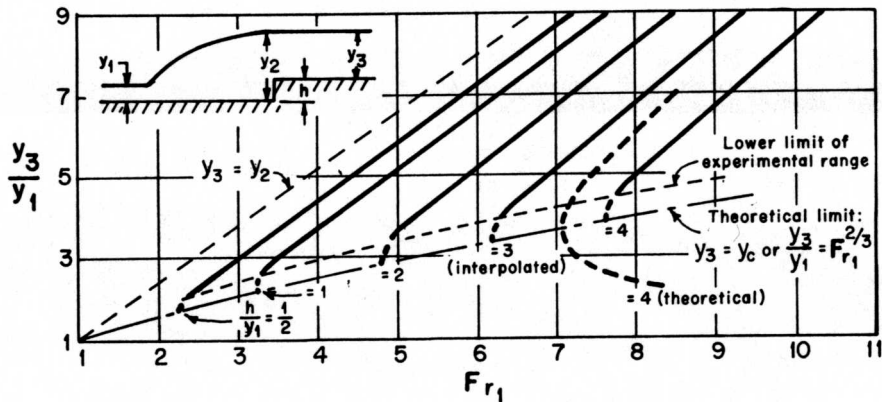


Figure 2.4 Jump Controlled by Abrupt Rise (Chaudhry, 1993)

### **2.2.5 Shortcomings of the Hydraulic Jump**

A free hydraulic jump is a jump without the aid of objects or obstructions in the path of flow. The free hydraulic jump is a desirable means of dissipating energy at high velocity flows. However, the free hydraulic jump is normally considered impractical and economically undesirable where design and economic considerations are concerned. As seen with the oscillating hydraulic jump form discussed in Section 2.2.1, the hydraulic jump was destructive to the downstream channel as well as the hydraulic structure itself. The main drawback of the free hydraulic jump is the length of structure needed to contain the jump to prevent the channel from being degraded and soil being carried downstream (Peterka, 1978). In order to produce the most stable and economical energy dissipator, or stilling basin, it is necessary to alter the hydraulic jump characteristics.

Reinforcement of these ideas was supported by two groups of researchers, Roberson et al. and Peterka. In 1978, Peterka stated that stilling basins are seldom designed to confine the entire length of the hydraulic jump, first, for economic reasons, and second, because there are means for modifying the jump characteristics to obtain comparable or better performance characteristics in shorter lengths. In 1995, Roberson et al. believed that a carefully designed stilling basin not only improved the dissipation characteristics of a hydraulic jump, it would also shorten its length and stabilize the position of the jump so that it was not sensitive to fluctuations in tailwater level. This latter attribute made the design safer.

These ideas can be accomplished by the introduction of the forced hydraulic jump. A forced hydraulic jump is caused by the introduction of additional resistive forces to the flow produced by the placement of objects in the flow path, which increases the conjugate depth. According to Chaudhry, the location of a hydraulic jump may be controlled by adding a variety of structures to the channel bottom, such as baffle blocks, sills, and drops or rises.

## Chapter 3

### Initial Investigations

Following a literature review to determine the history of riprap steps, it was discovered that there was insufficient information available to initiate the project. Additional information was needed regarding common drainage pipe sizes used by the WVDOH in designs where the new riprap step design was to be used and the gradation of stone that was to be supplied by local quarries.

#### 3.1 Drainage Pipe

The investigation focused on circular drainage pipes, disregarding all other non-circular drainage pipe geometries such as square, rectangular, arch and elliptical. Documentation of circular drainage pipe quantities placed for 1992-1997 was obtained from by the WVDOH's main office in Charleston, WV. After an extensive screening and summation of the data, frequency of application based on total length for each diameter, is listed in Table 3.1. It will be noted that 95% of all pipe placed into service is 4.25-foot diameter or less. Equivalent graphic plots are shown in Figures 3.1 and 3.2.

Diameter (ft)	Sum Avg. (Linear ft.)	%	Cumulative %	Diameter (ft)	Sum Avg. (Linear ft.)	%	Cumulative %
0.25	0.0	0.00	0.00	6.25	0.0	0.00	98.35
0.50	13740.1	12.17	12.17	6.50	82.9	0.07	98.43
0.75	3.8	0.00	12.17	6.75	0.0	0.00	98.43
1.00	806.5	0.71	12.89	7.00	927.4	0.82	99.25
1.25	6456.1	5.72	18.60	7.25	35.0	0.03	99.28
1.50	45260.7	40.08	58.69	7.50	0.0	0.00	99.28
1.75	32.2	0.03	58.72	7.75	0.0	0.00	99.28
2.00	21849.2	19.35	78.07	8.00	280.4	0.25	99.53
2.25	0.0	0.00	78.07	8.25	0.0	0.00	99.53
2.50	6380.8	5.65	83.72	8.50	0.0	0.00	99.53
2.75	1230.9	1.09	84.81	8.75	155.9	0.14	99.66
3.00	5212.0	4.62	89.43	9.00	52.9	0.05	99.71
3.25	203.0	0.18	89.60	9.25	0.0	0.00	99.71
3.50	2078.8	1.84	91.45	9.50	0.0	0.00	99.71
3.75	0.0	0.00	91.45	9.75	142.6	0.13	99.84
4.00	3491.4	3.09	94.54	10.00	78.5	0.07	99.91
4.25	0.0	0.00	94.54	10.25	0.0	0.00	99.91
4.50	1175.7	1.04	95.58	10.50	0.0	0.00	99.91
4.75	0.0	0.00	95.58	10.75	0.0	0.00	99.91
5.00	1764.0	1.56	97.14	11.00	22.3	0.02	99.93
5.25	225.2	0.20	97.34	11.25	0.0	0.00	99.93
5.50	219.0	0.19	97.54	11.50	0.0	0.00	99.93
5.75	0.0	0.00	97.54	11.75	15.3	0.01	99.94
6.00	923.0	0.82	98.35	12.00	67.0	0.06	100.00

**Circular Pipe Diameters-WVDOH Placement**

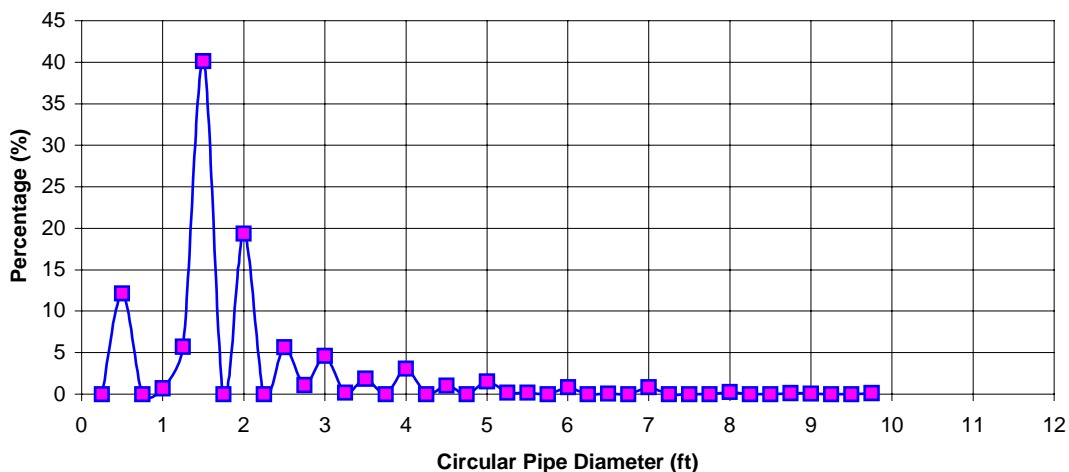


Figure 3.1 Circular Pipe Diameters – WVDOH Placement

**Cumulative Percentage Circular Pipe Diameters - WVDOH Placement**

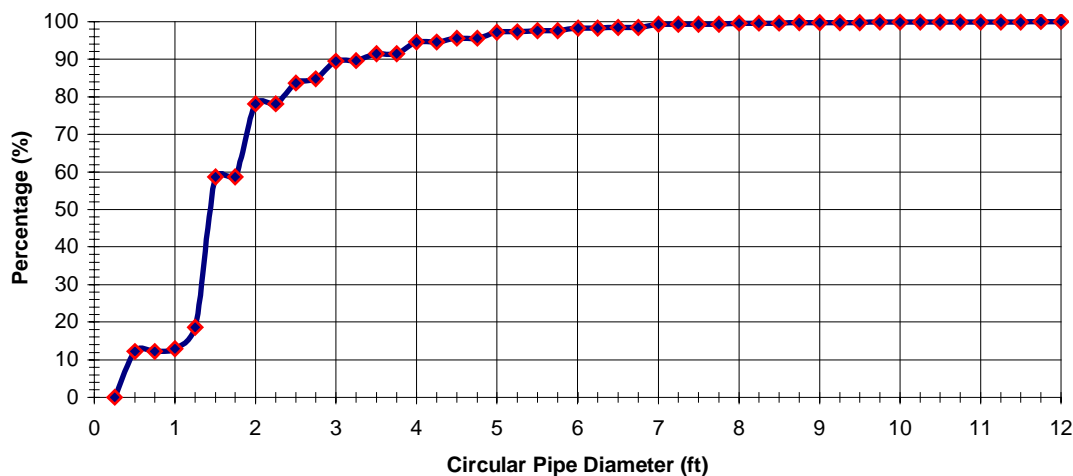


Figure 3.2 Cumulative Circular Pipe Diameters – WVDOH Placement

### 3.2 Rock Gradations for West Virginia Quarries

An important aspect of this project was to determine the rock gradations supplied to the WVDOH. The rock supplied by local quarries would potentially be used in the construction of the riprap step energy dissipator. At this early stage of development, the gradation required for the project was unknown. The necessity for investigating current rock gradations supplied to the WVDOH by rock quarries was evident. All ten district engineers were



contacted and requested to report a list of information on the quarries within their district that supplied rock for state funded projects. The lists of rock quarries supplying state funded projects with rock were compiled and analyzed. It was discovered that two rock quarries, Greer, and Martin Marietta, supplied in part, 44 of the 55 counties, 75 percent of West Virginia. The quarries were contacted and representative rock gradation samples obtained. Since rock gradation samples from Greer were from one representative mine near Morgantown, the samples were averaged and shown in Table 3.2. Martin Marietta's rock gradation samples were from four mine sites; Cave-In-Rock at Cave-In-Rock, IL (MM-A); Three Rivers Quarry at Smithland, KY (MM-B); Manheim Mine at Rowlesburg, WV (MM-C); and Snowflake Quarry at Fort Springs, WV (MM-D), and shown in Tables 3.3, 3.4, 3.5, and 3.6, respectively. The four quarries representative samples were averaged and shown in Table 3.2.

Sieve (in)	Sieve Dimensions (mm)	Percent Finer By Weight					
		Aggregate Type					
		R-7	R-6	R-4	#4	#57	#8
30.00	762.00	100					
24.00	609.60	12	100				
18.00	457.20	9	66				
12.00	304.80	6	32	100			
6.00	152.40		2	9			
3.00	76.20			25	100		
2.00	50.80				100	100	
1.50	38.10				95	100	
1.00	25.40				45	99	
0.75	19.05				8	87	
0.50	12.70				4	38	100
0.38	9.53				2	13	96
#4	4.75					3	28
#8	2.36					2	4
#16	1.18					1	3
Pan	0.00	0	0	0	0	0	0

Table 3.3 Rock Gradations for Cave-In-Rock Quarry at Cave-In-Rock, IL

Sieve (in)	Sieve Dimensions (mm)	Percent Finer By Weight										
		Aggregate Type										
		#1	#3	#4	#467	#5	#57	#67	#78	#7	#8	#9
4.00	101.60	100										
3.50	88.90	100										
3.00	76.20	88										
2.50	63.50	54	100									
2.00	50.80	-	95	100	100							
1.50	38.10	12	55	100	100	100	100					
1.00	25.40	-	9	22	75	90	96	100				
0.75	19.05	2	-	3	39	29	78	92	100	100		
0.50	12.70		2	-	15	3	38	47	92	92	100	
0.38	9.53			2	14	1	15	26	58	60	94	100
#4	4.75				2		2	2	11	11	22	86
#8	2.36						1	1	3	3	4	26
#16	1.18								2	2	1	2
Pan	0.00	0	0	0	0	0	0	0	0	0	0	0

Table 3.4 Rock Gradations for Three Rivers Quarry at Smithland, KY

Sieve (in)	Sieve Dimensions (mm)	Percent Finer By Weight									
		Aggregate Type									
		#1	#3	#357	#4	#467	#57	#67	#78	#7	#8
4.00	101.60	100									
3.50	88.90	95									
3.00	76.20	91									
2.50	63.50	40	100	100							
2.00	50.80	-	96	98	100	100					
1.50	38.10	10	60	-	96	96	100				
1.00	25.40	-	10	40	24	68	96	100			
0.75	19.05	1	-	-	4	46	72	91	100	100	
0.50	12.70		1	12	-	24	34	39	91	91	100
0.38	9.53			-	1	14	14	23	60	60	98
#4	4.75			1		3	3	6	10	10	18
#8	2.36						2	3	3	3	2
#16	1.18								2	2	1
Pan	0.00	0	0	0	0	0	0	0	0	0	0

Table 3.5 Rock Gradations for Manheim Mine at Rowlesburg, WV

Sieve (in)	Sieve Dimensions (mm)	Percent Finer By Weight				
		Aggregate Type				
		#1	#4	#467	#57	#8
4.00	101.60	100				
3.50	88.90	95				
3.00	76.20	-				
2.50	63.50	50				
2.00	50.80	-	100	100		
1.50	38.10	9	100	97	100	
1.00	25.40	-	58	86	100	
0.75	19.05	1	9	57	81	
0.50	12.70		-	36	28	100
0.38	9.53		1	21	8	88
#4	4.75			5	3	19
#8	2.36				2	5
#16	1.18					3
Pan	0.00	0	0	0	0	0

Table 3.6 Rock Gradations for Snowflake Quarry at Fort Springs, WV

Sieve (in)	Sieve Dimensions (mm)	Percent Finer By Weight					
		Aggregate Type					
		#3	#4	#57	#67	#8	#9
4.00	101.60						
3.50	88.90						
3.00	76.20						
2.50	63.50	100					
2.00	50.80	98	100				
1.50	38.10	55	98	100			
1.00	25.40	7	43	96	100		
0.75	19.05	-	7	-	91		
0.50	12.70	1	-	40	-	100	
0.38	9.53		2	15	34	87	100
#4	4.75			3	6	17	87
#8	2.36			1	1	6	19
#16	1.18					3	6
Pan	0.00	0	0	0	0	0	0

Sieve (in)	Sieve Dimensions (mm)	Percent Finer By Weight										
		Aggregate Type										
		#1	#3	#4	#467	#5	#57	#67	#78	#7	#8	#9
4.00	101.60	100										
3.50	88.90	97										
3.00	76.20	90										
2.50	63.50	48	100									
2.00	50.80		96	100	100							
1.50	38.10	10	57	99	98	100	100					
1.00	25.40		9	37	76	90	97	100				
0.75	19.05	1		6	47	29	77	51	100	100		
0.50	12.70		1		25	3	35	14	92	92	100	
0.38	9.53			2	16	1	13	10	59	60	92	100
#4	4.75				3		3	2	11	11	19	87
#8	2.36						2	1	3	3	4	23
#16	1.18								2	2	2	4
Pan	0.00	0	0	0	0	0	0	0	0	0	0	0

Another important aspect of this investigation was determining the similarities and differences between the gradations for supposed equivalent rock types. Sample rock gradations were compared from the five locations for rock/stone sizes #4, #57, and #8 shown in Figures 3.3, 3.4, and 3.5. An averaged aggregate gradation curves plot for West Virginia quarries is shown in Figure 3.6.

**Material Gradation Curves For #4 Stone**

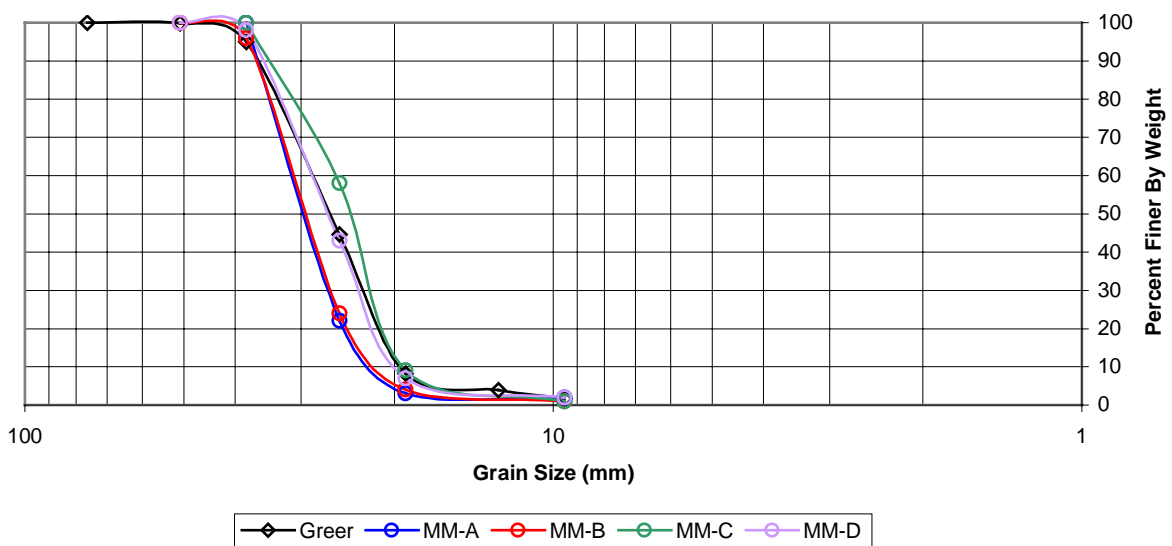


Figure 3.3 Sample Gradation Curves for #4 Stone

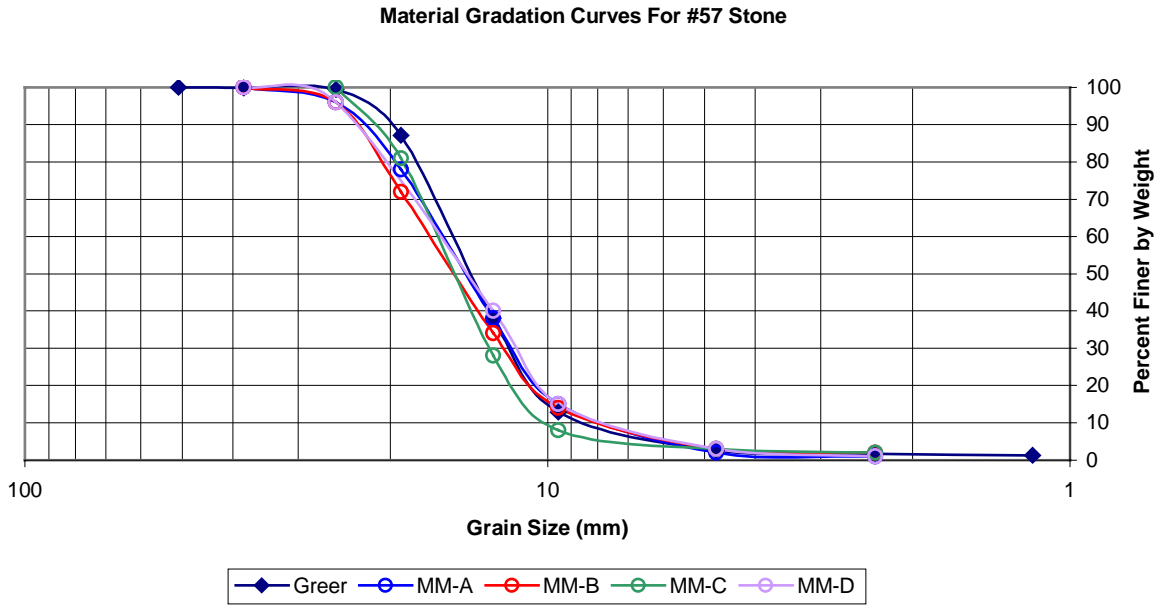


Figure 3.4 Sample Gradation Curves for #57 Stone

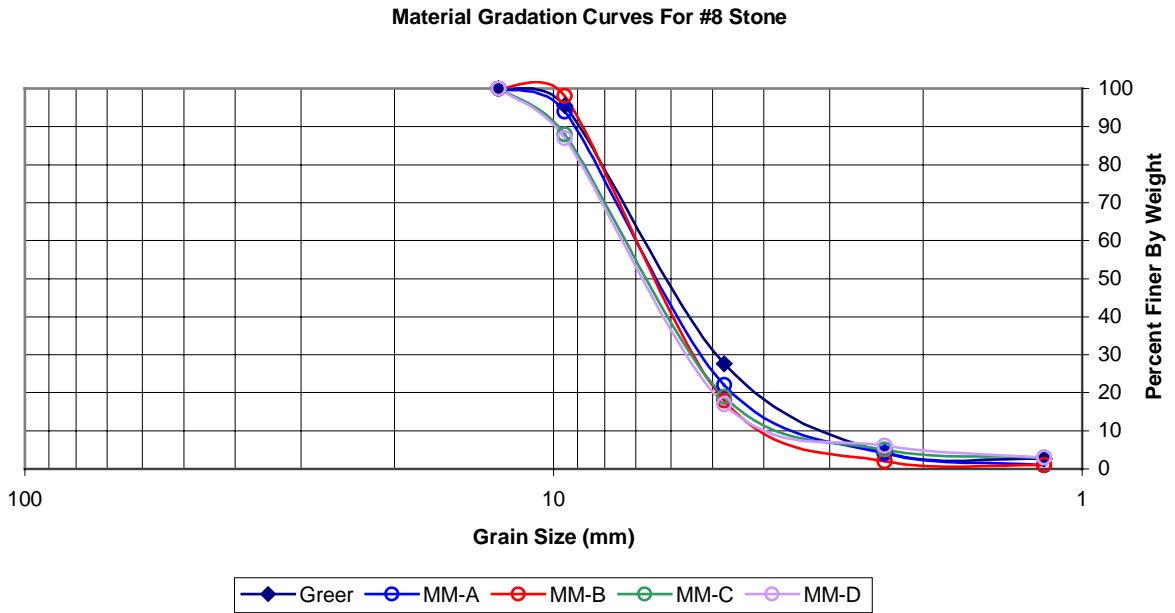


Figure 3.5 Sample Gradation Curves for #8 Stone

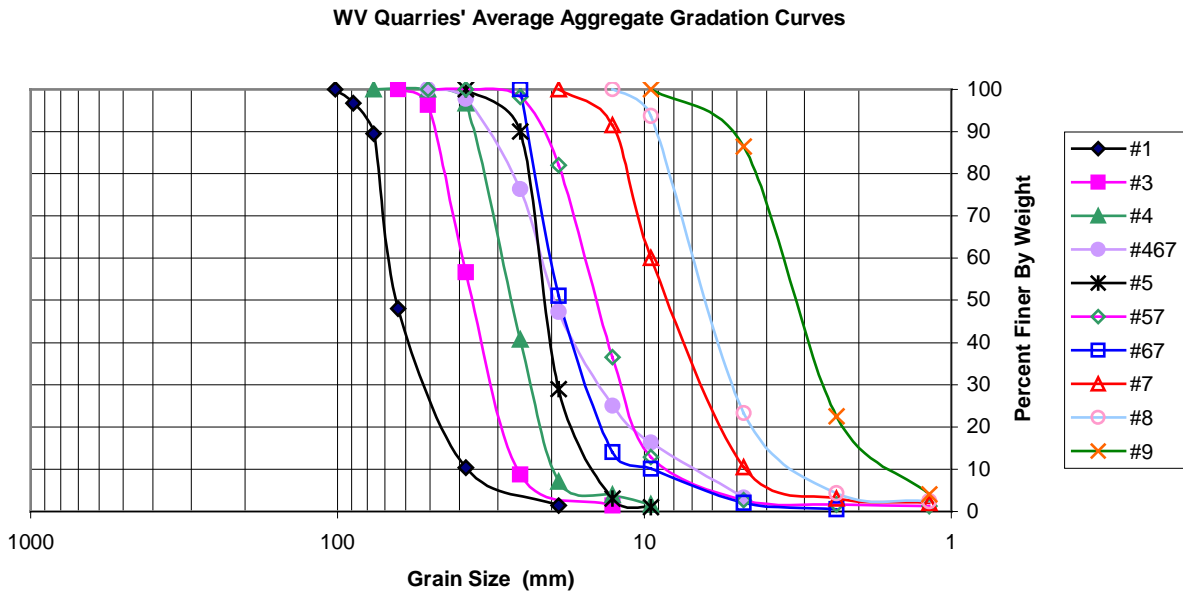


Figure 3.6 Averaged Aggregate Gradation Curves

After the data for the samples was compared, the differences between the five rock samples in Figures 3.3, 3.4, and 3.5 were considered negligible. The sample gradation data was combined in Figure 3.6 that shows ten commonly used rock size gradation curves. Once the range of rock gradations available for state funded projects was obtained, the selection of appropriate rock sizes for the model rock pallets was completed. The results from the quarry investigation provided information that may be used in furthering research of sizing rock for riprap step energy dissipator in the field. Scale model rock pallet (step) construction is discussed in more detail in Chapter 4.

### 3.3 Potential Computer Models

The investigation into the feasibility of an alternative riprap step design delved into the possibility of computer modeling the new design by using HEC-RAS, Version 2.0/2.1 and Riprap Design System, Version 2.0 software packages. After applying the software to several trial runs, it was determined that the software packages could not produce the type of results thought to be pertinent to the project. Therefore, the possibility of utilizing HEC-RAS and Riprap Design System software was dismissed.

## Chapter 4

### Procedure

#### 4.1 Development of Experimental Equipment

At the beginning of the research project the decision was made to construct a flume at WVU to support the testing of physical scale models rather than use an existing facility. The construction of a “custom-built” flume would permit modifications that would likely be necessary over the life of the project. The flume consisted of two tanks to allow for re-circulation of water, necessary piping, and various measuring devices. The flume was designed to accommodate a range of slopes and be within the economic constraints of the project budget, and was to be housed in the Civil Engineering Hydraulics Lab at West Virginia University.

#### 4.2 Pump Selection

A centrifugal pump was selected to provide the re-circulation of water necessary for the experiments. The pump was to operate at low head and would need to accommodate a range of flowrates. Preliminary calculations were performed using standard culvert capacity relationships to assure that the flume would properly model flow conditions that are expected in the field. The selection of a 4.25-inch diameter culvert model required that the maximum flow be approximately 200 gpm under inlet control conditions. This flowrate was used in determining the specifications needed for the pump. For a submerged culvert at the inlet the following equation applies (FHWA HDS #5, 1985):

$$\frac{HW_i}{D} = c \left| \frac{Q}{AD^{0.5}} \right| + Y - 0.5S^2 \quad (4.1)$$

Where:

$HW_i$  = Headwater depth above inlet control section invert (ft)

$D$  = Interior height of culvert Barrel (ft)

$Q$  = Discharge (cfs)

$A$  = Full cross sectional area of culvert barrel (ft<sup>2</sup>)

$S$  = Culvert Barrel Slope (ft/ft)

$Y, c$  = Constants from inlet control design equations

With the test culvert diameter at 4.25-inches and assuming 1-foot of headwater and 10% slope, Q was found to be approximately 200 gpm. The pump selected was purchased from the Interstate Pump Company, and provided slightly over 200 gpm, at 25 feet of head, which provided some excess capacity. The pump setup is shown in Figure 4.1.



Figure 4.1 Centrifugal Pump Setup

#### 4.3 Tank Selection

In order for the flume to properly re-circulate an adequate supply of water, two tanks were needed. The upstream tank needed to be tall, to supply sufficient head, while the downstream tank needed to be short in height so that flow could exit the culvert and be collected by gravity. It also needed to meet the volume requirements on the intake side of the pump. It was determined that the necessary volume for the operation of the flume was approximately 500 gallons. The downstream tank, a 150-gallon oval agricultural tank, was obtained from an agricultural supply store, and is shown in Figure 4.2. Due to the unusual dimensional requirements of the upstream tank, it was impossible to obtain the tank through commercial providers. Therefore, the decision was made to construct a custom designed upstream tank. The upstream tank was constructed from  $\frac{3}{4}$ -inch pressure treated plywood reinforced with 2 x 4 framing. The tank dimensions were 3' x 3' x 5' with an approximate volume of 340 gallons. A square opening, 1.5' x 1.5', was cut in the front of the upstream tank in





Figure 4.2 Downstream Tank

preparation for the addition of the inlet culvert box. The inlet box will be described in greater detail in another section. The completed blue and yellow upstream tank is shown in Figure 4.3. In the initial design stage of the upstream tank, a pond liner was to be used as a bladder for water containment. This proved difficult to install since the seams could not be easily fused to prevent water leakage. This problem was rectified by the removal of the pond liner and application of a waterproof coating on the inside surface of the plywood. The coating chosen was an elastomeric polymer, originally intended for sealing roofs. After several applications of the polymer, the tank was sufficiently waterproofed. It was found to be necessary to reinforce the outside of the upstream tank with 2 x 4 framing due to hydrostatic forces.



Figure 4.3 Upstream Tank

The outside of the upstream tank was painted for aesthetic purposes as well as mold prevention due to the constant high humidity in the hydraulics lab.

#### **4.4 Frame Development**

In order to provide a structure to accommodate piping, piezometer bank, flowmeter, slope adjustment, testing channel, and to keep tanks in a fixed position, a support frame was constructed. The frame consisted of perforated, galvanized 1.25-inch angle iron, which provided an easy means of construction. The framing was simply cut to size and bolted together with 5/16-inch bolts. Trapezoidal braces were constructed on the top of the frame to provide a cradle for the return flow piping. The frame also allows for slope adjustment, which will be discussed in greater detail in a later section.

#### **4.5 Inlet and Outlet Boxes**

Two cast acrylic boxes were constructed to allow for visual examination of physical flow phenomenon present at this inlet and outlet of the culvert. The inlet box dimensions were 1.5' x 1.5' x 1.5' and it was constructed from 0.5-inch cast acrylic. The inlet box was constructed to create uniform and steady flow conditions approaching the inlet of the model culvert. The inlet box is shown below in Figure 4.4.



Figure 4.4 Inlet Box

The outlet box dimensions were 2' x 4' x 1.04' and was also constructed from 0.5-inch cast acrylic. Twenty, 2-inch holes and eight, 1.5-inch holes were drilled out on the downstream end of the outlet box to provide adequate drainage exiting through the floor of the outlet box. A screen was constructed from 0.25-inch hardware cloth and placed over the drilled out holes to prevent debris from entering the downstream tank. A coiled section of hardware cloth was suspended from an angle iron brace, directly below the drilled holes in the outlet box, into the



Figure 4.5 Outlet Box

upper portion of the downstream tank. The coiled hardware cloth prevented air bubbles created by descending, splashing flow into the tank from being pumped throughout the system and producing erroneous flowrate readings. The purpose of the outlet box construction was to serve as a container for the hydraulic models. A testing channel constructed from the same 0.5-inch cast acrylic was placed within the outlet box. This testing channel will be discussed in greater detail in another section. The outlet box is shown in Figure 4.5.

#### 4.6 Piping Assembly

The water supply piping network for the testing flume consisted of 3-inch PVC sewer pipe. Clear acrylic pipe was selected for the model culvert. The PVC pipe proved easy to work with as all fittings could be glued together and cutting the pipe to size could be accomplished with simple tools. Two, 3-inch gate valves provided the flow adjustments needed for experimental runs. One gate valve was located at the upstream tank, near the end of the supply line from the pump, and the flow could be reduced or increased by the valve. The second gate valve was placed at the outlet tank and served as a bypass valve. To provide a low flow capability, the bypass valve was opened to allow some of the supply line flow to re-circulate back into the outlet tank. This bypass was necessary in

order to maintain a minimum required pump flowrate during low discharge testing, about 50 gpm. The supply line was extended vertically downward into the upstream tank so that the submerged jet would dissipate excess turbulent energy in the flow prior to reaching the culvert inlet. The test culvert was constructed of 4.25-inch inside diameter transparent acrylic pipe. One major problem with the test culvert was keeping it sealed at the inlet and outlet boxes, while still allowing for slope adjustment. Sealing was accomplished by the use of two rubber grommets attached to the inlet and outlet boxes with custom washers machined from standard plastic stock. The grommets were attached to the pipe with pipe clamps and proved extremely effective at sealing the test culvert and allowing for slope adjustment. The test culvert is shown in Figure 4.6.



Figure 4.6 Test Culvert

#### 4.7 Measuring Devices

To provide data crucial for hydraulic calculations, several measuring devices were used. The devices implemented in the experimental procedures are as follows:

- Flowmeter
- Piezometer Board
- Three-Point Depth Gage
- Pitot Tube Device
- Slope Adjustment Devices

The measuring devices are discussed in further detail in this section, along with associated problems, corrections, and construction considerations where appropriate.

#### 4.7.1 Flowmeter

A flowmeter was purchased that reads flowrate in gallons per minute over a range of 40-450 gpm with  $\pm 2.0\%$  full-scale linearity and  $\pm 1.0\%$  full-scale repeatability. The flowmeter is shown in Figure 4.7.

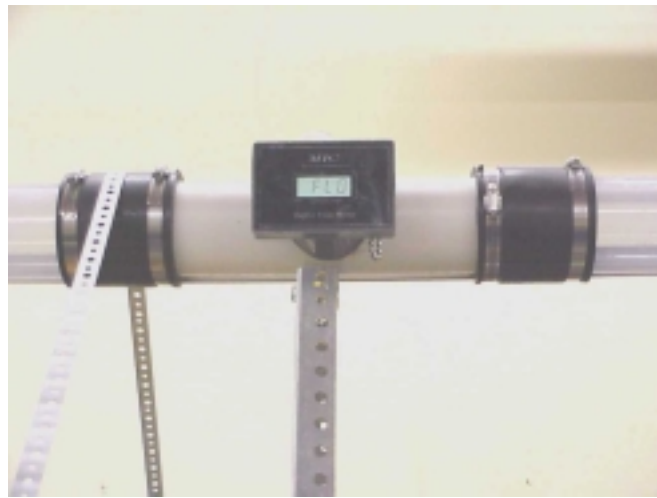


Figure 4.7 Flowmeter

Initially, the supply line, from the downstream to upstream tank, contained a double elbow bend upstream of the flowmeter. This location produced erroneous flowmeter readings with high fluctuations. It was determined that the double bend was producing vortices that were causing the incorrect readings. It was also suspected that air was being trapped at certain locations in the supply line. To correct these problems, three modifications were made. First, the double elbow bend was removed and replaced with a single elbow. Second, the overhead supply line was replaced with translucent 3-inch PVC pipe to allow for visual inspection of the flow entering and exiting the flowmeter. Third, several air bleeds were placed along the overhead supply line to remove any trapped air from the line. These corrections eliminated the problems mentioned, and provided greater assurance of accurate measurements.

#### 4.7.2 Piezometer Board

In order to measure the water surface elevation at various locations in the test culvert, a piezometer board was constructed. The board consisted of nineteen, ¼-inch Plexiglas tubes attached to a ¼-inch plywood board. Scales were mounted next to the tubes with bolts and wing nuts that could slide vertically, in a milled slot, to allow for the establishment of a zero reading. The tubes were attached to tygon tubing at the bottom, and connected to the test culvert at various points through brass fittings. First, 1/32-inch diameter holes were drilled in the test culvert invert to serve as the piezometer tap. The brass fittings were threaded into small rectangular blocks of Plexiglas that were glued to the test culvert around the previously drilled holes. This produced a row of piezometer tap measurements along the invert of the test culvert from which uniform flow depth could be established. The piezometer setup is shown in Figure 4.8.



Figure 4.8 Piezometer Board

#### 4.7.3 Three-point Depth Gage

To obtain water depths, a point gage was borrowed from an existing flume and modified by adding two lateral points (prongs). The modified three-point depth gage was to provide a more accurate representation of the average flow depth along any cross section in the test channel. The point gage had a vernier scale that was accurate to 0.001-foot. The scale is shown in Figure 4.9. First, the center point was lowered to the water surface and a reading was taken. Next the lateral points were lowered and another reading was taken. The average of the “inside” and “outside” depth reading is the average flow depth for that cross section. A track was constructed of 1 ½-inch



aluminum angle that allowed the point gage to travel along the testing channel so depth reading could be taken at various points. To provide longitudinal measurement along the testing channel, a scale was bolted on the outside of the outlet box and a pointer was attached to the side of the gage. The three-point depth gage is shown in Figure 4.10.

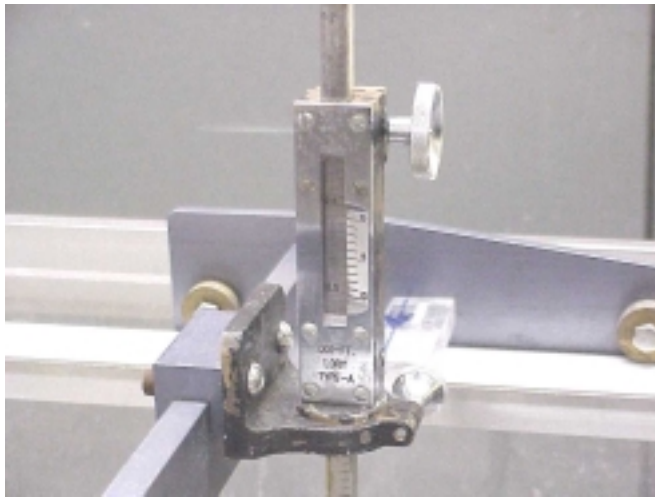


Figure 4.9 Point Gage Scale

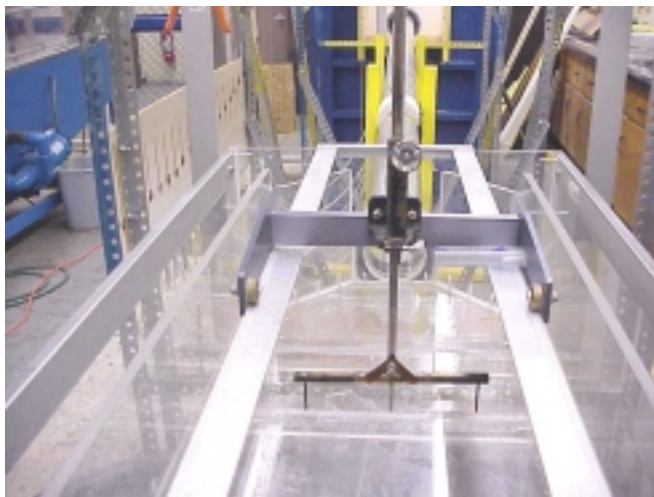


Figure 4.10 Three-Point Depth Gage

Table 4.1 shows the distance from the culvert outlet to the point where each of the water surface elevation readings were taken. Figure 4.11 shows the positions of the cross-section where each of the water surface elevation readings along the horizontal length of the testing channel were obtained.

Table 4.1 Water Surface Elevation Readings	
Test Channel Cross-Section	Horizontal Distance From Culvert (mm)
AA	139.5
A	269.5
B	434.5
C	624.5
D	779.5
DD	879.5
E	931.5

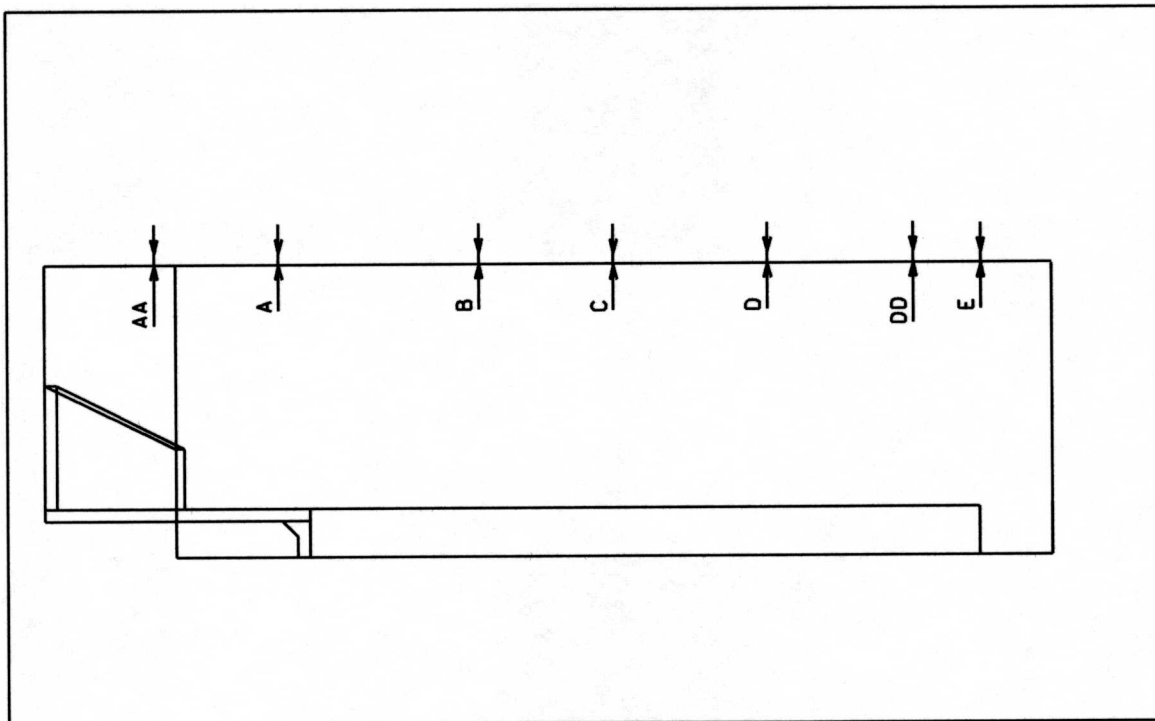


Figure 4.11 Position of Water Surface Elevation Readings

#### 4.7.4 Pitot Tube Device

In order to more accurately compute the energy grade line for various model tests, it was decided that the velocity profile for the rectangular test section needed to be established. A Pitot tube was constructed using 5mm-glass tubing. When this tube was first tested there were many oscillations present, so a 3-milimeter-glass tube was inserted inside the horizontal section of the existing tube to produce a damping effect. Next the Pitot tube was



clamped into a Plexiglas cradle and then fitted to a Plexiglas slide and track to allow for vertical and lateral adjustments. A metric scale and pointer were then fixed to the apparatus to allow for depth and total head measurements. The rectangular channel cross section was then divided into 15 evenly spaced subsections and tick marks were placed on the surface of the Plexiglas track. The completed apparatus can be seen in Figures 4.12 and 4.13.

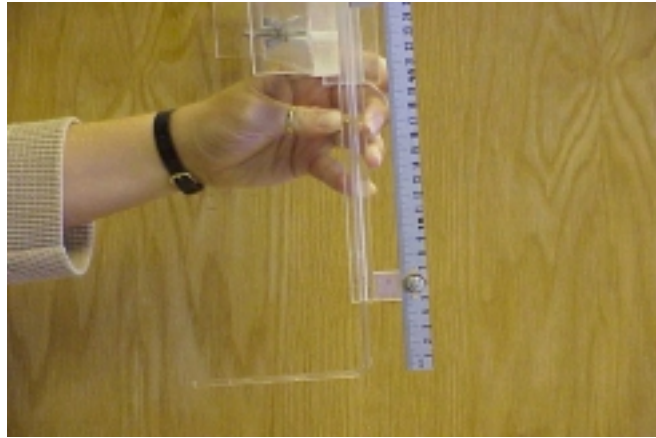


Figure 4.12 Pitot Device (side view)



Figure 4.13 Pitot Device (front view)

In applying the Pitot tube for establishing the velocity profile the Energy equation was used:

$$\frac{p}{\gamma} + \frac{V^2}{2g} + z = \text{PitotMeasurementAboveDatum} \quad (4.2)$$

Where:

$p$  = Pressure

$\gamma$  = Specific weight of water

$V$  = Velocity

$g$  = Acceleration due to gravity

$z$  = Height above zero datum

The first term,  $\frac{p}{\gamma}$ , represents local pressure head, is assumed to be the depth of water above the centerline of the

Pitot tube, a hydrostatic assumption. The second term,  $\frac{V^2}{2g}$  which represents the velocity head, was computed in

mm/s with the value for acceleration due to gravity being 9807 mm/s<sup>2</sup>. The last term,  $z$ , represents the datum elevation that was taken as the elevation of the false floor in the rectangular channel. The datum was established by placing the center of the Pitot tube at the surface of the false floor and recording the depth from the scale attached to the Pitot apparatus.

To determine the value for the velocity correction factor, alpha, the following expression was used:

$$\alpha = \frac{1}{V^3 A} \sum_{15} u^3 dA \quad (4.3)$$

Where  $\alpha$  is the value for the velocity correction factor. The point velocity found from the Pitot tube is represented by  $u$ . The term  $dA$  is each incremental area in which a corresponding measurement was taken. The values in the numerator are then summed from 1 to 15, as there were 15 sections of measurement. In the denominator,  $V$  represents the average velocity and  $A$  is the total cross-sectional area of the flow.

#### 4.7.5 Slope Adjustment Devices

Slopes of 2, 4, 6 and 8% were selected for testing in the experimental runs. Therefore it was crucial that the flume could be adjusted accordingly. To allow for slope variation, the outlet box rested on adjustable supports at the front and back of the box. The supports could be bolted at incremental heights on the vertical columns on either

side of the box. Two pieces of all-thread steel rod were attached to the support on the left and right of the box, along with another piece of steel angle. This piece of steel angle was adjusted by lifting up the box and turning nuts on the threaded rod to achieve the desired setting. Next, a datum was established by attaching five scales to the frame, using surveying equipment, and then all slope adjustments were calculated based on that elevation. One scale was placed at the test culvert inlet and the other four scales around the outlet box so it could easily be leveled. The slope adjustment setup is shown in Figure 4.14. A close-up of the support adjustment is shown in Figure 4.15.



Figure 4.14 Outlet Box Slope Adjustment



Figure 4.15 Support Adjustment

#### 4.8 Model Construction

Four principal components were required to perform the planned hydraulic model tests of riprap step: 1) a culvert outlet configuration consisting of headwall, wingwall, and apron, 2) a testing channel, 3) the cast acrylic pallets, and 4) the rock pallets to be tested. Since plans were available for the existing culvert apron design, the scale model was easily constructed of 0.5-inch thick cast acrylic. All dimensions were expressed as a function of culvert diameter and the scale model was constructed based on this non-dimensionality. A rectangular testing channel was used to contain the flow within lateral boundaries. To produce the rectangular channel, two vertical walls were attached to the model apron, and two concrete pallets were built to simulate downstream channel conditions. The pallet, either the smooth cast acrylic or the rock that was closest to the apron was referred to as the Zone 1 pallet, and the farthest downstream pallet as the Zone 2 pallet. The Zone 2 pallet was raised as required to simulate a smooth or riprap step as desired. Two vertical cast acrylic extensions were added to the wingwalls to prevent flows from short-circuiting over the wingwalls due to splashing, etc. The testing channel is shown in Figure 4.16.



Figure 4.16 Testing Channel

Zone 1 pallets, either smooth cast acrylic or rough rock, were constructed so that an averaged flow depth remained at zero datum. Twelve Zone 2 pallets, shown in Table 4.2, were constructed, six cast acrylic and six rock.

Table 4.2 Zone 2 Pallets Nominal Step Heights		
Cast Acrylic (Actual Height)	Rock Height (Area Averaged)	SI Units (mm)
0.0	0.0	0.00
0.5	0.5	12.7
1.0	1.0	25.4
1.5	1.5	38.1
2.0	2.0	50.8
2.5	2.5	63.5

The smooth cast acrylic pallets were to be used as a smooth step reference model for the rough rock pallets (riprap step). The pallets are discussed in the following sections. For simplicity purposes, the steps will be referenced by inches and not SI values.

#### 4.8.1 Cast Acrylic Pallets

The 0.5-inch cast acrylic pallets, referred to as smooth pallets, were constructed for both Zones 1 and 2. A single pallet, 352mm x 413mm x 12.7mm, was constructed for Zone 1. The Zone 1 pallet was cemented in place at a location where the upper surface would be at zero datum. Six Zone 2 pallets, 300mm long and 413mm wide. The pallets were precisely cut and constructed to obtain the desired range of step heights as listed in Table 4.2. All construction joints for the smooth pallets in Zone 2 were sealed with Silicon cement. At the base of each step, with exception of the 0.0-inch step, a section of rubber weather door stripping was attached with Silicon cement to the inner portion of the step's flow impact panel as well as the inner portion of the step's back panel. Glue strips prevented an unaccountable loss of flow under the step. Given the very careful construction of the steps, a very tight fit was achieved between the test channel wall and the wall of the step preventing significant bypassing of flow. Realizing a need for ease of step removal and placement, one hole was drilled through both sides of the test channel into the in-place step. Metal pins were inserted into the holes to hold the steps in place. This process was repeated for each of the six steps. The removal and replacement process involved: 1) removing pins, 2) removing step, 3) placing new step, 4) inserting pins, and 5) taking measurements for the next step height. Photographs of the smooth step assembly are shown in Figures 4.17 and 4.18.

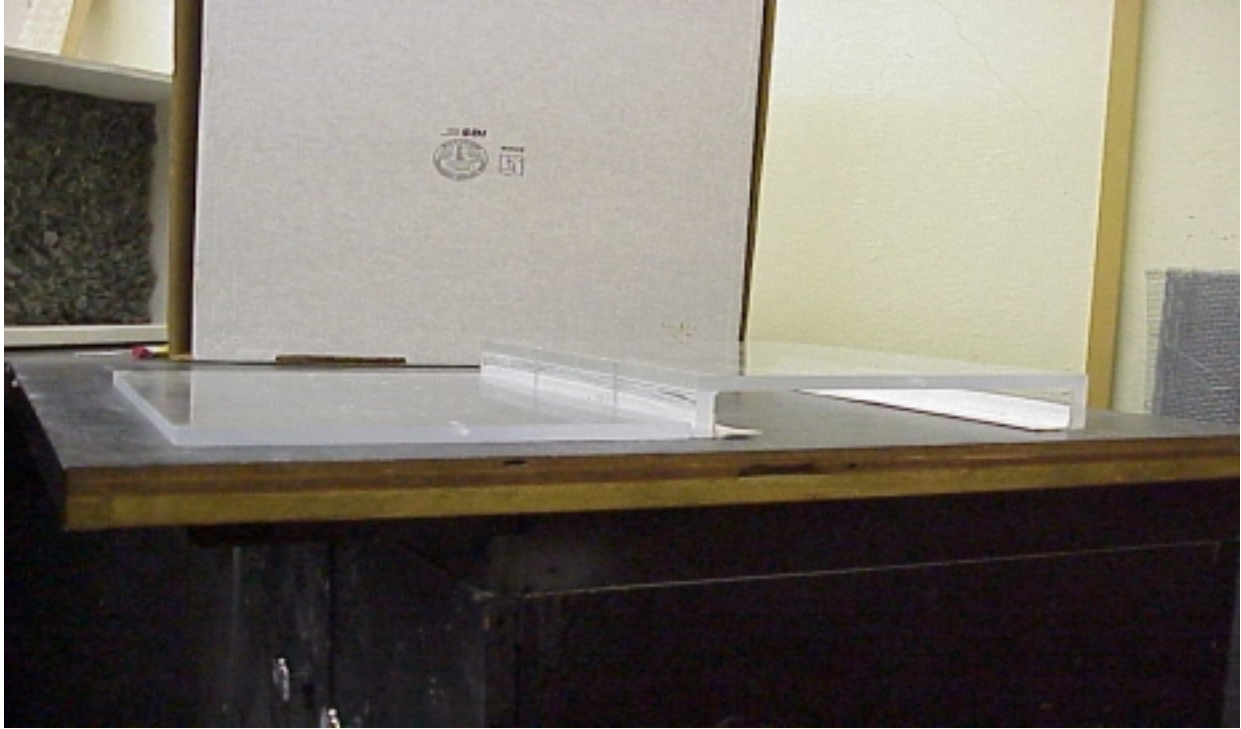


Figure 4.17 Sample Cast Acrylic Assembly Profile

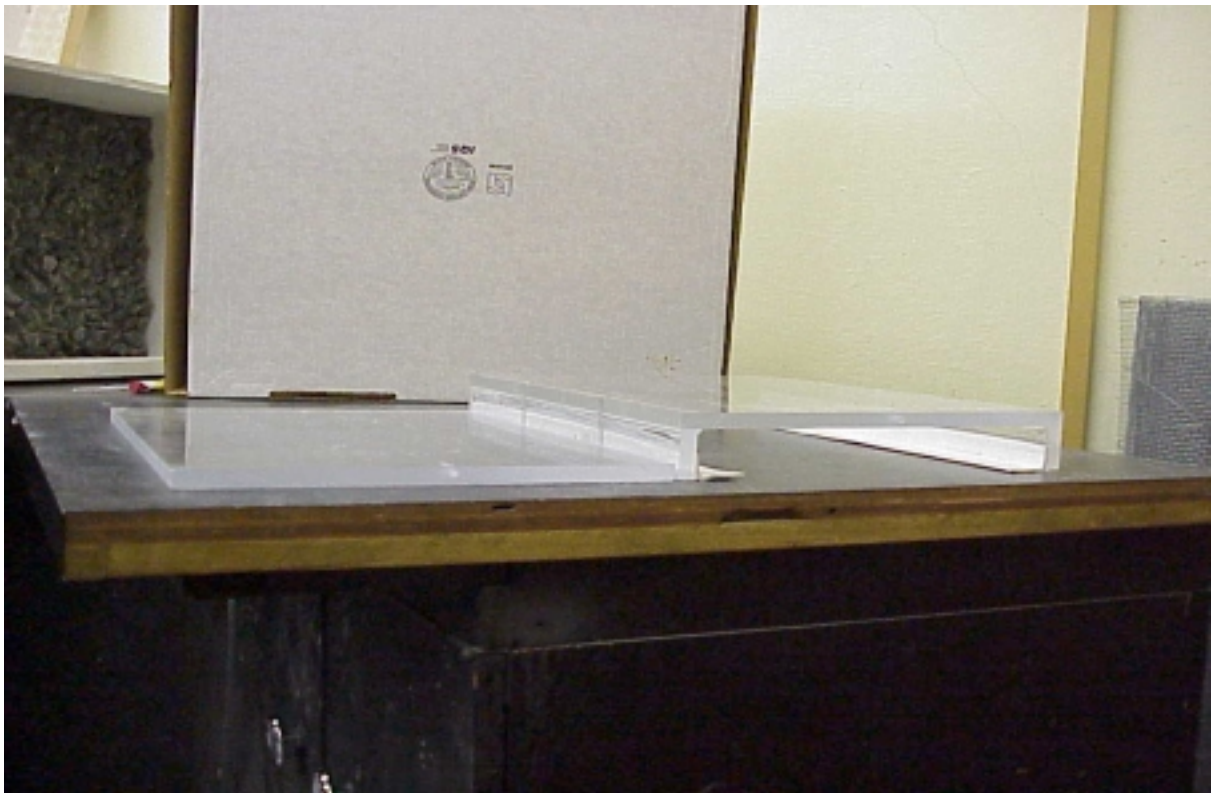


Figure 4.18 Sample Cast Acrylic Assembly

#### 4.8.2 Rock Pallets

Rock samples, ranging from 6-inch stone to #8 stone, were obtained from Greer quarry. The stone was thoroughly cleaned and dried. After representative stone samples were inspected, dimensions and characteristics were recorded and shown in Table 4.3 below.

Stone Type (Size)	Number of Sides	Length (mm)	Width (mm)	Height (mm)	Circumference (mm)
6"	6	160	110	90	353
6"	6	140	70	65	310
6"	4	140	103	90	305
6"	6	115	100	86	242
6"	5	120	100	74	338
6"	5	140	90	80	290
1	7	50	45	38	135
1	5	60	47	30	138
1	5	80	47	42	145
1	4	85	80	72	200
1	7	57	37	33	150
1	3	112	60	48	165
1	5	70	50	43	150
1	6	55	50	38	155
1	6	105	65	60	225
1	5	60	36	29	125
4	4	70	37	35	140
4	4	46	35	32	118
4	4	37	29	31	95
4	5	55	31	27	120
4	5	53	45	30	110
4	5	36	35	22	96
4	4	75	61	20	130
4	4	45	36	20	105
4	6	49	18	12	75
4	3	41	20	25	72
4	5	28	22	17	82
4	5	42	33	25	95
57	5	32	15	19	85
57	4	38	22	19	72
57	5	22	14	13	60
57	6	28	20	13	63
57	5	27	25	16	80
57	4	29	23	14	64
57	5	28	11	12	43
57	4	33	17	11	55
57	4	17	15	10	40
57	4	19	14	14	52
57	5	30	28	8	61

Stone Type (Size)	Number of Sides	Length (mm)	Width (mm)	Height (mm)	Circumference (mm)
67	5	20	13	20	57
67	6	17	16	13	51
67	4	19	17	16	55
67	6	21	19	18	62
67	4	22	16	17	55
67	5	23	12	14	50
67	4	13	10	11	35
67	4	16	12	8	40
67	5	15	9	8	31
67	5	15	12	10	38
67	4	20	13	10	36
8	4	16	11	8	29
8	4	15	10	8	27
8	4	18	8	12	35
8	5	20	10	8	35
8	4	14	10	8	30

Six rock gradations were randomly selected to construct the Zone 2 rock pallets listed in Section 4.8. Table 4.4 shows the relationship between step equivalent, pallet number and rock type.

Step Equivalent (in)	Pallet Number	Rock Type
0.0	Matching Zone 1 and Zone 2	# 57 #67
0.5	2	#1 #57 #67
1.0	5	#1 #57
1.5	3	6-inch #4 #67
2.0	8	6-inch #1 #57
2.5	7	6-inch #1

Forms, constructed from 2x4 lumber, and connected using 2-inch wood screws, served as molds for the rock pallets. Plastic florescent light cover grids, providing support for the vinyl cement used, were cut into 352mm



x 413mm and 300mm x 413mm sections for Zones 1 and 2, respectively, and placed in the forms. Vinyl cement was mixed and poured into the wooden forms and evenly screeded with a flat edge. The specific equivalent step height rock gradation was lightly inserted into the cement progressing from the largest to the smallest rock type. A single layer of the largest rock type was placed such that every rock contacted with the next. Voids between the rocks occur when uniformly graded rock is clustered together. In order to fill the voids, the second largest rock type was inserted into the cement. This process was repeated until the smallest of the rock types in the specific equivalent step height rock gradation was used. The rock pallets constructed are shown in Figures 4.19, 4.20, 4.21, 4.22, 4.23 and 4.24.



Figure 4.19 0.0-inch Equivalent Step Height

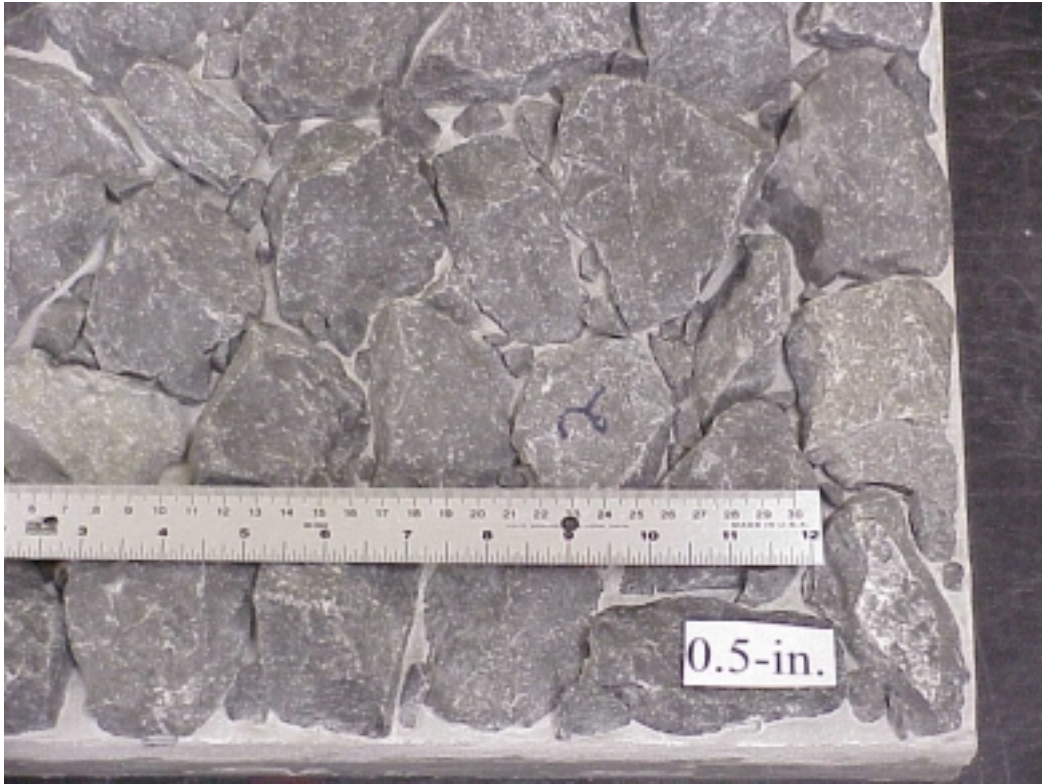


Figure 4.20 0.5-inch Equivalent Step Height

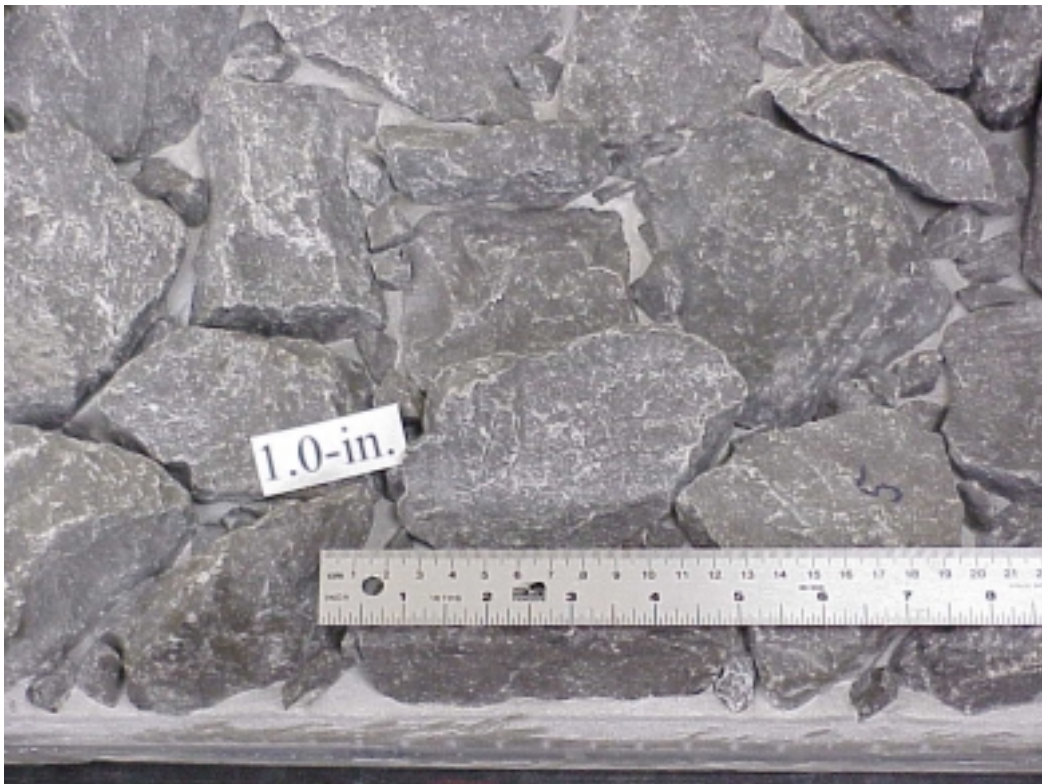


Figure 4.21 1.0-inch Equivalent Step Height





Figure 4.22 1.5-inch Equivalent Step Height

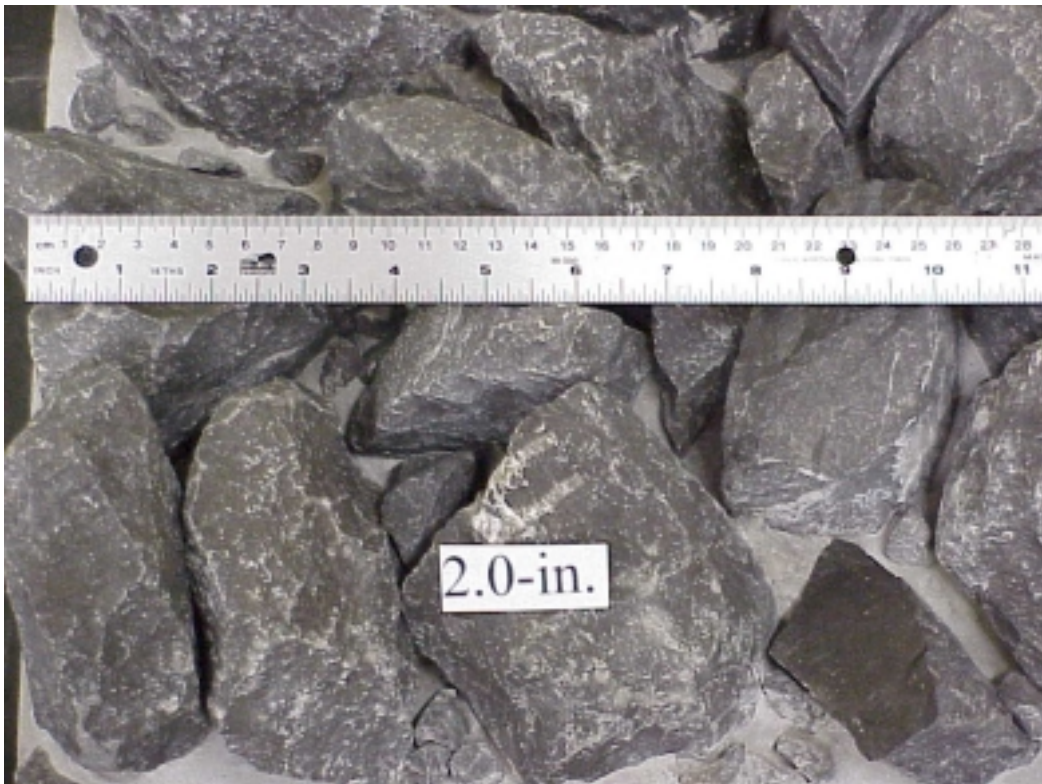


Figure 4.23 2.0-inch Equivalent Step Height



Figure 4.24 2.5-inch Equivalent Step Height

The cement rock pallets were moistened during the 48-hour curing period and then removed from the wooden forms. At various flowrates, the water surface would not flow over the highest rock in the pallet. Since the equivalent step height calculations were based on the assumption that the water height would be greater than the highest rock in the pallet, it was necessary to perform volumetric displacement tests on each of the rock pallets. Incremental water and rock volume data was recorded for future application in the energy calculations in the testing channel. Volumetric displacement testing boxes, 352mm x 413mm x 254mm, and 300mm x 413mm x 254mm, were constructed from  $\frac{3}{4}$ -inch plywood, 1"x10" lumber, and 2-inch wood screws. Two, 3-inch holes were drilled into the bottom section of the plywood allowing a space for hand removal of the pallet after the volumetric test was completed. The plastic grids were then removed and the pallet was positioned into the tightly fitting volumetric testing box. In order to reduce surface tension effects, the surface of the rock pallet was moistened and the water level in the box was increased until the water surface was in the same horizontal plane as the cement surface containing the protruding rock. Incremental volumes of water were added and corresponding water surface elevations noted shown in Figure 4.25.

### Water Volume Displacement Tests - All Equivalent Step Heights

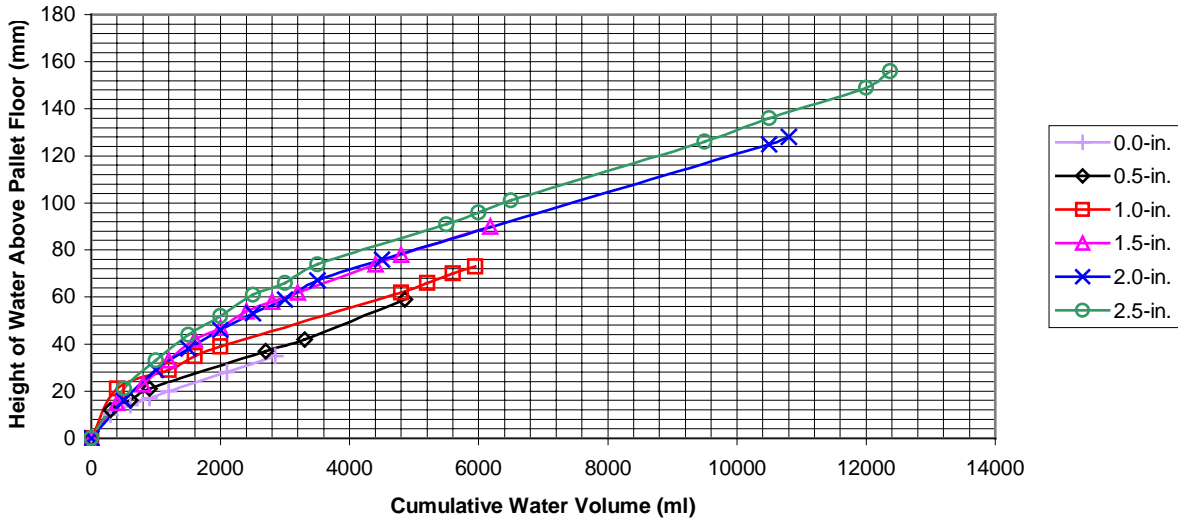


Figure 4.25 Water Volume Displacement Tests

To prevent chipping and disfigurement of the pallets, a 0.5-inch plexiglas section with pallet dimensions was cemented onto the bottom of each cement pallet base. After the completion of the volumetric displacement tests, calculations were performed to determine the necessary shim heights to achieve the nominal step height desired.

To prevent confusion in later sections, a diagram of a sample riprap step cross-section with flow is shown in Figure 4.26.

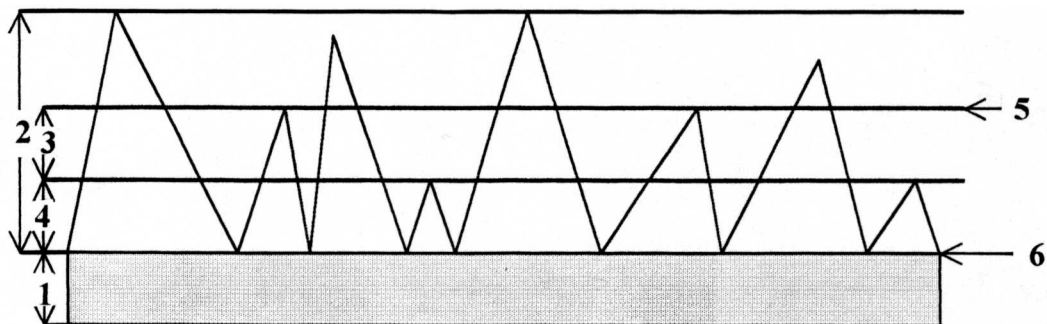


Figure 4.26 Sample Riprap Step Cross-section With Flow

Where:

1 = Cement base thickness

2 = Equivalent (nominal) riprap step height

3 = Depth of water

4 = Actual (melted) rock height

5 = Water surface elevation

6 = Zero datum

## Chapter 5

### Analysis

Following the completion of the testing flume, hypotheses were developed for the investigation of the riprap steps. In order for the riprap steps to meet the goals of the project the following criteria had to be satisfied.

The design must be:

- Reasonably easy to construct on site
- Economically feasible
- Applicable to various culvert sizes and flowrates
- Self cleaning and require low maintenance (not directly addressed by experimentation)
- Capable of re-establishing natural flow conditions downstream of the outlet

The riprap steps constructed were intended for culvert diameters equal to or less than 4.25 feet.

#### 5.1 Data Collection

Following the completion of the testing flume, several riprap step heights and/or gradations were tested. The purpose was to observe which riprap steps forced a hydraulic jump and provided the best energy attenuation. The twelve riprap steps, each having a unique height and/or configuration were tested. Each experimental run required the measurement of five main parameters:

- Flowrate
- Three point depth data
- Headwater at inlet
- Slope
- Piezometer readings

A data sheet was developed to accommodate the various data taken. Culvert slopes tested were 2, 4, 6, and 8 percent. Headwater was read at the beginning of each test, measured from the invert of the test culvert. Piezometer readings were taken before the pump was turned on to establish a tare reading (zero depth). The depth reading was computed as an average of the middle point and the reading from the two lateral points of the three-point gage. Along with the three-point depth measurements, the flow behavior at the culvert outlet, interactions with the wingwalls, and any adverse effects or flow anomalies were noted based on visual observations. Flowrates of 50, 75,

100, 125, and 150 gpm were applied to each step height, both smooth cast acrylic and rock riprap, at each of the four slopes.

## 5.2 Equivalent or ‘Melted’ Riprap Step Height

Further explanation is needed in order to fully understand what is meant by equivalent riprap step height. When using the ‘smooth’ cast acrylic steps, the flow in the test channel impacted each step at its given height, either 0.5, 1.0, 1.5, 2.0 or 2.5-inches. A simple subtraction operation provided the necessary flow depth measurement. A more complicated approach was needed to obtain the equivalent step height with the rock steps. As mentioned earlier, the equivalent step heights were calculated based on the assumption that the flow would completely cover the rock in the step. Rarely was this the case with the riprap steps. With the use of the volumetric displacement test data, the volume and actual effective (‘melted’) height of the rock impacted by the flow was calculated. The comparison between the equivalent riprap step height and the effective ‘melted’ riprap step height is presented in Table 5.1. **Note:** The riprap step height given is for reference purposes only, and is not the actual step height based on wetted rock volume (referenced to as the ‘melted’ height). Calculations were performed on the ‘melted’ height.

Slope (%)	Flowrate (gpm)	0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
		(in)				
2	50	0.347	0.894	1.22	1.81	1.95
2	75	0.382	0.944	1.26	1.82	1.96
2	100	0.414	0.931	1.27	1.81	1.97
2	125	0.465	0.933	1.29	1.82	1.97
2	150	0.474	0.945	1.30	1.83	1.96
4	50	0.360	0.917	1.26	1.81	1.95
4	75	0.386	0.927	1.28	1.82	1.96
4	100	0.442	0.928	1.27	1.82	1.96
4	125	0.478	0.933	1.37	1.82	1.97
4	150	0.503	0.949	1.29	1.83	1.98
6	50	0.350	0.881	1.26	1.81	1.95
6	75	0.375	0.903	1.27	1.81	1.96
6	100	0.411	0.931	1.26	1.82	1.97
6	125	0.456	0.926	1.27	1.80	1.97
6	150	0.433	0.925	1.29	1.82	2.01
8	50	0.353	0.921	1.23	1.81	1.95
8	75	0.368	0.891	1.24	1.81	1.95
8	100	0.405	0.905	1.25	1.81	1.96
8	125	0.400	0.929	1.28	1.82	1.96
8	150	0.348	0.928	1.27	1.82	1.41



### 5.3 Water Surface Elevation Data Influences

Many types of flow influenced the experimenter's ability to obtain accurate water surface elevation readings. Some of the influences are: 1) reverse flow, 2) not fully expanded jet, 3) spurting flow, 4) swirling flow, 5) splashing flow, 6) pooling, and 7) hydraulic jump. **Note:** The letter or abbreviation in parenthesis by each of the flow influences is a representative symbol referenced in Section 5.20.

#### 5.3.1 Reverse Flow (R)

One influence on the water surface elevation readings was the presence of reverse flow of the test channel. Reverse flow is common with expanding jets into open channel flow in channels, especially rectangular channels. Figure 5.1 shows an example of reverse flow experienced in the test channel. A boundary could be seen



Figure 5.1 Reverse Flow in Test Channel

between the reverse flow, characterized by vortices, and the expanding jet exiting the test culvert and flowing across Zone 1. Two different water surface elevations, inside and outside the boundary between the two types of flow, caused great difficulty in obtaining accurate water surface elevation readings.

### 5.3.2 Not Fully Expanded Jet (X)

Before initializing the project, based on previous research, it was believed that the dimensions of the test channel would be adequate for all the experimental runs. After initializing the experimental runs, it was discovered that high flowrates produced a jet in the test channel that could not fully expand before impacting against the step in Zone 2. Refer to Figure 5.2. As a result, two different water surface elevations, inside and outside the boundary between the un-expanded jet and the more uniform flow, caused difficulty in obtaining accurate readings.

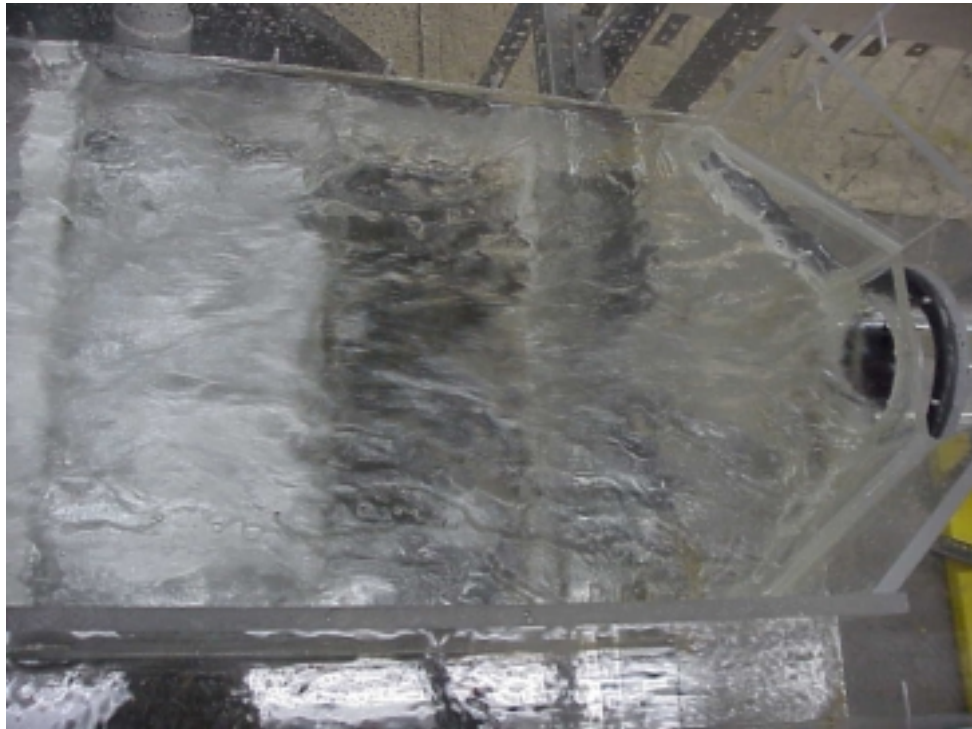


Figure 5.2 Not Fully Expanded Jet

### 5.3.3 Spurting Flow (P)

A characteristic of flowing water impacting an object is a spurting flow. As the flow in the test channel impacted against the step in Zone 2, often a spurting flow would occur as seen in Figure 5.3. The spurting flow is sometimes referred to as a “rooster tail”. Due to the impossibility of collecting water surface elevation readings at particular areas in Zone 2 caused by the spurting flow, averaging values with the three-point gage was not possible and a single reading had to be applied for the entire cross-section.



Figure 5.3 Spurting Flow

#### 5.3.4 Swirling Flow (W)

A rarely observed phenomenon occurred in a couple experimental runs. A flow instability, or the Coanda effect, was believed to have been present. The Coanda effect is primarily a resulting problem of turbulent flow and turbulent mixing. When the flow proceeds down the center of a channel with vortices on either side, an unstable situation is formed. With circulating water, a momentary pressure change is experienced resulting in a higher pressure on one wall of the testing channel than the other. Since water flows from high pressure to low pressure, the flow goes in the direction of the wall with the lower pressure. The jet is most stable attached to the wall. A balance is reached between the momentum component toward the wall and the pressure. When the balance is reached, the jet moves away from the wall and tries to attach itself to the other wall as a pressure change takes place (Fluid Amplifiers, 1966).

Most often a balance between momentum and pressure is reached with no such effects occurring. Only on rare occasions was this effect seen, as in Figure 5.4. Instead of impacting the step at the center, the impact would occur at one side. The water surface elevation readings were difficult to obtain due to the oscillating flow with varied elevations.

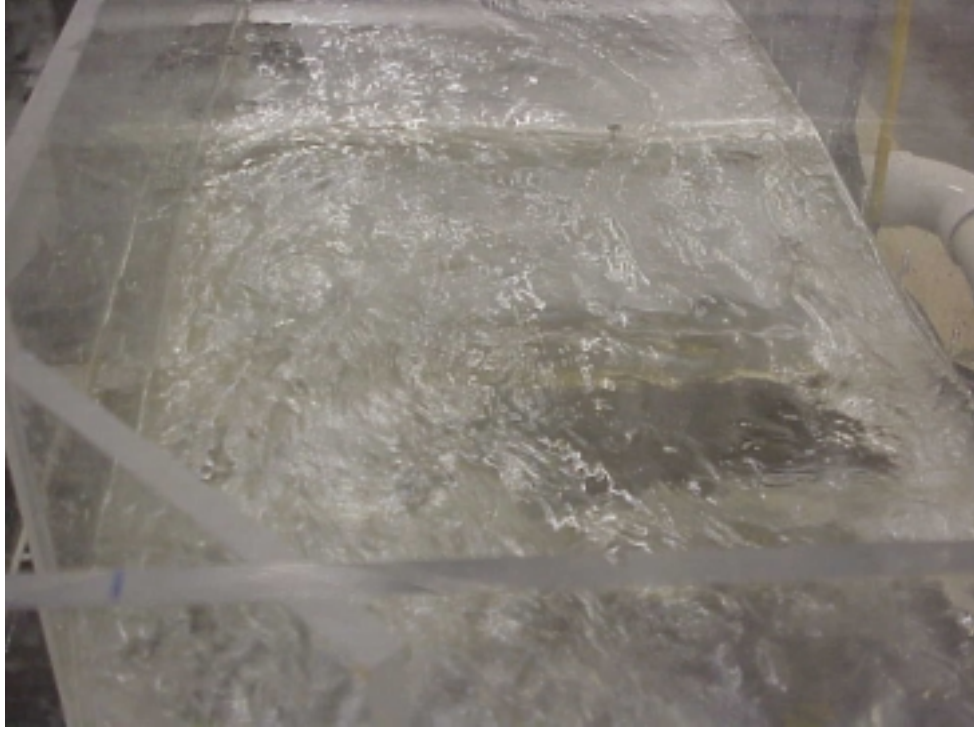


Figure 5.4 Swirling Flow

### 5.3.5 Splashing Flow (S)

Splashing flow occurred primarily with riprap steps. Unlike the smooth cast acrylic steps, riprap steps have a rough, angular surface consisting of many obstacles and voids. As the flow impacts the rock in the step, flow splashes and becomes more turbulent, increasing energy dissipation. As a result of the splashing against the rock, especially larger rock in the 2.0-inch and 2.5-inch equivalent riprap steps, accurate water surface elevations readings were difficult to obtain. See Figure 5.5.

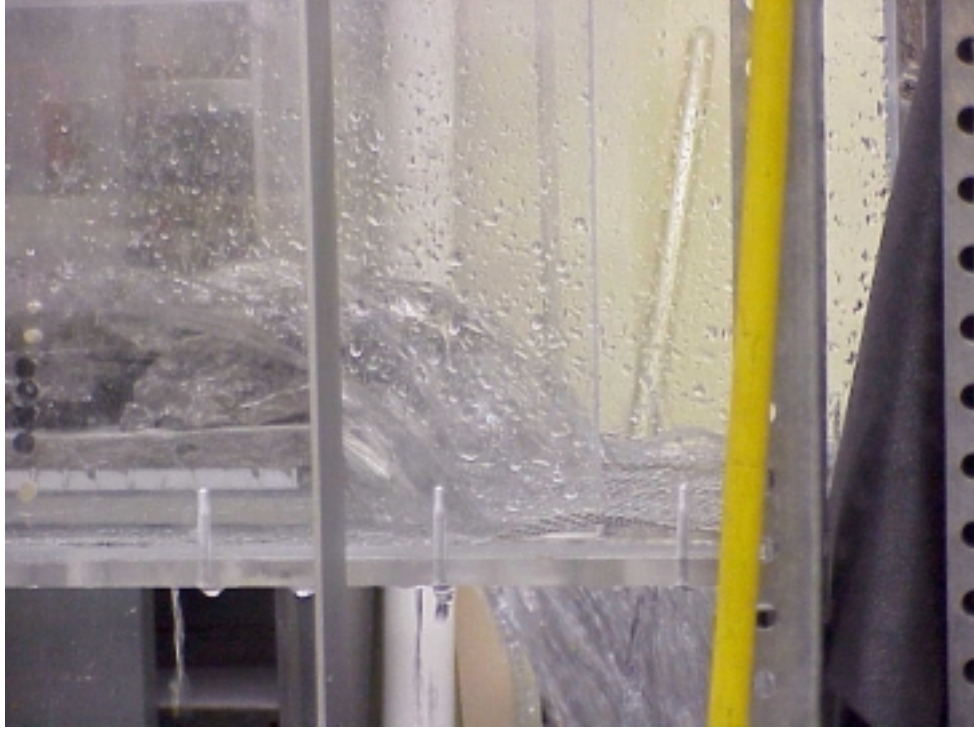


Figure 5.5 Splashing Flow

### 5.3.6 Hydraulic Jump

Hydraulic jumps were discussed in Section 2.2.1. Froude numbers of the jumps in the test channel were less than 4.5. Types of flows will be classified as the following:

- **J0** = No Jump ( $Fr < 1$ )
- **J1** = Weak Jump ( $1 < Fr < 2.5$ )
- **J2** = Oscillating Jump ( $2.5 < Fr < 4.5$ )
- **^** = Jump Located in Test Channel
- **\*** = Jump Located in Test Culvert

Example: **J2\*** Representing Oscillating Jump in Test Culvert

### 5.3.7 Pooling (L)

Pooling, accumulation of water in Zone 1 due to the increase step height in Zone 2, of the flow occurred at higher step heights. Pooling effects raised the energy grade lines, EGL, giving the appearance that the increase in step height was not an effective means of dissipating energy in Zone 2 of the test channel. Pooling and EGLs are discussed further in later sections.



#### 5.4 Velocity Profile Investigation

To determine the value for alpha, the velocity head correction factor, the following expression was used:

$$\alpha = \frac{1}{V^3 A} \int_0^{15} u^3 dA \quad (5.1)$$

Where:

$\alpha$  = Velocity correction factor

$u$  = Point velocity found from the Pitot tube

$dA$  = Incremental area at which measurements were taken

$V$  = Average velocity

$A$  = Total cross-sectional area of flow

The values in the numerator are then summed from 1 to 15, as there were 15 sections of measurement. Initial calculations were performed at 50 gpm at 8 % slope, since the flow appearance at 8% slope appeared the most non-uniform. The first method used values obtained solely from the Pitot tube. Table 5.2 lists the data measurements and results of the computations.

1	2	3	4	5	6	7	8	9	10
Width Increments	Depth From Bottom of Tube	Pitot Reading	Pitot Depth	Depth From Center of Tube	$\rho/\gamma$	Point Velocity @ section	Area @ section	$(u^3)dA$	Incremental Flowrate
(Section)	(mm)	(mm)	(mm)	(mm)	(mm)	(mm/s)	(mm <sup>2</sup> )		(mm <sup>3</sup> /s)
1	241	45.0	250	244	6.50	869	317	2.078E+11	275150
2	241	60.0	247	244	3.50	1053	317	3.694E+11	333322
3	241	85.0	248	244	4.50	1257	317	6.282E+11	397867
4	242	125	249	245	4.50	1537	289	1.050E+12	444452
5	248	135	253	251	2.50	1612	124	5.191E+11	199739
6	248	140	253	251	2.50	1642	124	5.488E+11	203473
7	248	150	253	251	2.50	1701	124	6.097E+11	210742
8	248	153	253	251	2.50	1715	124	6.253E+11	212520
9	248	160	253	251	2.50	1758	124	6.727E+11	217768
10	248	155	253	251	2.50	1729	124	6.410E+11	214284
11	248	145	253	251	2.50	1672	124	5.790E+11	207139
12	248	140	253	251	2.50	1642	124	5.488E+11	203473
13	241	140	247	244	3.50	1636	317	1.387E+12	518091
14	241	90.0	246	244	2.50	1310	317	7.119E+11	414805
15	241	75.0	246	244	2.50	1192	317	5.369E+11	377580
SUMS:						22326	3180	9.636E+12	4430403

The first column, width increments, is the section number assigned to each location of measurement. The second column, depth from bottom of tube, is the location of the water surface found by locating the point at which the Pitot tube first contacts the surface of the flow. The third column, Pitot reading, is the value obtained by recording the

height of water that appeared in the Pitot tube. Note that due to oscillations, the Pitot reading was an average based on visual inspection. The fourth column, Pitot depth, is the location of the Pitot tube when it was placed into the flow to obtain a Pitot reading. The fifth column, depth from center of tube, is an adjustment of column two. In order to produce more accurate results, the initial water surface measurement was taken from the bottom of the tube and then half diameter adjustment was applied to give the water surface elevation from the center of the tube. Column six,  $\rho/\gamma$ , is the height of the column of water from the center of the Pitot tube to the surface of the flow, (column 4) minus (column 5). Column seven, point velocity @ section, is the value for  $u$  as determined from the energy equation solving for  $V$ . Column eight, area @ section, is the value of the incremental cross sectional area at the corresponding width increment. The value for width is found by dividing the total width of the channel, 413mm, by the number of width increments, 15. The height for the incremental cross-sectional area is found by subtracting the datum elevation from the depth of water from the center of the tube. Column nine,  $(u^3)dA$  is the product of the cube of the point velocity and the incremental area, (column 7)<sup>3</sup>\*(column 8). Column ten is the incremental flowrate found by the product of columns seven and eight. Note that columns eight, nine, and ten are summed, with the total given for each at the bottom of the table.

For the first method of determining alpha by the Pitot data alone, the value for the numerator is the sum of column nine. The value for the average velocity,  $V$ , is found by dividing the total of the incremental flowrates by the total of the incremental areas. The value for  $A$  is the sum of the incremental areas.

A second method of determining alpha was by the use of data obtained by experiments performed using the three-point gage and flowmeter. The average velocity, total area, and alpha values were obtained by the use of the three point data. Alpha was calculated by using the same numerator values as in the first method, however the denominator values were obtained from the three point gage data. The values obtained from the two methods are shown in Table 5.3

Table 5.3 Alpha Values Obtained by Methods 1 and 2 (50 gpm at 8% Slope)			
Results Based on Pitot Data		Results from Three-Point Data	
Average Velocity (mm/s)	1390	Average Velocity (mm/s)	1150
Area (mm <sup>2</sup> )	3180	Area (mm <sup>2</sup> )	2760
Alpha	1.12	Alpha	2.32

The same procedure was performed at 100 gpm at 8% slope and the velocity correction factor obtained by the two methods at this setting is displayed in Table 5.4.

Table 5.4 Alpha Values Obtained by Methods 1 and 2 (100 gpm at 8% Slope)			
Results Based on Pitot Data		Results from Three-Point Data	
Average Velocity (mm/s)	1800	Average Velocity (mm/s)	1630
Area (mm <sup>2</sup> )	4670	Area (mm <sup>2</sup> )	3880
Alpha	1.05	Alpha	1.70

The values obtained from the three-point gage were presumed to be less accurate than the Pitot data and were not adopted. Since the value for the velocity correction factor was nearly equal to unity in the Pitot tube analysis and based on past research, it was not considered in the energy calculations and alpha was considered to equal unity.

### 5.5 Test Culvert Analysis

Since the flow was observed to be almost uniform near the culvert outlet, uniform flow depth was assumed at the test culvert outlet for a given flowrate and slope. To obtain the best representative value of uniform flow depth at the outlet of the test culvert, Piezometer data for each slope and flowrate for the six configurations was compiled in Microsoft Excel. The spreadsheet, titled Test Culvert Analysis, contained the depth data for all 19 piezometers for each configuration. Since the reading obtained from the Piezometer is the pressure head at the culvert invert, a conversion was necessary to give the depth of flow perpendicular to the culvert invert. The equation is simply a trigonometric operation and was performed as follows:

$$y_n = \frac{(R_a - R_t)}{\text{COS}(\Theta)} \quad (5.2)$$

Where:

$R_a$  = Actual reading from piezometer (pressure head)

$R_t$  = Tare reading for piezometer (zero depth and pressure head)

$y_n$  = Uniform depth perpendicular to the test culvert

$\Theta$  = Slope of test culvert (degrees)



The 19 piezometer tap values were examined and it was concluded that the values had reached uniform flow conditions from taps 10-19 in most instances. Where wave action was pronounced or presence of a jump was detected (due to backwater effects at the outlet, those tap readings were not included in the calculations. The taps that most accurately depicted uniform flow depth were then averaged and recorded for each slope and flowrate. The values were then summarized in a table for each riprap step and averaged again over the six experimental configurations. The result is the value used for uniform flow depth at the test culvert outlet for a given slope and flowrate, as shown in red in Table 5.5.

Table 5.5 Test Culvert Analysis								
Uniform Flow Depth in Test Culvert (m)								
Culvert Slope (%)	Flowrate (gpm)	0.0-inch	0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch	Average Uniform Flow Depth Over Runs (m)
2	50	0.0360	0.0360	0.0360	0.0360	0.0360	0.0370	0.0362
2	75	0.0437	0.0445	0.0438	0.0440	0.0438	0.0440	0.0439
2	100	0.0510	0.0510	0.0510	0.0510	0.0510	0.0510	0.0510
2	125	0.0560	0.0560	0.0560	0.0570	0.0570	0.0570	0.0565
2	150	0.0610	0.0610	0.0620	0.0610	0.0610	0.0600	0.0610
4	50	0.0314	0.0316	0.0313	0.0313	0.0317	0.0330	0.0315
4	75	0.0388	0.0388	0.0390	0.0392	0.0392	0.0390	0.0390
4	100	0.0450	0.0455	0.0450	0.0450	0.0450	0.0450	0.0451
4	125	0.0505	0.0505	0.0505	0.0505	0.0505	0.0507	0.0505
4	150	0.0557	0.0553	0.0557	0.0557	0.0568	0.0553	0.0558
6	50	0.0287	0.0284	0.0287	0.0282	0.0280	0.0278	0.0284
6	75	0.0345	0.0345	0.0345	0.0345	0.0345	0.0345	0.0345
6	100	0.0405	0.0405	0.0405	0.0405	0.0405	0.0400	0.0405
6	125	0.0455	0.0465	0.0460	0.0455	0.0455	0.0455	0.0458
6	150	0.0504	0.0504	0.0500	0.0500	0.0500	0.0500	0.0502
8	50	0.0273	0.0272	0.0272	0.0273	0.0273	0.0282	0.0273
8	75	0.0336	0.0334	0.0331	0.0330	0.0330	0.0330	0.0332
8	100	0.0387	0.0387	0.0387	0.0387	0.0387	0.0385	0.0387
8	125	0.0441	0.0441	0.0442	0.0444	0.0446	0.0446	0.0443
8	150	0.0488	0.0493	0.0493	0.0490	0.0490	0.0485	0.0491

## 5.6 Equivalent Rectangular Froude Number

In the early stages of channel data analysis, it became apparent that the calculated culvert outlet Froude number was misleading. The Froude number was calculated based on hydraulic depth for the circular cross-section of the test culvert. This resulted in the Froude number approaching zero as the culvert fills. A transformation from circular to rectangular cross-section was found in the development of the Contra Costa energy dissipator, reviewed in HEC-14 (1983). The circular to rectangular transform eliminates the decrease in hydraulic depth with the increase of flow depth in a circular cross-section. HEC-14 stated that for oval, circular, elliptical or shapes other than rectangular or square, the flow at the culvert must be converted to an equivalent rectangular cross-section with a width equal to twice the depth of flow. The equivalent rectangular flow depth,  $y_e$ , is determined from the following relationship:

$$y_e = \left(\frac{A}{2}\right)^{0.5} \quad (5.3)$$

Where:

$y_e$  = Equivalent rectangular flow depth

$A$  = Area of the flow cross-section

Following the transform of the flow depth, the equivalent rectangular Froude number can be determined from using  $y_e$  rather than the actual hydraulic depth at the culvert outlet. So, the relationship for the Froude number becomes:

$$Fr = \frac{V}{\sqrt{gy_e}} \quad (5.4)$$

The introduction of the transformed rectangular cross-section produced Froude numbers that were better suited for non-dimensional reference use. Values obtained for the uniform flow depth, from Section 5.5, were converted to the equivalent rectangular flow depth and calculations proceeded further.

## 5.7 Energy Calculations

Based on the uniform flow depth established in Section 5.5, the following parameters were calculated using a spreadsheet:

- Velocity at test culvert outlet
- Flow area
- Equivalent rectangular flow depth at culvert outlet,  $y_e$
- Culvert  $\Phi$

Culvert  $\Phi$  was the sector angle used to calculate the circular cross-sectional area of the flow at a given flow depth.

Culvert  $\Phi$  is depicted below in Figure 5.6.

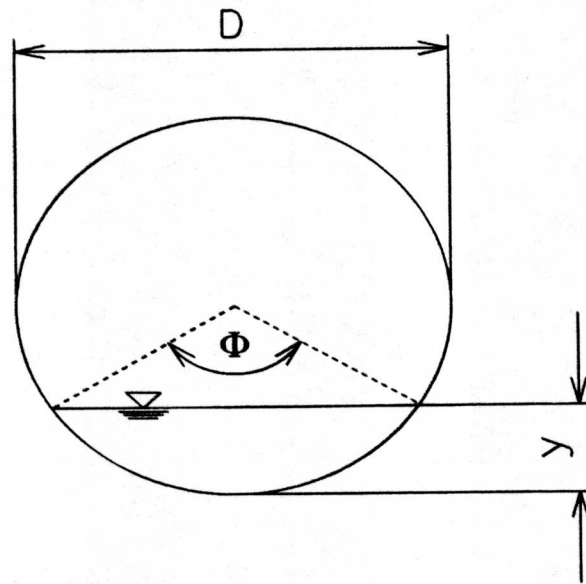


Figure 5.6 Culvert  $\Phi$

Given a value for the depth of flow in the test culvert,  $\Phi$  was determined from the following equation:

$$\Phi = 2\cos^{-1}\left(1 - \frac{2y}{D}\right) \quad (5.5)$$

The flow area of the culvert was found from an equation relating the diameter of the test culvert and culvert  $\Phi$ , shown below.

$$A = \frac{D^2}{8}(\Phi - \sin\Phi) \quad (5.6)$$

Since the cross-sectional area of the flow and the flowrate were both known, the velocity could be determined by dividing the flowrate by the cross-sectional area. The adopted values of uniform flow depth from Section 5.5, for the test culvert at fixed slopes and flowrates are shown in Table 5.6.

Culvert Slope	Flowrate	Average Uniform Flow Depth Over Runs	Test Culvert Phi	Average Flow Area	Velocity @ Test Culvert Outlet	Equivalent Rectangular Flow Depth @ Test Culvert Outlet
(%)	(gpm)	(m)	(rad)	(m <sup>2</sup> )	(m/s)	(m)
2	50	0.0362	2.47	0.00269	1.17	0.0367
2	75	0.0439	2.77	0.00350	1.35	0.0418
2	100	0.0510	3.03	0.00426	1.48	0.0461
2	125	0.0565	3.24	0.00485	1.63	0.0492
2	150	0.0610	3.40	0.00533	1.78	0.0516
4	50	0.0315	2.29	0.00224	1.41	0.0335
4	75	0.0390	2.58	0.00298	1.59	0.0386
4	100	0.0451	2.81	0.00362	1.74	0.0426
4	125	0.0505	3.01	0.00420	1.88	0.0459
4	150	0.0558	3.21	0.00477	1.99	0.0488
6	50	0.0284	2.15	0.00191	1.65	0.0309
6	75	0.0345	2.40	0.00252	1.88	0.0355
6	100	0.0405	2.63	0.00313	2.02	0.0396
6	125	0.0458	2.84	0.00369	2.14	0.0430
6	150	0.0502	3.00	0.00416	2.28	0.0456
8	50	0.0273	2.11	0.00183	1.73	0.0302
8	75	0.0332	2.35	0.00239	1.98	0.0346
8	100	0.0387	2.57	0.00294	2.15	0.0384
8	125	0.0443	2.78	0.00354	2.23	0.0421
8	150	0.0491	2.96	0.00404	2.35	0.0449

Since the uniform flow depth was constant at a given slope and flowrate, the remainder of the calculations dealt with comparing the conditions at the culvert outlet with those downstream in the testing channel. The parameters obtained from the rectangular test channel are as follows:

- Average flow depth
- Flow area
- Velocity

The average flow depth was obtained by examining the values for flow depth from the three-point gage measurements along the designated seven channel positions shown in Figure 4.11. Plots of the water surface elevation for a given run were then examined to identify any values that were outliers due to wave action or experimental error. The points that were termed acceptable, as best displaying the observed flow depth in the testing channel, were then averaged to produce the mean flow depth in the testing channel. The flow area of the given run

was determined from the product of the average flow depth with the width of the testing channel. The velocity was found by simply dividing the flowrate by the cross-sectional area of the flow. Next, the Froude number at the culvert outlet was calculated as described in Section 5.6. The Froude number was also calculated in the testing channel. The Froude number at the culvert outlet and testing channel were calculated to provide a non-dimensional reference to flow conditions. The energy at the culvert outlet was calculated from the following expression:

$$CulvertOutletEnergy = \frac{V^2}{2g} + y + z \quad (5.7)$$

Where:

$V$  = Average velocity at culvert outlet

$g$  = Acceleration due to gravity

$y$  = Uniform flow depth at culvert outlet (actual depth)

$z$  = Step height above zero datum

The energy in the testing channel and the EGL were calculated using Equation 5.7, except that velocity and uniform flow depth were those of the testing channel. The energy at the culvert outlet and testing channel are then compared in the form of a non-dimensional energy difference of the following form:

$$Non - DimensionalEnergyDifference = \frac{OutletEnergy - ChannelEnergy}{OutletEnergy} \quad (5.8)$$

An example of the spreadsheet format used for the energy calculations is shown in Table 5.7. In following sections, each type of step, either cast acrylic or riprap, and step height will be presented and discussed with the results presented in this latter format.

Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross-Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non-Dimensional Energy Difference
50								
75								
100								
125								
150								

After observing the flow characteristics in the test channel for the 0.0-inch smooth, cast acrylic step for several flowrates, it was determined that there was an extreme amount of wave action, making accurate measurements of depth impossible. Therefore, it was considered that analysis could not be completed due to excessive measurement error. Several sample calculations using data from these runs were completed. The sample calculations confirmed that there was too much wave action to obtain useful information. Since the riprap pallet with the equivalent step height and the matching 'smooth' cast acrylic step were to have been compared, it was decided that the calculations for the 0.0-inch riprap step would only be used as a reference for the five, riprap steps, 0.5-inch, 1.0-inch, 1.5-inch, 2.0-inch, and 2.5-inch. The 0.0-inch riprap step calculations in their entirety will be presented in a later section.

### 5.8 0.5-inch Cast Acrylic Step

Graphs of the water surface elevation for tests conducted at 2, 4, 6, and 8% slopes are shown in Figures 5.7, 5.8, 5.9, and 5.10. After the water surface elevation was established, average flow depth was determined. From the flow depth and the results from Section 5.5, the aforementioned energy calculations were conducted. The results for the energy calculations for the 0.5-inch cast acrylic step are shown in Tables 5.8, 5.9, 5.10, and 5.11.

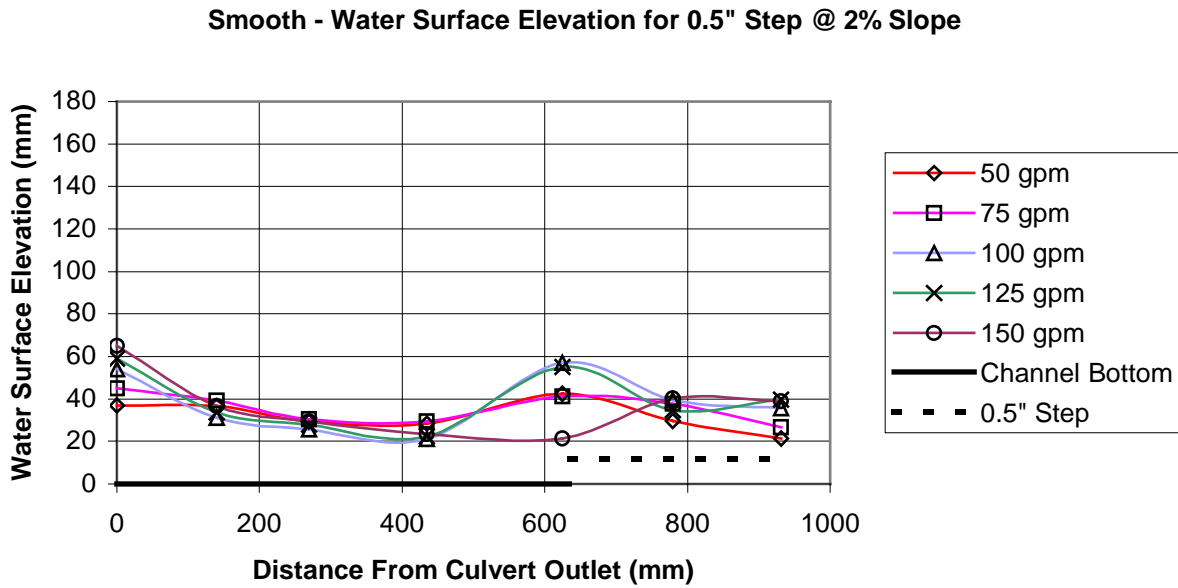


Figure 5.7 Plot of Water Surface Elevation for 0.5-inch Cast Acrylic Step at 2% Culvert Slope

Smooth - Water Surface Elevation for 0.5" Step @ 4% Slope

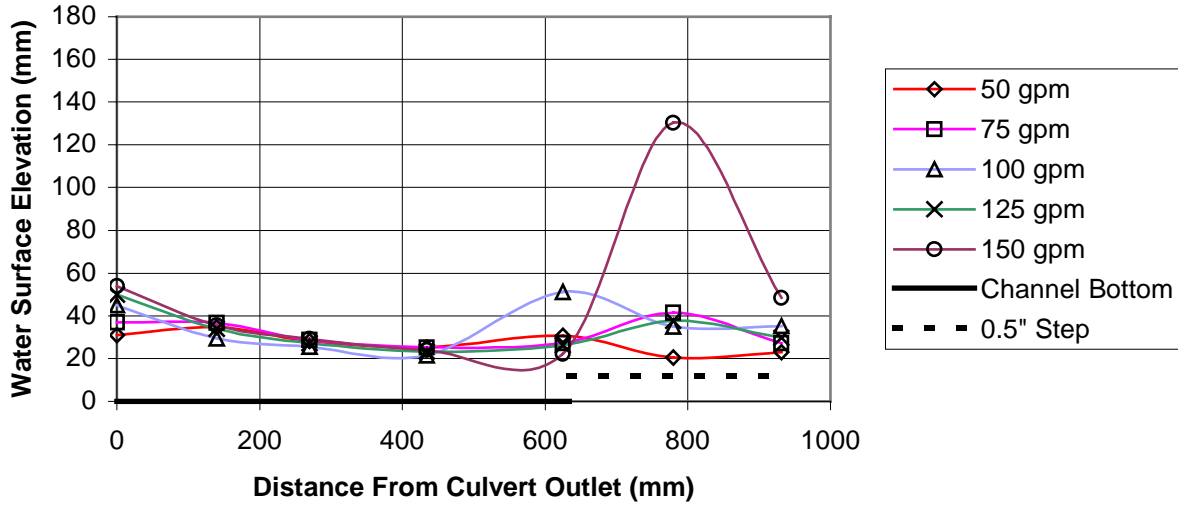


Figure 5.8 Plot of Water Surface Elevation for 0.5-inch Cast Acrylic Step at 4% Culvert Slope

Smooth - Water Surface Elevation for 0.5" Step @ 6% Slope

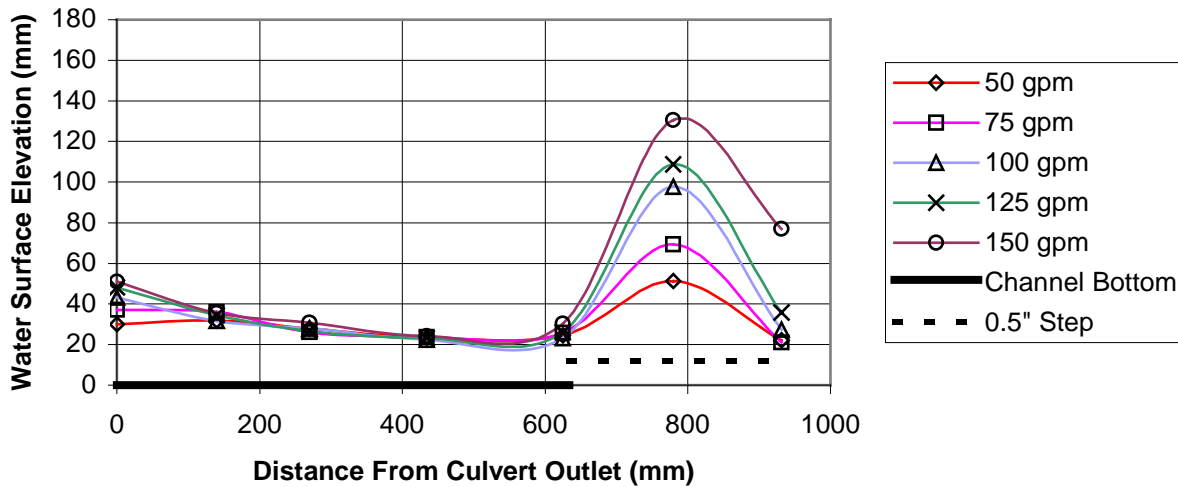


Figure 5.9 Plot of Water Surface Elevation for 0.5-inch Cast Acrylic Step at 6% Culvert Slope



**Smooth - Water Surface Elevation for 0.5 " Step @ 8% Slope**

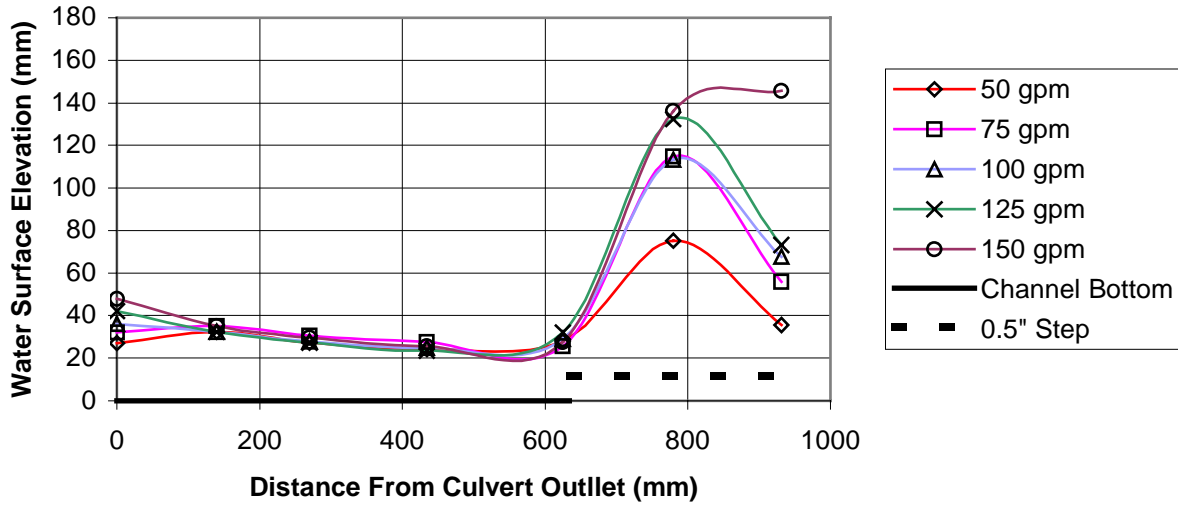


Figure 5.10 Plot of Water Surface Elevation for 0.5-inch Cast Acrylic Step at 8% Culvert Slope

Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0136	0.00563	0.560	2.31	1.53	107	41.5	0.612
75	0.0203	0.00837	0.566	2.38	1.27	135	48.5	0.640
100	0.0256	0.0106	0.597	2.38	1.19	163	55.7	0.659
125	0.0254	0.0105	0.753	2.45	1.51	194	66.2	0.659
150	0.0277	0.0114	0.829	2.54	1.59	222	74.6	0.664

Table 5.9 Energy Calculations for 0.5-inch Cast Acrylic Step @ 4% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.00983	0.00406	0.777	2.97	2.51	134	52.6	0.607
75	0.0224	0.00925	0.512	3.00	1.09	170	47.7	0.719
100	0.0232	0.00957	0.660	3.02	1.38	197	57.3	0.709
125	0.0219	0.00903	0.874	3.03	1.89	230	72.7	0.685
150	0.0775	0.0320	0.296	3.02	0.340	260	93.8	0.640

Table 5.10 Energy Calculations for 0.5-inch Cast Acrylic Step @ 6% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0247	0.0102	0.309	3.71	0.629	166	41.5	0.750
75	0.0333	0.0138	0.344	3.79	0.603	214	51.2	0.761
100	0.0507	0.0209	0.302	3.73	0.428	247	67.2	0.728
125	0.0604	0.0249	0.317	3.67	0.412	270	77.4	0.713
150	0.0919	0.0380	0.250	3.70	0.263	311	107	0.656

Table 5.11 Energy Calculations for 0.5-inch Cast Acrylic Step @ 8% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0436	0.0180	0.175	3.95	0.268	183	57.0	0.688
75	0.0735	0.0303	0.156	4.09	0.184	230	86.6	0.623
100	0.0786	0.0325	0.194	4.06	0.221	273	92.5	0.661
125	0.0908	0.0375	0.210	3.90	0.223	301	105	0.651
150	0.1291	0.0533	0.178	3.87	0.158	326	143	0.562

### 5.9 1.0-inch Cast Acrylic Step

Graphs of the water surface elevation for tests conducted at 2, 4, 6, and 8% slopes are shown in Figures 5.11, 5.12, 5.13, and 5.14. After the water surface elevation was established, average flow depth was determined. From the flow depth and the results from Section 5.5, the aforementioned energy calculations were conducted. The results for the energy calculations for the 1.0-inch cast acrylic step are shown in Tables 5.12, 5.13, 5.14 and 5.15.

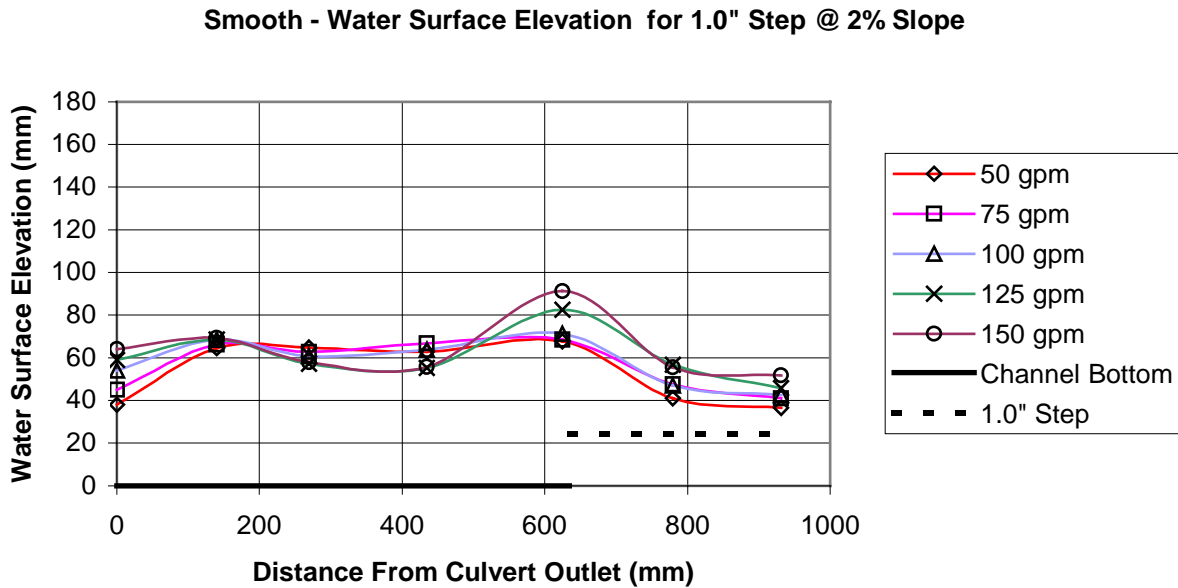


Figure 5.11 Plot of Water Surface Elevation for 1.0-inch Cast Acrylic Step at 2% Culvert Slope

Smooth - Water Surface Elevation for 1.0" Step @ 4% Slope

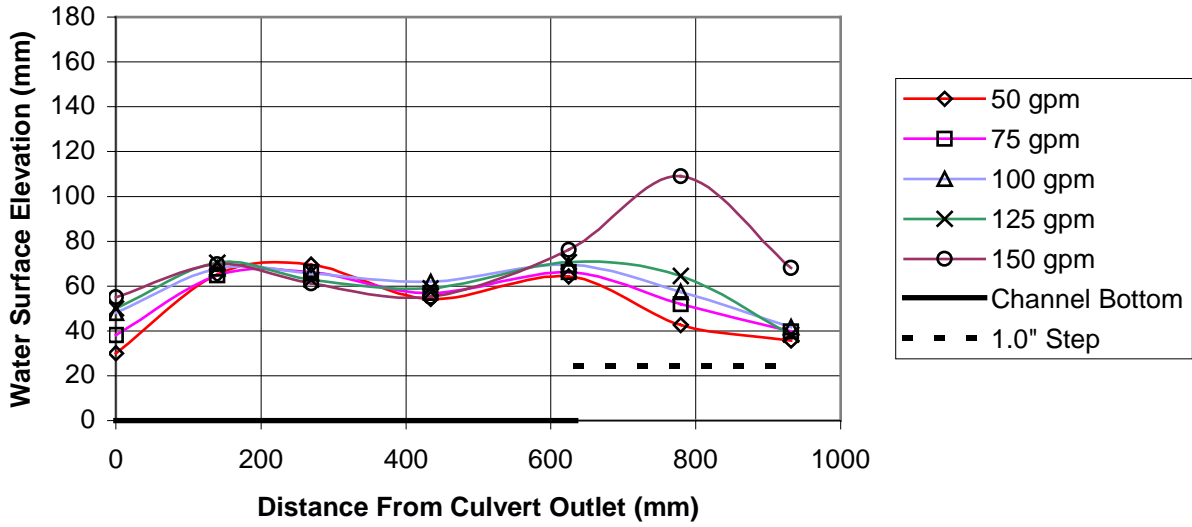


Figure 5.12 Plot of Water Surface Elevation for 1.0-inch Cast Acrylic Step at 4% Culvert Slope

Smooth - Water Surface Elevation for 1.0" Step @ 6% Slope

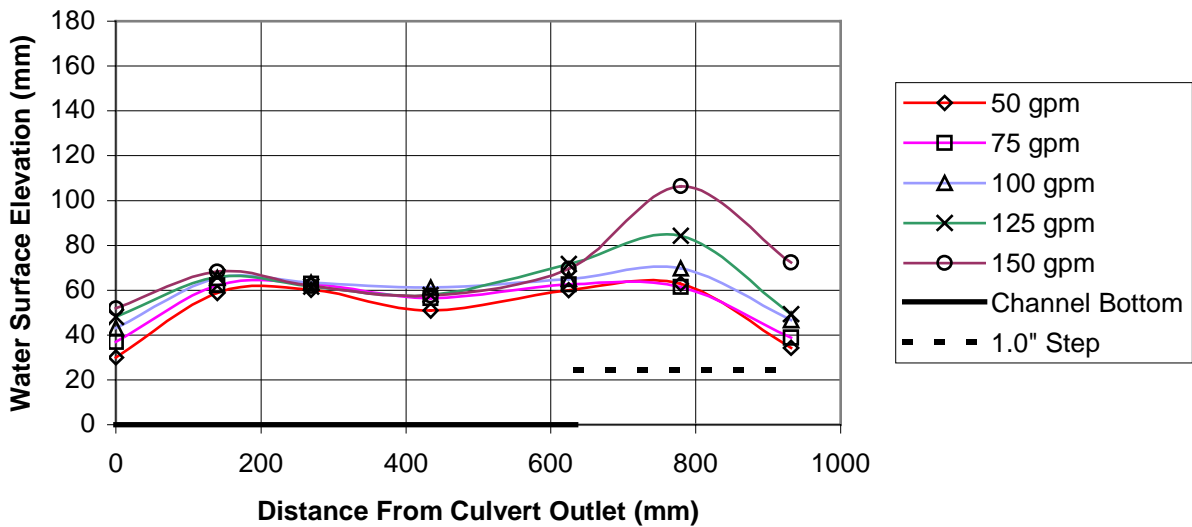


Figure 5.13 Plot of Water Surface Elevation for 1.0-inch Cast Acrylic Step at 6% Culvert Slope

Smooth - Water Surface Elevation for 1.0" Step @ 8% Slope

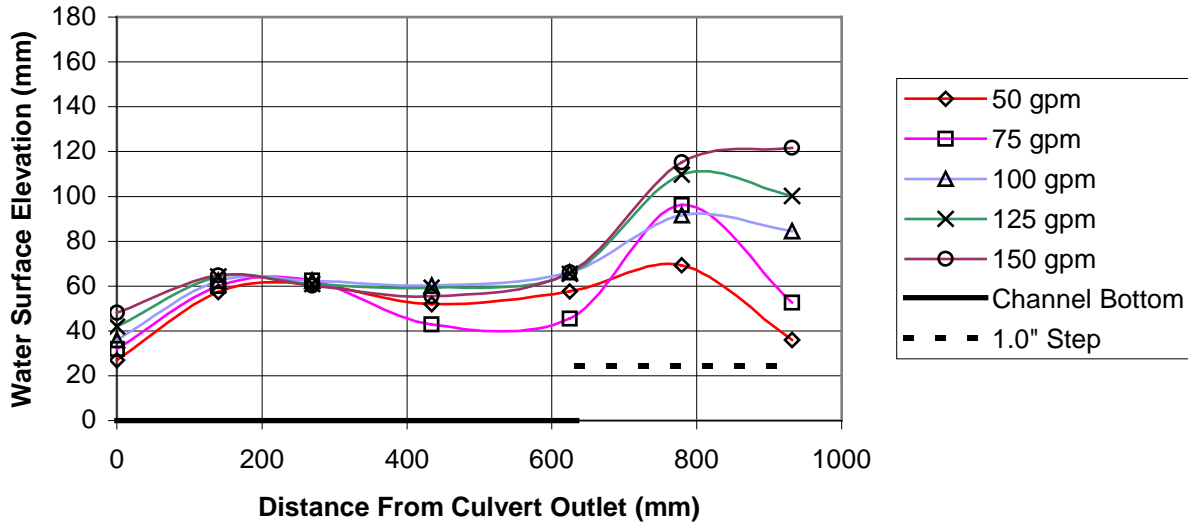


Figure 5.14 Plot of Water Surface Elevation for 1.0-inch Cast Acrylic Step at 8% Culvert Slope

Table 5.12 Energy Calculations for 1.0-inch Cast Acrylic Step @ 2% Slope								
Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0144	0.00595	0.530	2.31	1.41	107	53.2	0.504
75	0.0199	0.00821	0.577	2.38	1.31	138	61.2	0.557
100	0.0203	0.00840	0.752	2.38	1.68	163	73.5	0.550
125	0.0269	0.0111	0.711	2.45	1.38	194	77.0	0.603
150	0.0292	0.0121	0.786	2.54	1.47	217	85.1	0.607

Table 5.13 Energy Calculations for 1.0-inch Cast Acrylic Step @ 4% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0148	0.00611	0.517	2.97	1.36	136	52.8	0.611
75	0.0214	0.00884	0.536	3.00	1.17	168	60.4	0.640
100	0.0251	0.0104	0.608	3.02	1.22	201	68.4	0.659
125	0.0271	0.0112	0.707	3.03	1.37	230	76.9	0.666
150	0.0642	0.0265	0.357	3.02	0.450	258	95.1	0.631

Table 5.14 Energy Calculations for 1.0-inch Cast Acrylic Step @ 6% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0242	0.0100	0.315	3.71	0.647	162	53.7	0.669
75	0.0257	0.0106	0.447	3.79	0.890	214	60.2	0.719
100	0.0338	0.0140	0.452	3.73	0.785	247	68.6	0.722
125	0.0424	0.0175	0.451	3.67	0.700	276	77.1	0.720
150	0.0651	0.0269	0.352	3.70	0.441	316	95.8	0.697

Table 5.15 Energy Calculations for 1.0-inch Cast Acrylic Step @ 8% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0282	0.0116	0.271	3.95	0.516	183	56.3	0.692
75	0.0500	0.0206	0.229	4.09	0.328	234	77.1	0.671
100	0.0638	0.0263	0.240	4.06	0.303	273	91.1	0.666
125	0.0806	0.0333	0.237	3.90	0.267	299	108	0.640
150	0.0941	0.0389	0.244	3.87	0.254	326	122	0.627

### 5.10 1.5-inch Cast Acrylic Step

Graphs of the water surface elevation for tests conducted at 2, 4, 6, and 8% slopes are shown in Figures 5.15, 5.16, 5.17, and 5.18. After the water surface elevation was established, average flow depth was determined. From the flow depth and the results from Section 5.5, the aforementioned energy calculations were conducted. The results for the energy calculations for the 1.5-inch cast acrylic step are shown in Tables 5.16, 5.17, 5.18 and 5.19.

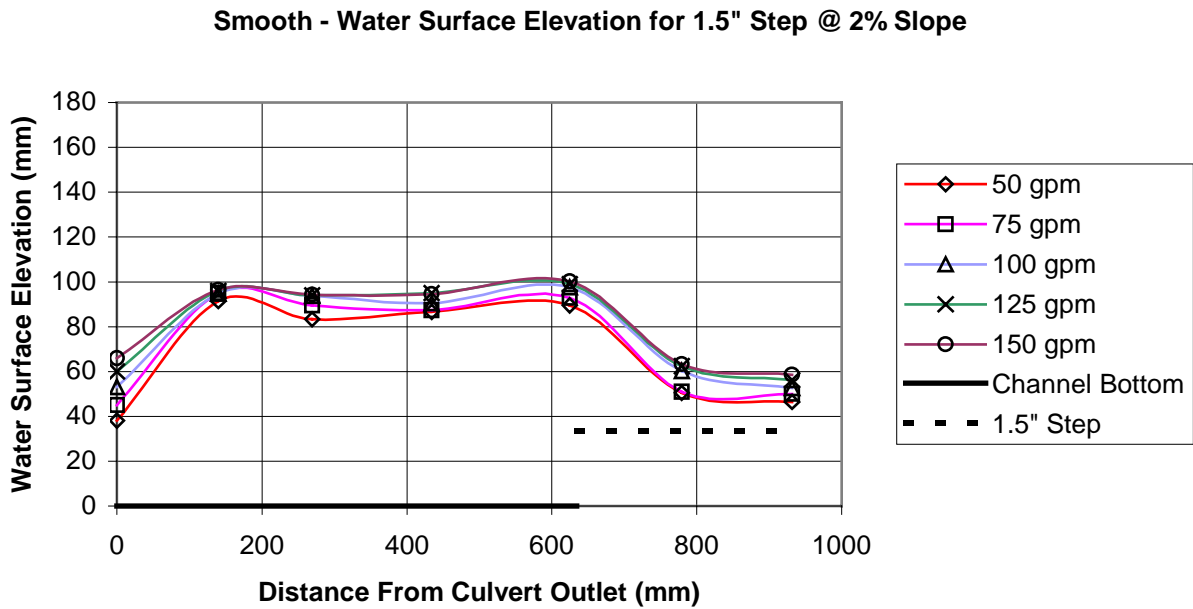


Figure 5.15 Plot of Water Surface Elevation for 1.5-inch Cast Acrylic Step at 2% Culvert Slope

Smooth - Water Surface Elevation for 1.5" Step @ 4% Slope

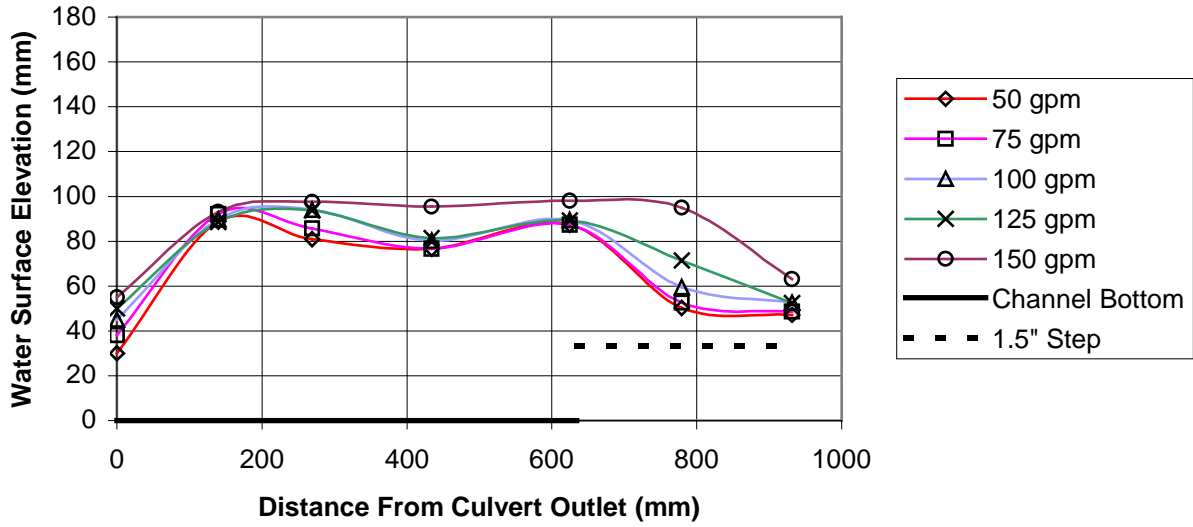


Figure 5.16 Plot of Water Surface Elevation for 1.5-inch Cast Acrylic Step at 4% Culvert Slope

Smooth - Water Surface Elevation for 1.5" Step @ 6% Slope

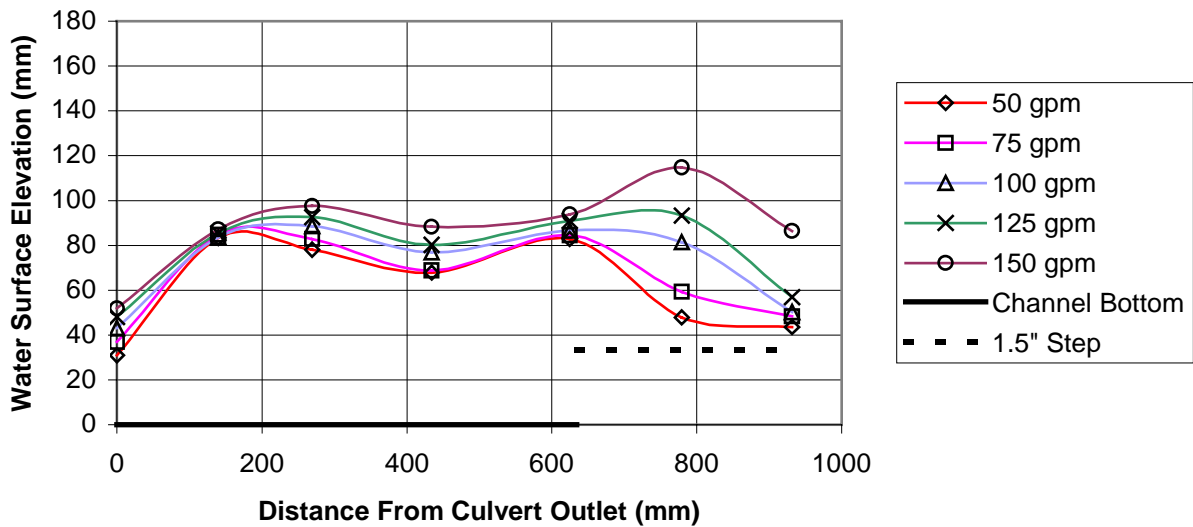


Figure 5.17 Plot of Water Surface Elevation for 1.5-inch Cast Acrylic Step at 6% Culvert Slope



Smooth - Water Surface Elevation for 1.5" Step @ 8% Slope

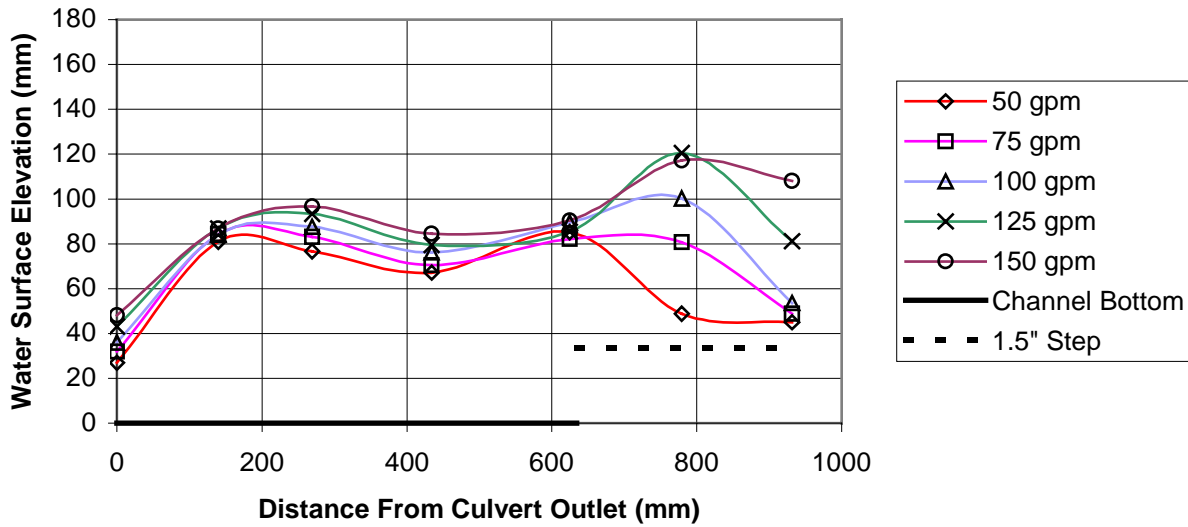


Figure 5.18 Plot of Water Surface Elevation for 1.5-inch Cast Acrylic Step at 8% Culvert Slope

Table 5.16 Energy Calculations for 1.5-inch Cast Acrylic Step @ 2% Slope								
Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0152	0.00629	0.501	2.31	1.30	107	61.3	0.428
75	0.0172	0.00711	0.666	2.38	1.62	137	73.1	0.467
100	0.0233	0.00963	0.656	2.38	1.37	163	78.5	0.519
125	0.0261	0.0108	0.731	2.45	1.44	189	86.6	0.542
150	0.0278	0.0115	0.825	2.54	1.58	222	95.7	0.569

Table 5.17 Energy Calculations for 1.5-inch Cast Acrylic Step @ 4% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0155	0.00639	0.494	2.97	1.27	136	61.1	0.550
75	0.0174	0.00718	0.660	3.00	1.60	166	72.8	0.562
100	0.0229	0.00944	0.669	3.02	1.41	201	78.9	0.607
125	0.0287	0.0119	0.665	3.03	1.25	230	84.5	0.633
150	0.0458	0.0189	0.501	3.02	0.747	258	91.8	0.644

Table 5.18 Energy Calculations for 1.5-inch Cast Acrylic Step @ 6% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0125	0.00516	0.611	3.71	1.75	168	64.8	0.615
75	0.0206	0.00850	0.557	3.79	1.24	214	69.6	0.675
100	0.0326	0.0135	0.469	3.73	0.829	247	77.0	0.688
125	0.0418	0.0173	0.457	3.67	0.713	282	85.7	0.696
150	0.0674	0.0278	0.341	3.70	0.419	316	106	0.663

Table 5.19 Energy Calculations for 1.5-inch Cast Acrylic Step @ 8% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0136	0.0056	0.560	3.95	1.53	181	62.9	0.653
75	0.0315	0.0130	0.364	4.09	0.656	237	71.5	0.698
100	0.0437	0.0180	0.350	4.06	0.535	273	83.1	0.695
125	0.0677	0.0279	0.282	3.90	0.347	296	105	0.646
150	0.0794	0.0328	0.289	3.87	0.327	329	117	0.645

### 5.11 2.0-inch Cast Acrylic Step

Graphs of the water surface elevation for tests conducted at 2, 4, 6, and 8% slopes are shown in Figures 5.19, 5.20, 5.21, and 5.22. After the water surface elevation was established, average flow depth was determined. From the flow depth and the results from Section 5.5, the aforementioned energy calculations were conducted. The results for the energy calculations for the 2.0-inch cast acrylic step are shown in Tables 5.20, 5.21, 5.22 and 5.23.

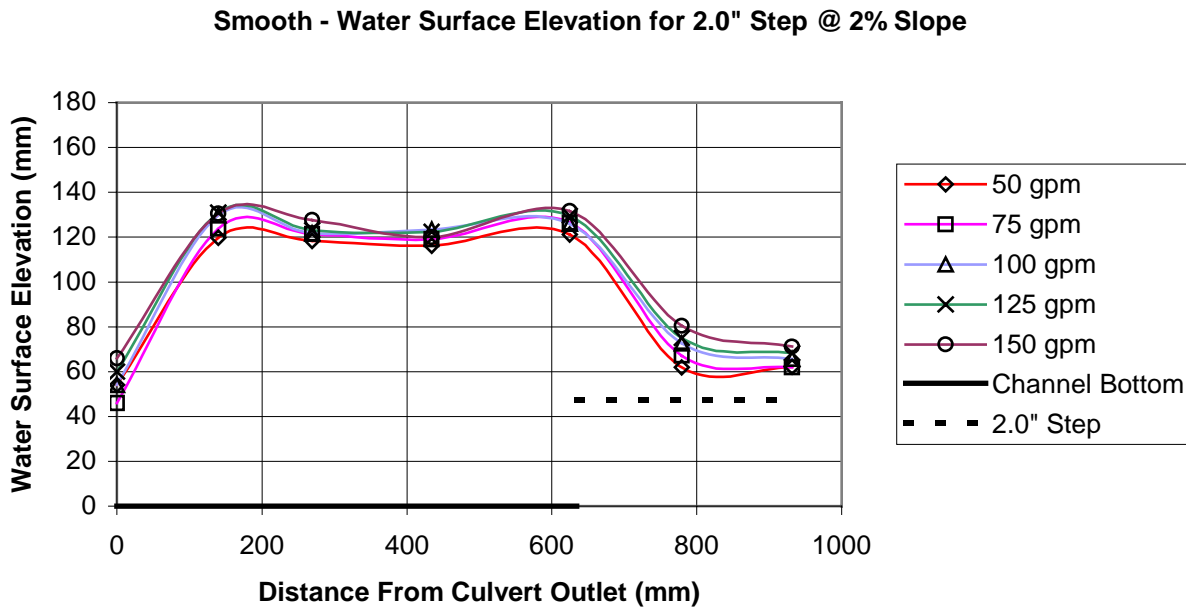


Figure 5.19 Plot of Water Surface Elevation for 2.0-inch Cast Acrylic Step at 2% Culvert Slope

**Smooth - Water Surface Elevation for 2.0" Step @ 4% Slope**

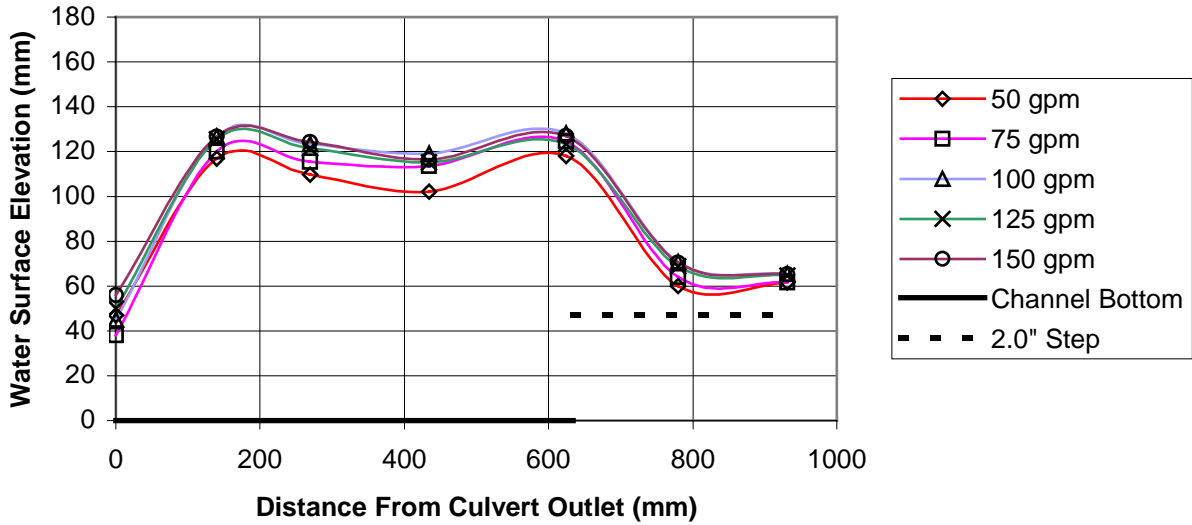


Figure 5.20 Plot of Water Surface Elevation for 2.0-inch Cast Acrylic Step at 4% Culvert Slope

**Smooth - Water Surface Elevation for 2.0" Step @ 6% Slope**

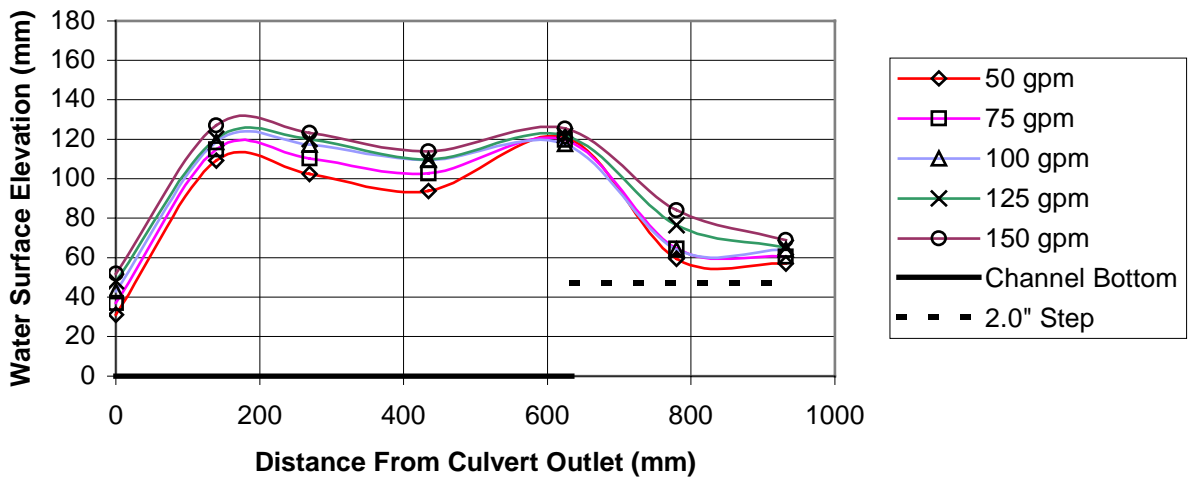


Figure 5.21 Plot of Water Surface Elevation for 2.0-inch Cast Acrylic Step at 6% Culvert Slope

Smooth - Water Surface Elevation for 2.0" Step @ 8% Slope

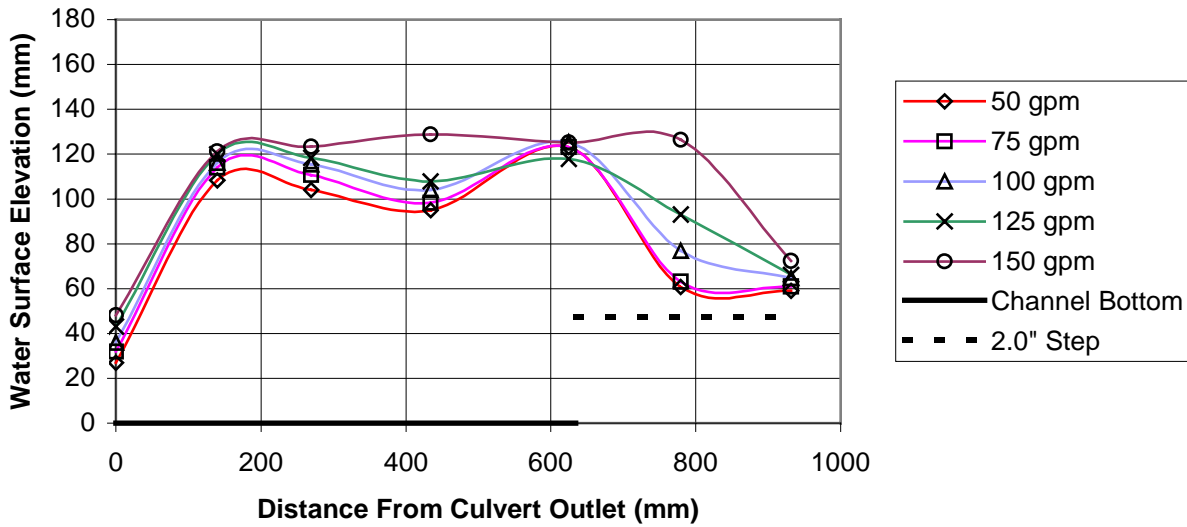


Figure 5.22 Plot of Water Surface Elevation for 2.0-inch Cast Acrylic Step at 8% Culvert Slope

Table 5.20 Energy Calculations for 2.0-inch Cast Acrylic Step @ 2% Slope								
Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0148	0.00611	0.517	2.31	1.36	107	75.7	0.294
75	0.0172	0.00711	0.666	2.38	1.62	137	98.5	0.281
100	0.0219	0.00906	0.697	2.38	1.50	163	93.9	0.425
125	0.0245	0.0101	0.781	2.45	1.60	189	103	0.456
150	0.0286	0.0118	0.803	2.54	1.52	222	109	0.510

Table 5.21 Energy Calculations for 2.0-inch Cast Acrylic Step @ 4% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0136	0.00563	0.560	2.97	1.53	133	76.9	0.422
75	0.0156	0.00645	0.734	3.00	1.88	168	98.0	0.416
100	0.0209	0.00862	0.732	3.02	1.62	201	95.5	0.525
125	0.0195	0.00806	0.980	3.03	2.24	230	116	0.498
150	0.0207	0.00853	1.111	3.02	2.47	249	131	0.475

Table 5.22 Energy Calculations for 2.0-inch Cast Acrylic Step @ 6% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0110	0.00453	0.696	3.71	2.12	171	83.0	0.515
75	0.0154	0.00636	0.745	3.79	1.92	214	103	0.519
100	0.0169	0.00699	0.904	3.73	2.22	247	106	0.572
125	0.0235	0.00969	0.814	3.67	1.70	282	105	0.629
150	0.0293	0.0121	0.782	3.70	1.46	316	108	0.659

Table 5.23 Energy Calculations for 2.0-inch Cast Acrylic Step @ 8% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0126	0.00522	0.604	3.95	1.72	181	78.5	0.567
75	0.0148	0.00611	0.776	4.09	2.04	237	104	0.559
100	0.0235	0.00972	0.649	4.06	1.35	273	92.3	0.662
125	0.0325	0.0134	0.589	3.90	1.04	295	97.4	0.669
150	0.0521	0.0215	0.440	3.87	0.616	329	109	0.668

### 5.12 2.5-inch Cast Acrylic Step

Graphs of the water surface elevation for tests conducted at 2, 4, 6, and 8% slopes are shown in Figures 5.23, 5.24, 5.25, and 5.26. After the water surface elevation was established, average flow depth was determined. From the flow depth and the results from Section 5.5 the aforementioned energy calculations were conducted. The results for the energy calculations for the 2.5-inch cast acrylic step are shown in Tables 5.24, 5.25, 5.26 and 5.27.

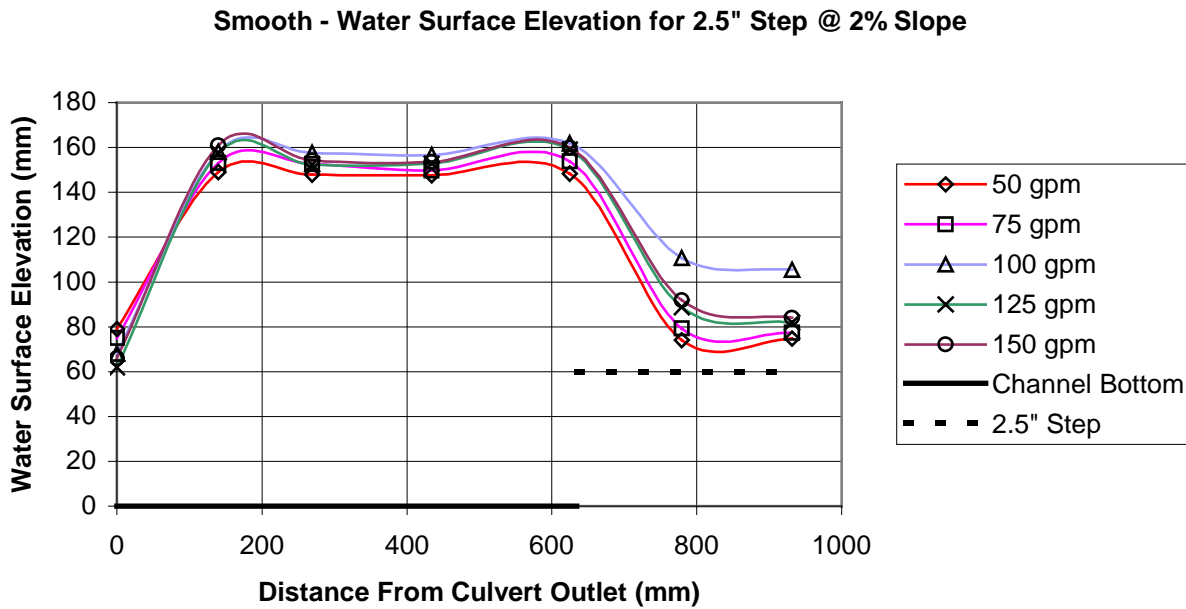


Figure 5.23 Plot of Water Surface Elevation for 2.5-inch Cast Acrylic Step at 2% Culvert Slope

Smooth - Water Surface Elevation for 2.5" Step @ 4% Slope

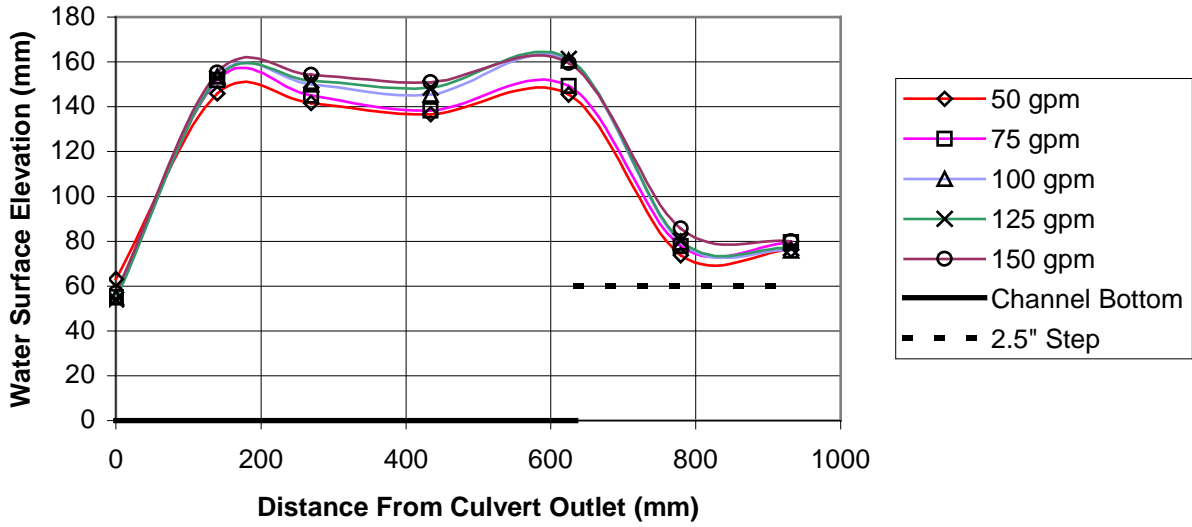


Figure 5.24 Plot of Water Surface Elevation for 2.5-inch Cast Acrylic Step at 4% Culvert Slope

Smooth - Water Surface Elevation for 2.5" Step @ 6% Slope

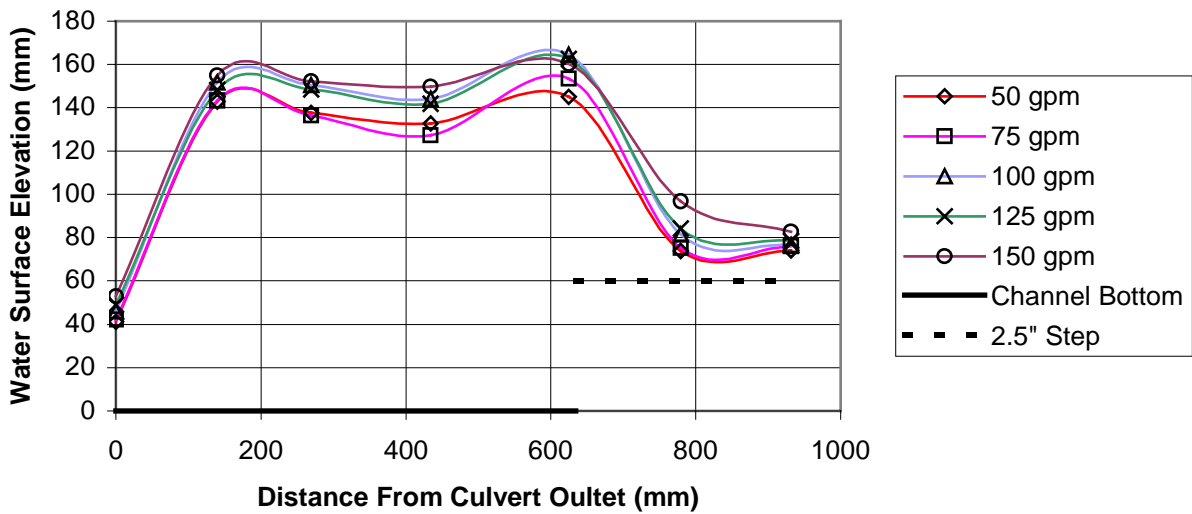


Figure 5.25 Plot of Water Surface Elevation for 2.5-inch Cast Acrylic Step at 6% Culvert Slope



Smooth - Water Surface Elevation for 2.5" Step @ 8% Slope

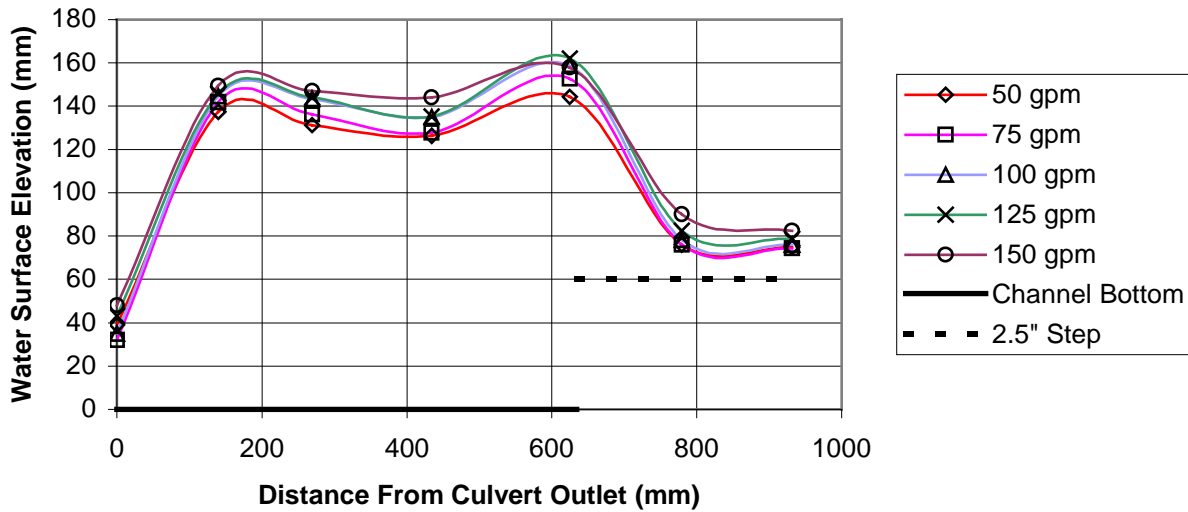


Figure 5.26 Plot of Water Surface Elevation for 2.5-inch Cast Acrylic Step at 8% Culvert Slope

Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0143	0.00592	0.533	2.31	1.42	103	88.9	0.137
75	0.0182	0.00752	0.630	2.38	1.49	137	98.5	0.281
100	0.0212	0.00875	0.722	2.38	1.58	163	108	0.340
125	0.0253	0.0104	0.756	2.45	1.52	189	114	0.395
150	0.0279	0.0115	0.822	2.54	1.57	228	122	0.462

Table 5.25 Energy Calculations for 2.5-inch Cast Acrylic Step @ 4% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0149	0.00617	0.511	2.97	1.34	123	88.3	0.284
75	0.0187	0.00771	0.614	3.00	1.44	168	98.0	0.416
100	0.0178	0.00733	0.861	3.02	2.06	201	116	0.424
125	0.0186	0.00768	1.028	3.03	2.41	229	133	0.422
150	0.0228	0.00941	1.007	3.02	2.13	260	135	0.483

Table 5.26 Energy Calculations for 2.5-inch Cast Acrylic Step @ 6% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0140	0.00579	0.545	3.71	1.47	174	89.2	0.487
75	0.0156	0.00645	0.734	3.79	1.88	214	103	0.519
100	0.0191	0.00787	0.803	3.73	1.86	254	112	0.559
125	0.0214	0.00884	0.893	3.67	1.95	282	122	0.567
150	0.0297	0.0123	0.772	3.70	1.43	316	120	0.620

Table 5.27 Energy Calculations for 2.5-inch Cast Acrylic Step @ 8% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0155	0.00639	0.494	3.95	1.27	169	88.0	0.479
75	0.0152	0.00626	0.756	4.09	1.96	237	104	0.559
100	0.0171	0.00708	0.892	4.06	2.18	275	118	0.573
125	0.0206	0.00850	0.929	3.90	2.07	295	125	0.577
150	0.0263	0.0109	0.872	3.87	1.72	336	125	0.628

### 5.13 0.0-inch Equivalent Riprap Step

Graphs of the water surface elevation for tests conducted at 2, 4, 6, and 8% slopes are shown in Figures 5.27, 5.28, 5.29, and 5.30. After the water surface elevation was established, average flow depth was determined. From the flow depth and the results from Section 5.5, the aforementioned volumetric displacement tests and energy calculations were conducted. The results for the energy calculations for the 0.0-inch equivalent riprap step are shown in Tables 5.28, 5.29, 5.30, and 5.31.

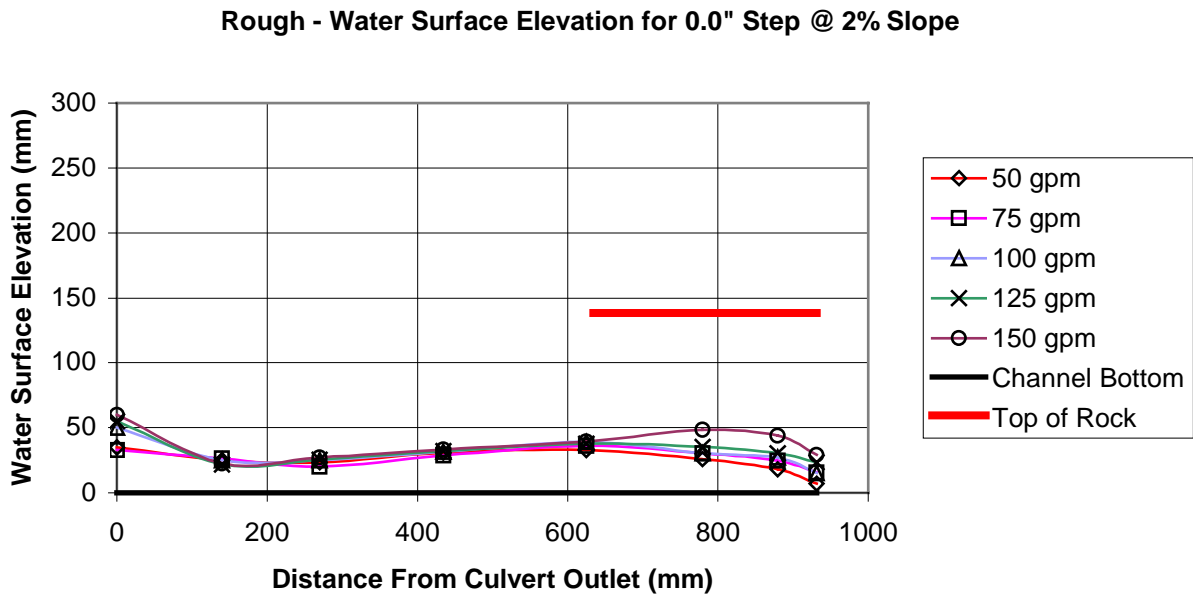


Figure 5.27 Plot of Water Surface Elevation for 0.0-inch Equivalent Riprap Step at 2% Culvert Slope

**Rough - Water Surface Elevation for 0.0" Step @ 4% Slope**

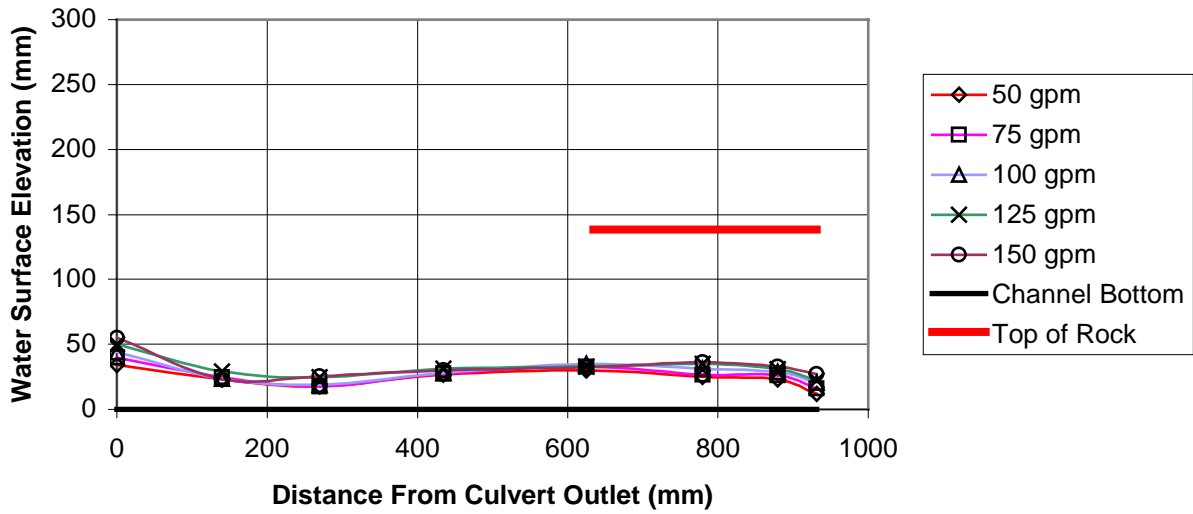


Figure 5.28 Plot of Water Surface Elevation for 0.0-inch Equivalent Riprap Step at 4% Culvert Slope

**Rough - Water Surface Elevation for 0.0" Step @ 6% Slope**

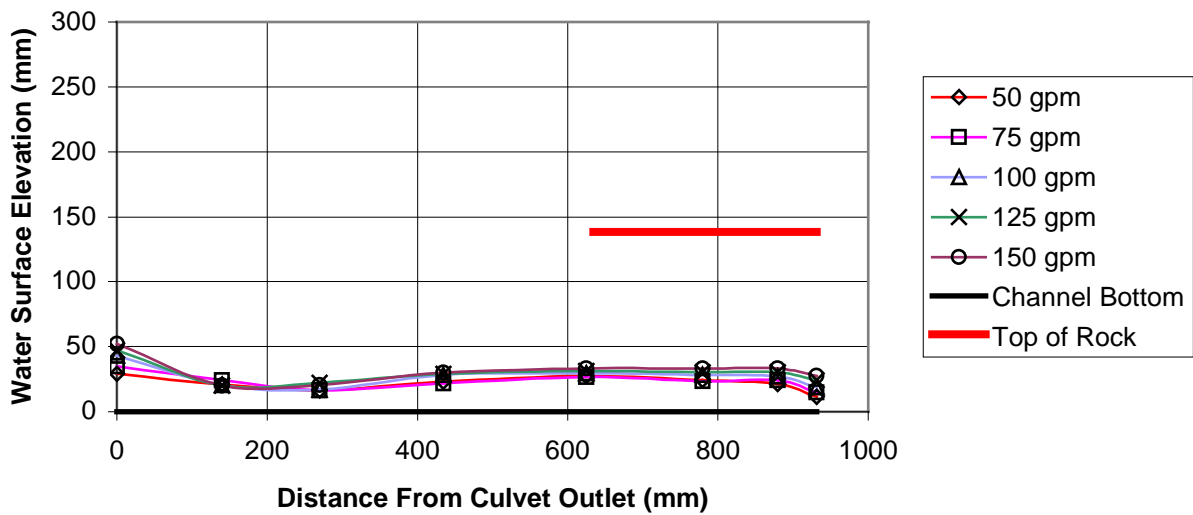


Figure 5.29 Plot of Water Surface Elevation for 0.0-inch Equivalent Riprap Step at 6% Culvert Slope

**Rough - Water Surface Elevation for 0.0" Step @ 8% Slope**

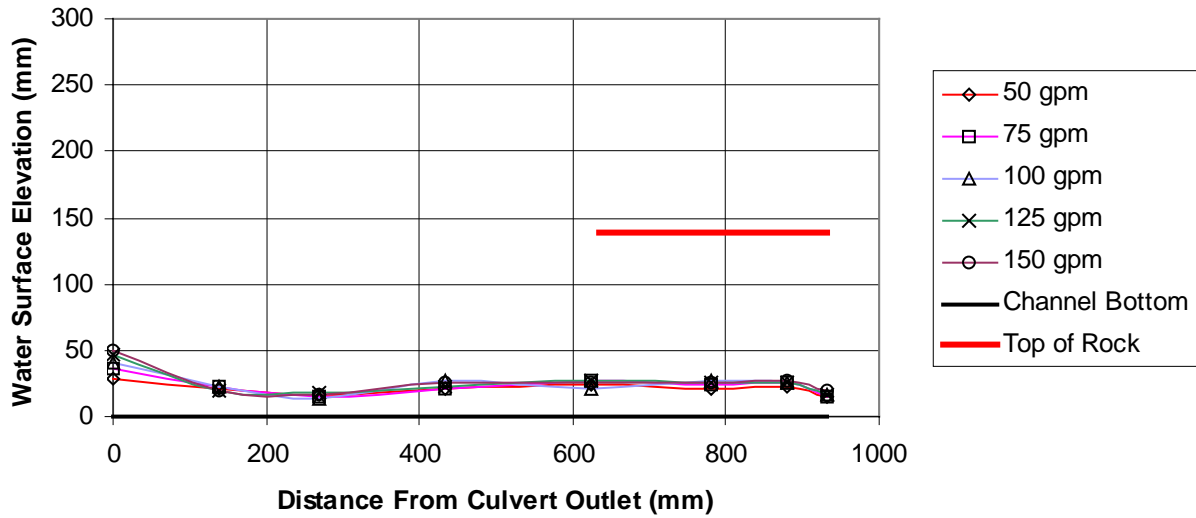


Figure 5.30 Plot of Water Surface Elevation for 0.0-inch Equivalent Riprap Step at 8% Culvert Slope

Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0240	0.00991	0.319	2.31	0.657	107	29.2	0.728
75	0.0274	0.0113	0.418	2.38	0.806	139	36.3	0.738
100	0.0287	0.0119	0.532	2.38	1.00	163	43.2	0.736
125	0.0328	0.0136	0.582	2.45	1.03	194	50.1	0.742
150	0.0365	0.0151	0.628	2.54	1.05	222	56.6	0.745

Table 5.29 Energy Calculations for 0.0-inch Equivalent Riprap Step @ 4% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0239	0.00988	0.320	2.97	0.660	134	29.1	0.785
75	0.0264	0.0109	0.434	3.00	0.852	170	36.0	0.788
100	0.0301	0.0124	0.508	3.02	0.935	197	43.3	0.785
125	0.0328	0.0135	0.583	3.03	1.03	230	50.1	0.783
150	0.0344	0.0142	0.666	3.02	1.15	260	57.1	0.779

Table 5.30 Energy Calculations for 0.0-inch Equivalent Riprap Step @ 6% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0229	0.00944	0.334	3.71	0.706	166	28.6	0.824
75	0.0239	0.00988	0.479	3.79	0.989	214	35.6	0.834
100	0.0277	0.0115	0.551	3.73	1.06	247	43.2	0.825
125	0.0305	0.0126	0.627	3.67	1.15	270	50.5	0.821
150	0.0332	0.0137	0.690	3.70	1.21	311	57.5	0.815

Table 5.31 Energy Calculations for 0.0-inch Equivalent Riprap Step @ 8% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0219	0.00903	0.350	3.95	0.755	183	28.1	0.844
75	0.0249	0.0103	0.460	4.09	0.931	230	35.7	0.843
100	0.0261	0.0108	0.585	4.06	1.16	273	43.6	0.840
125	0.0262	0.0108	0.729	3.90	1.44	301	53.3	0.823
150	0.0266	0.0110	0.862	3.87	1.69	326	64.5	0.806

### 5.14 0.5-inch Equivalent Riprap Step

Graphs of the water surface elevation for tests conducted at 2, 4, 6, and 8% slopes are shown in Figures 5.31, 5.32, 5.33, and 5.34. After the water surface elevation was established, average flow depth was determined. From the flow depth and the results from Section 5.5, the aforementioned volumetric displacement tests and energy calculations were conducted. The results for the energy calculations for the 0.5-inch equivalent riprap step are shown in Tables 5.32, 5.33, 5.34, and 5.35.

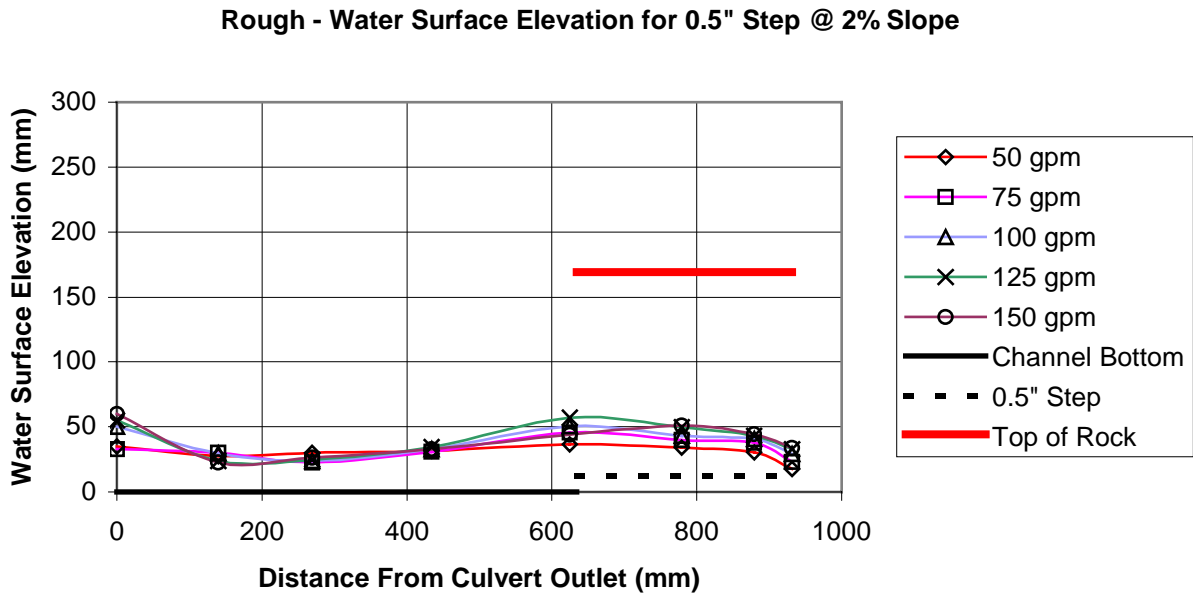


Figure 5.31 Plot of Water Surface Elevation for 0.5-inch Equivalent Riprap Step at 2% Culvert Slope

**Rough - Water Surface Elevation for 0.5" Step @ 4% Slope**

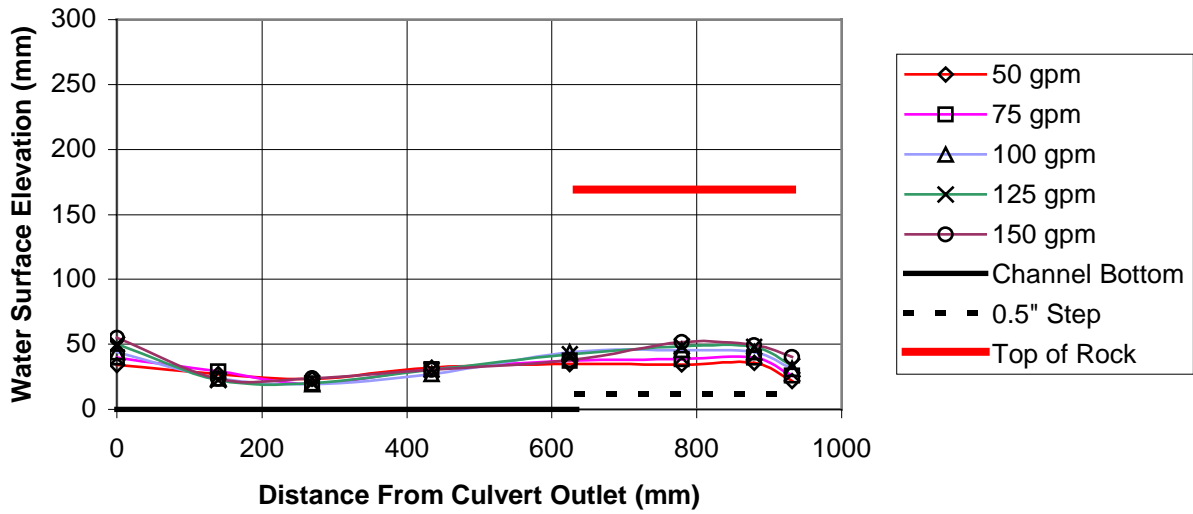


Figure 5.32 Plot of Water Surface Elevation for 0.5-inch Equivalent Riprap Step at 4% Culvert Slope

**Rough - Water Surface Elevation for 0.5" Step @ 6% Slope**

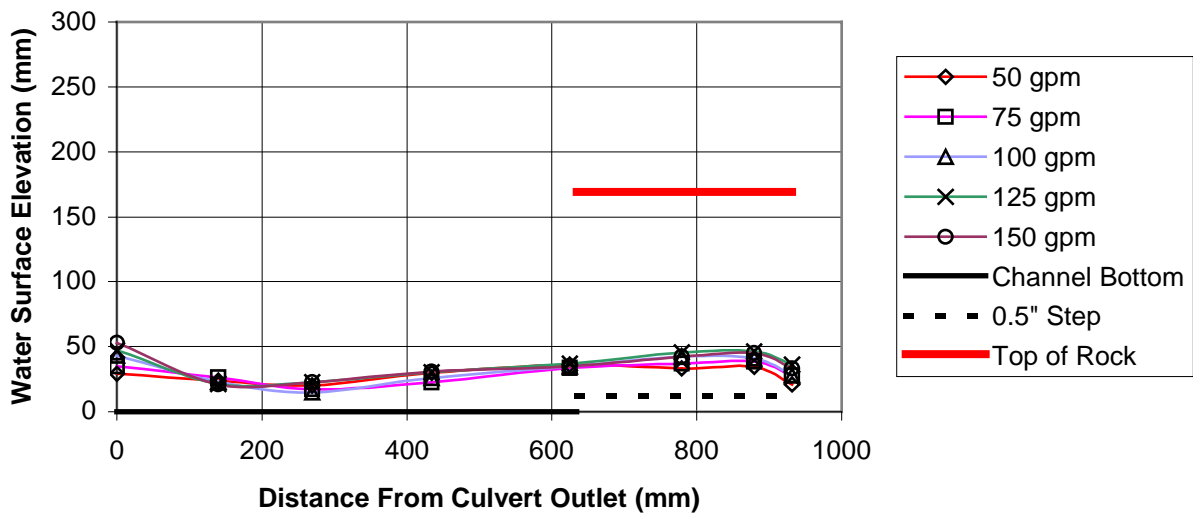


Figure 5.33 Plot of Water Surface Elevation for 0.5-inch Equivalent Riprap Step at 6% Culvert Slope



**Rough - Water Surface Elevation for 0.5" Step @ 8% Slope**

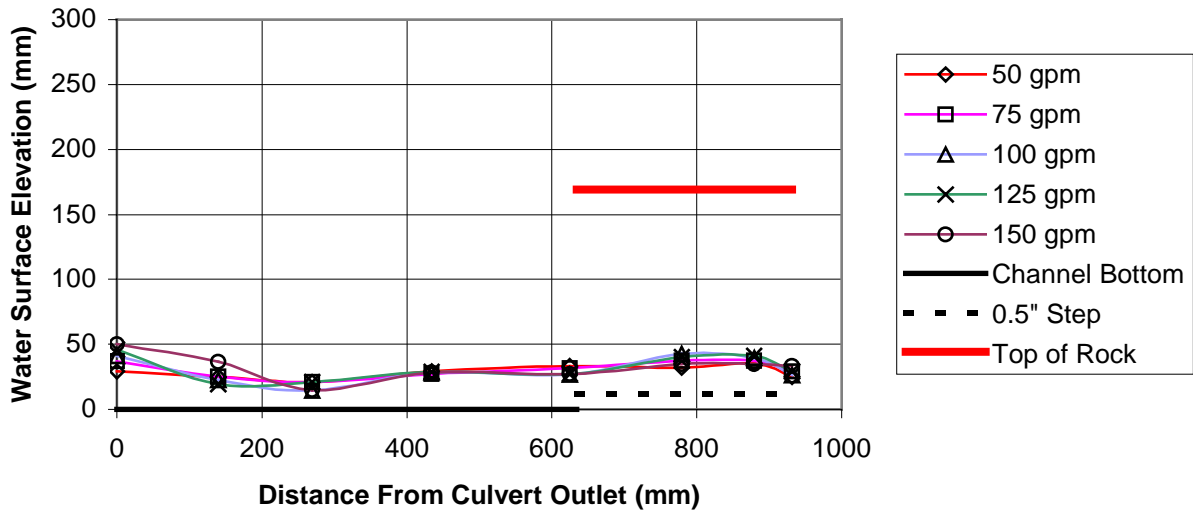


Figure 5.34 Plot of Water Surface Elevation for 0.5-inch Equivalent Riprap Step at 8% Culvert Slope

Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0233	0.00964	0.327	2.31	0.684	107	37.6	0.649
75	0.0291	0.0120	0.394	2.38	0.739	139	46.7	0.653
100	0.0314	0.0130	0.487	2.38	0.878	163	54.0	0.669
125	0.0347	0.0143	0.552	2.45	0.946	194	62.0	0.681
150	0.0357	0.0147	0.643	2.54	1.09	222	68.8	0.690

Table 5.33 Energy Calculations for 0.5-inch Equivalent Riprap Step @ 4% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross-Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non-Dimensional Energy Difference
50	0.0258	0.0106	0.297	2.97	0.590	134	39.4	0.705
75	0.0294	0.0121	0.391	3.00	0.728	170	46.9	0.723
100	0.0334	0.0138	0.458	3.02	0.801	197	55.3	0.719
125	0.0360	0.0149	0.531	3.03	0.893	230	62.5	0.729
150	0.0378	0.0156	0.607	3.02	1.00	260	69.4	0.734

Table 5.34 Energy Calculations for 0.5-inch Equivalent Riprap Step @ 6% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross-Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non-Dimensional Energy Difference
50	0.0249	0.0103	0.307	3.71	0.622	166	38.6	0.767
75	0.0283	0.0117	0.406	3.79	0.771	214	46.2	0.785
100	0.0311	0.0128	0.492	3.73	0.890	247	53.9	0.782
125	0.0344	0.0142	0.556	3.67	0.958	270	61.7	0.771
150	0.0327	0.0135	0.701	3.70	1.24	311	68.8	0.779

Table 5.35 Energy Calculations for 0.5-inch Equivalent Riprap Step @ 8% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross-Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non-Dimensional Energy Difference
50	0.0246	0.0102	0.310	3.95	0.631	183	38.5	0.790
75	0.0280	0.0116	0.410	4.09	0.782	230	45.9	0.800
100	0.0307	0.0127	0.498	4.06	0.907	273	53.6	0.803
125	0.0303	0.0125	0.631	3.90	1.16	301	60.7	0.798
150	0.0262	0.0108	0.875	3.87	1.73	326	74.1	0.773

### 5.15 1.0-inch Equivalent Riprap Step

Graphs of the water surface elevation for tests conducted at 2, 4, 6, and 8% slopes are shown in Figures 5.35, 5.36, 5.37, and 5.38. After the water surface elevation was established, average flow depth was determined. From the flow depth and the results from Section 5.5, the aforementioned volumetric displacement tests and energy calculations were conducted. The results for the energy calculations for the 1.0-inch equivalent riprap step are shown in Tables 5.36, 5.37, 5.38, and 5.39.

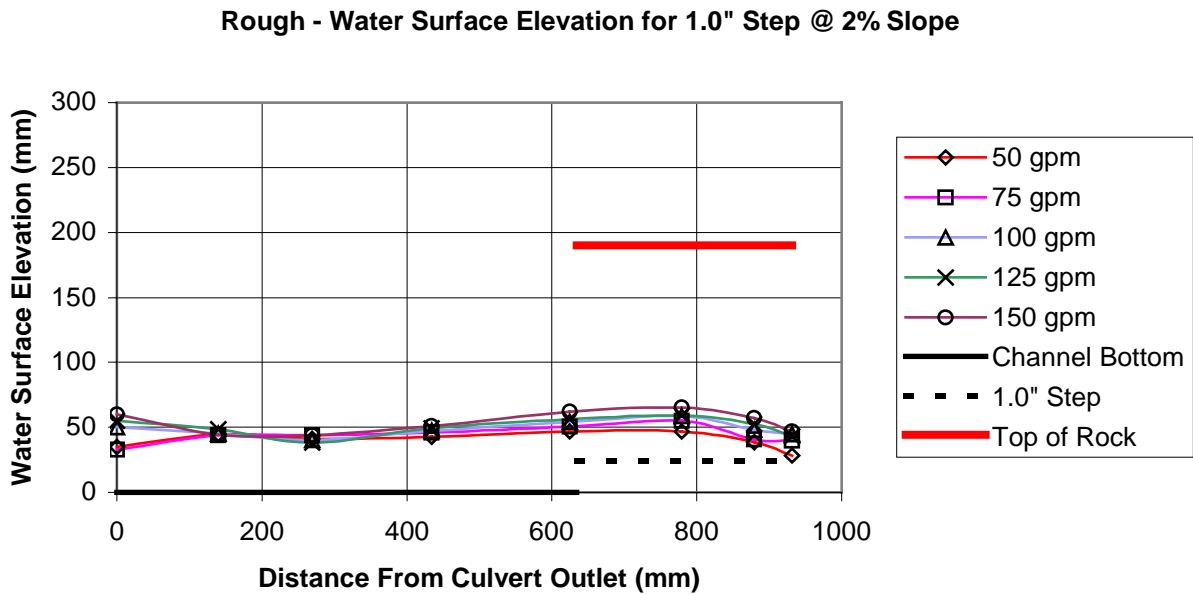


Figure 5.35 Plot of Water Surface Elevation for 1.0-inch Equivalent Riprap Step at 2% Culvert Slope

**Rough - Water Surface Elevation for 1.0" Step @ 4% Slope**

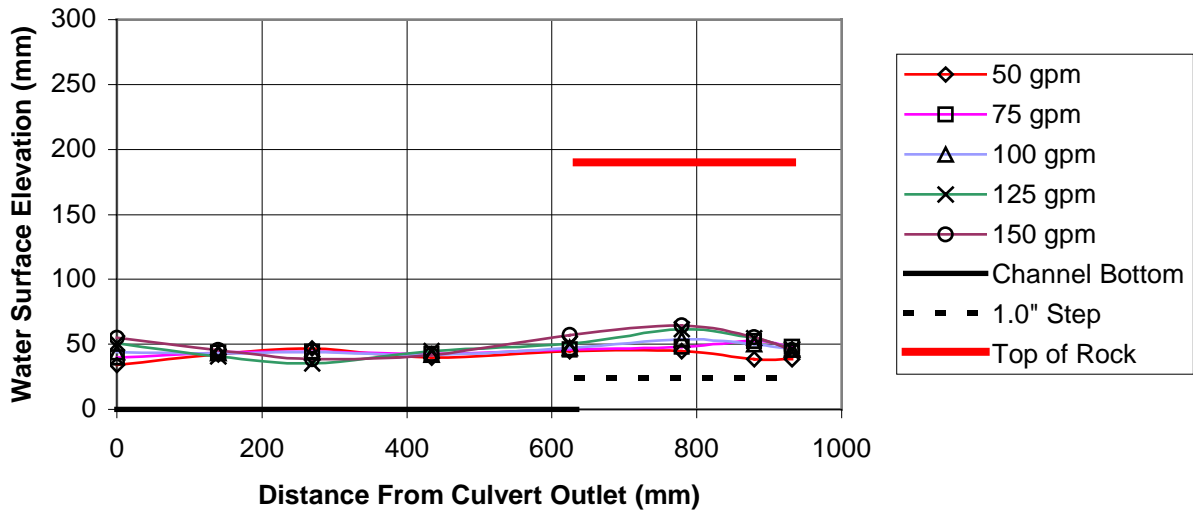


Figure 5.36 Plot of Water Surface Elevation for 1.0-inch Equivalent Riprap Step at 4% Culvert Slope

**Rough - Water Surface Elevation for 1.0" Step @ 6% Slope**

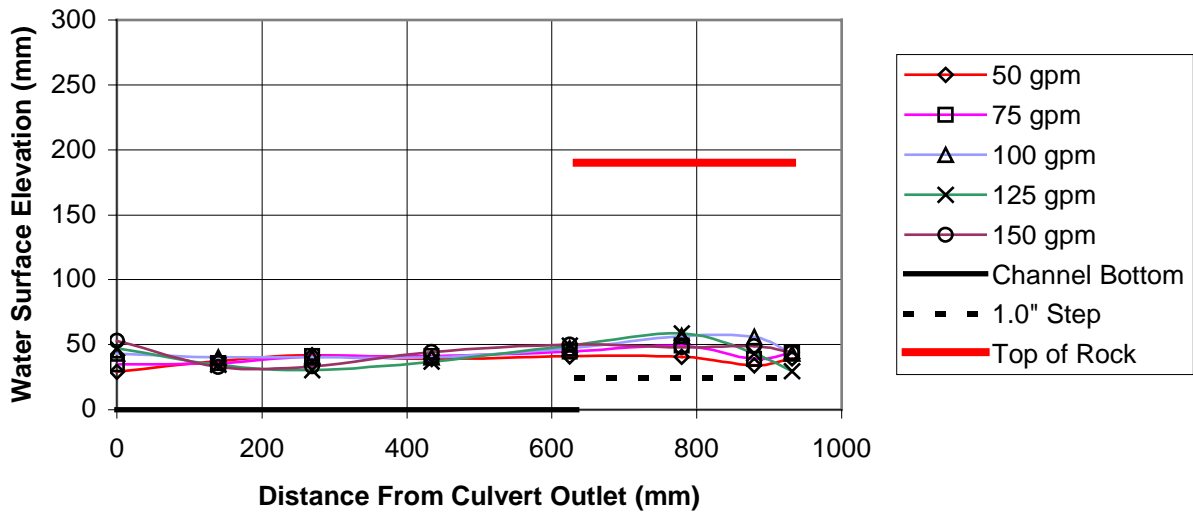


Figure 5.37 Plot of Water Surface Elevation for 1.0-inch Equivalent Riprap Step at 6% Culvert Slope

**Rough - Water Surface Elevation for 1.0" Step @ 8% Slope**

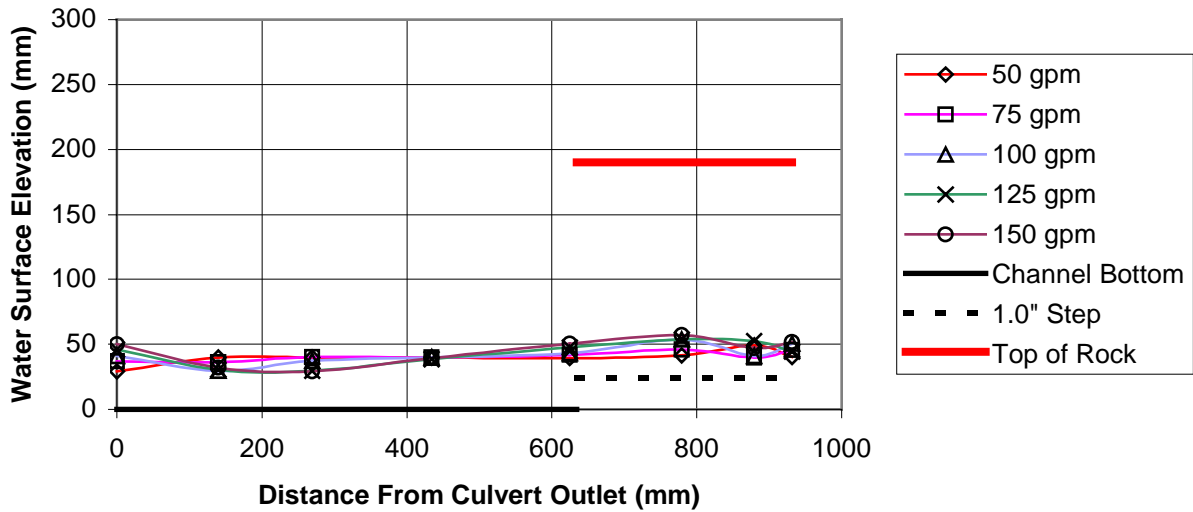


Figure 5.38 Plot of Water Surface Elevation for 1.0-inch Equivalent Riprap Step at 8% Culvert Slope

Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth	Average Flow Area	Average Flow Velocity	Fr # Based on Circular Cross-Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet	Average Energy in Zone 2	Non-Dimensional Energy Difference
	(m)	(m <sup>2</sup> )	(m/s)			(mm)	(mm)	
50	0.0200	0.00825	0.383	2.31	0.865	107	50.1	0.532
75	0.0237	0.00980	0.484	2.38	1.00	139	59.6	0.569
100	0.0297	0.0123	0.515	2.38	0.954	163	66.9	0.591
125	0.0323	0.0133	0.591	2.45	1.05	194	73.8	0.620
150	0.0371	0.0153	0.618	2.54	1.02	222	80.6	0.628

Table 5.37 Energy Calculations for 1.0-inch Equivalent Riprap Step @ 4% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0185	0.00762	0.414	2.97	0.974	134	50.5	0.628
75	0.0268	0.0111	0.429	3.00	0.837	170	59.7	0.644
100	0.0284	0.0117	0.538	3.02	1.02	197	66.7	0.668
125	0.0344	0.0142	0.555	3.03	0.956	230	73.8	0.680
150	0.0359	0.0148	0.638	3.02	1.08	260	80.8	0.686

Table 5.38 Energy Calculations for 1.0-inch Equivalent Riprap Step @ 6% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0150	0.00618	0.511	3.71	1.33	166	50.7	0.687
75	0.0211	0.00872	0.543	3.79	1.19	214	59.1	0.725
100	0.0326	0.0135	0.469	3.73	0.830	247	67.5	0.727
125	0.0273	0.0113	0.700	3.67	1.35	270	75.8	0.725
150	0.0248	0.0102	0.924	3.70	1.87	311	91.9	0.709

Table 5.39 Energy Calculations for 1.0-inch Equivalent Riprap Step @ 8% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0219	0.00906	0.349	3.95	0.751	183	51.5	0.718
75	0.0202	0.00835	0.567	4.09	1.27	230	59.3	0.747
100	0.0246	0.0101	0.623	4.06	1.27	273	67.3	0.753
125	0.0298	0.0123	0.642	3.90	1.19	301	74.4	0.751
150	0.0287	0.0119	0.799	3.87	1.51	326	84.8	0.740

### 5.16 1.5-inch Equivalent Riprap Step

Graphs of the water surface elevation for tests conducted at 2, 4, 6, and 8% slopes are shown in Figures 5.39, 5.40, 5.41, and 5.42. After the water surface elevation was established, average flow depth was determined. From the flow depth and the results from Section 5.5, the aforementioned volumetric displacement tests and energy calculations were conducted. The results for the energy calculations for the 1.5-inch equivalent riprap step are shown in Tables 5.40, 5.41, 5.42, and 5.43.

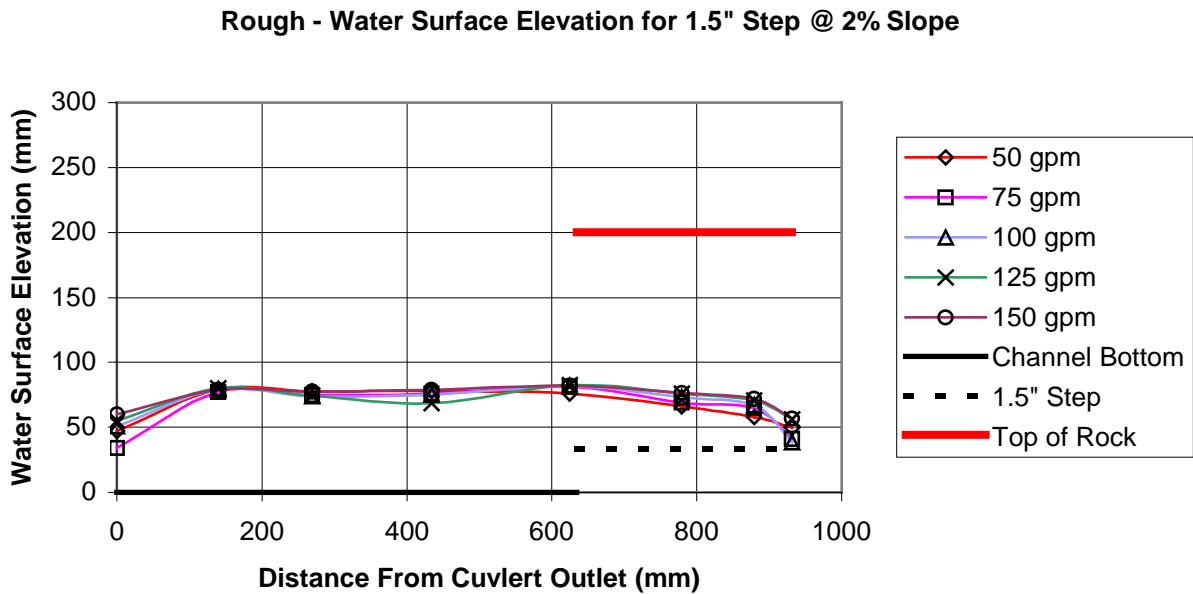


Figure 5.39 Plot of Water Surface Elevation for 1.5-inch Equivalent Riprap Step at 2% Culvert Slope

**Rough - Water Surface Elevation for 1.5" Step @ 4% Slope**

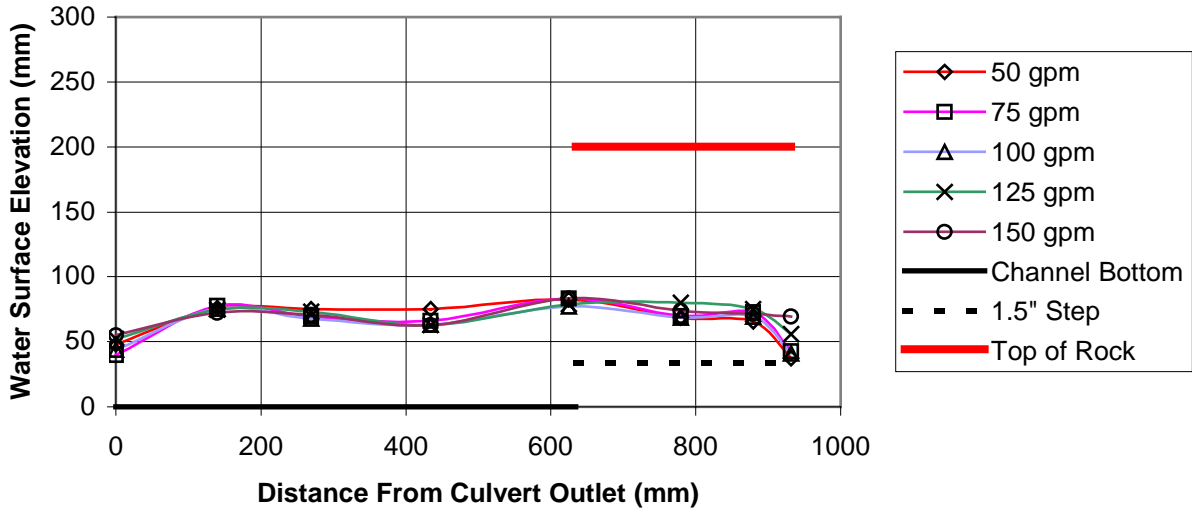


Figure 5.40 Plot of Water Surface Elevation for 1.5-inch Equivalent Riprap Step at 4% Culvert Slope

**Rough - Water Surface Elevation for 1.5" Step @ 6% Slope**

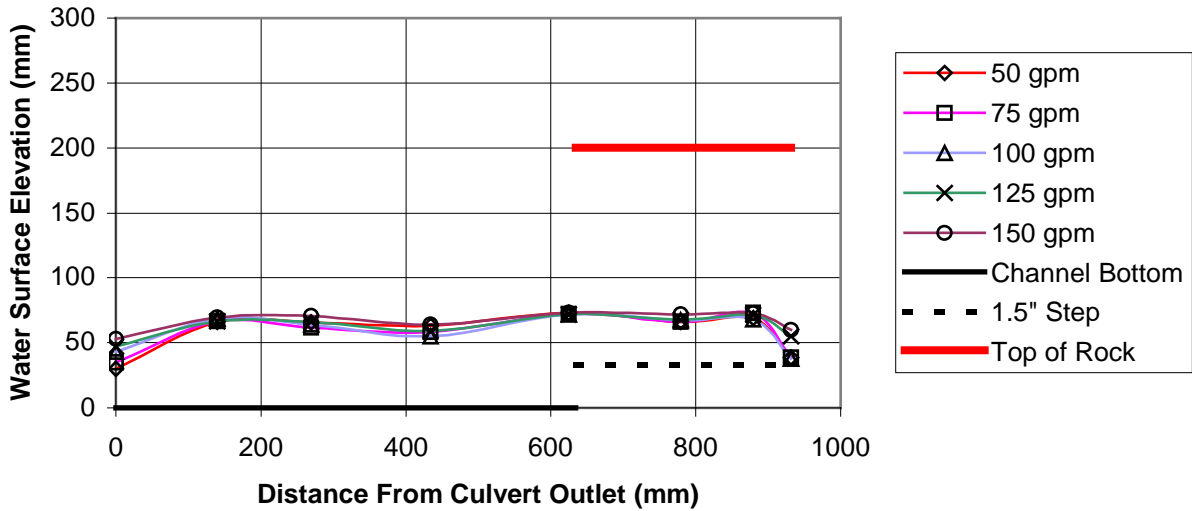


Figure 5.41 Plot of Water Surface Elevation for 1.5-inch Equivalent Riprap Step at 6% Culvert Slope



**Rough - Water Surface Elevation for 1.5" Step @ 8% Slope**

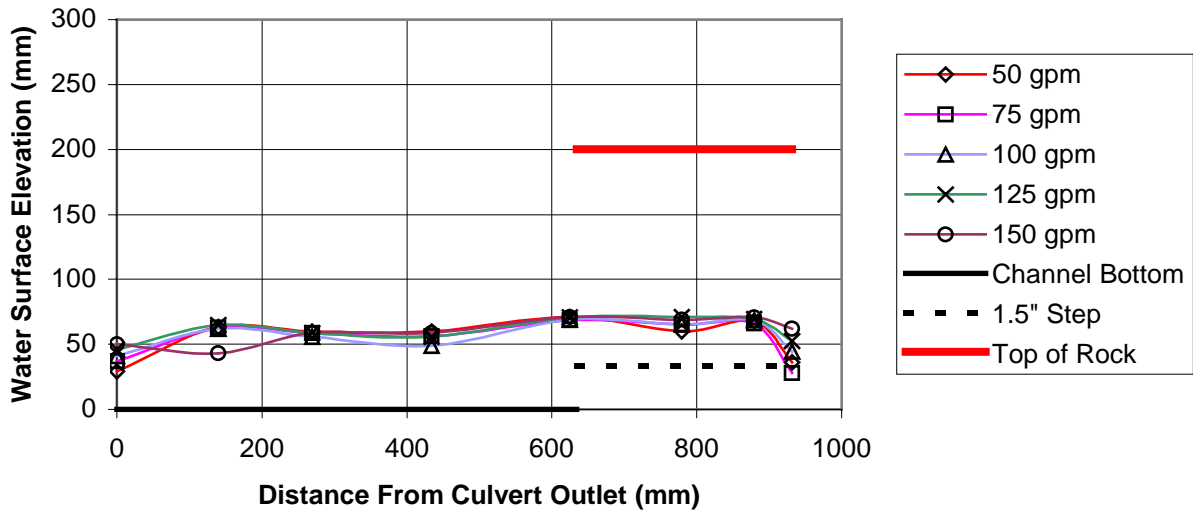


Figure 5.42 Plot of Water Surface Elevation for 1.5-inch Equivalent Riprap Step at 8% Culvert Slope

Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0312	0.0129	0.245	2.31	0.444	107	65.2	0.392
75	0.0375	0.0155	0.408	2.38	0.557	139	72.4	0.472
100	0.0375	0.0155	0.408	2.38	0.673	163	78.3	0.521
125	0.0404	0.0167	0.474	2.45	0.753	194	84.6	0.553
150	0.0410	0.0169	0.560	2.54	0.883	222	89.9	0.595

Table 5.41 Energy Calculations for 1.5-inch Equivalent Riprap Step @ 4% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0352	0.0145	0.217	2.97	0.369	134	69.5	0.488
75	0.0386	0.0159	0.297	3.00	0.483	170	75.7	0.545
100	0.0366	0.0151	0.417	3.02	0.696	197	77.8	0.613
125	0.0420	0.0173	0.455	3.03	0.709	230	87.3	0.621
150	0.0399	0.0165	0.574	3.02	0.918	260	89.5	0.653

Table 5.42 Energy Calculations for 1.5-inch Equivalent Riprap Step @ 6% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0356	0.0147	0.215	3.71	0.363	166	69.9	0.585
75	0.0373	0.0154	0.307	3.79	0.508	214	74.3	0.653
100	0.0358	0.0148	0.427	3.73	0.721	247	77.1	0.688
125	0.0373	0.0154	0.512	3.67	0.847	270	83.0	0.706
150	0.0394	0.0163	0.582	3.70	0.937	311	89.4	0.717

Table 5.43 Energy Calculations for 1.5-inch Equivalent Riprap Step @ 8% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0325	0.0134	0.236	3.95	0.418	183	66.5	0.633
75	0.0339	0.0140	0.338	4.09	0.586	230	71.4	0.698
100	0.0351	0.0145	0.435	4.06	0.742	273	76.6	0.719
125	0.0377	0.0156	0.506	3.90	0.833	301	83.3	0.719
150	0.0376	0.0155	0.610	3.87	1.00	326	88.9	0.730

### 5.17 2.0-inch Equivalent Riprap Step

Graphs of the water surface elevation for tests conducted at 2, 4, 6, and 8% slopes are shown in Figures 5.43, 5.44, 5.45, and 5.46. After the water surface elevation was established, average flow depth was determined. From the flow depth and the results from Section 5.5, the aforementioned volumetric displacement tests and energy calculations were conducted. The results for the energy calculations for the 2.0-inch equivalent riprap step are shown in Tables 5.44, 5.45, 5.46, and 5.47.

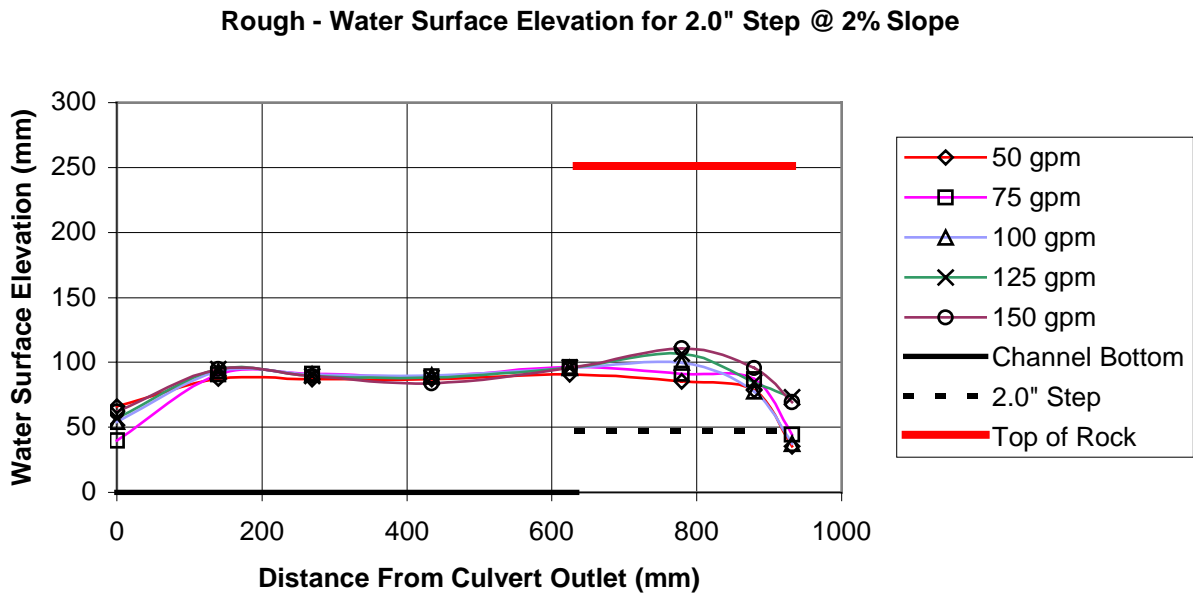


Figure 5.43 Plot of Water Surface Elevation for 2.0-inch Equivalent Riprap Step at 2% Culvert Slope

**Rough - Water Surface Elevation for 2.0" Step @ 4% Slope**

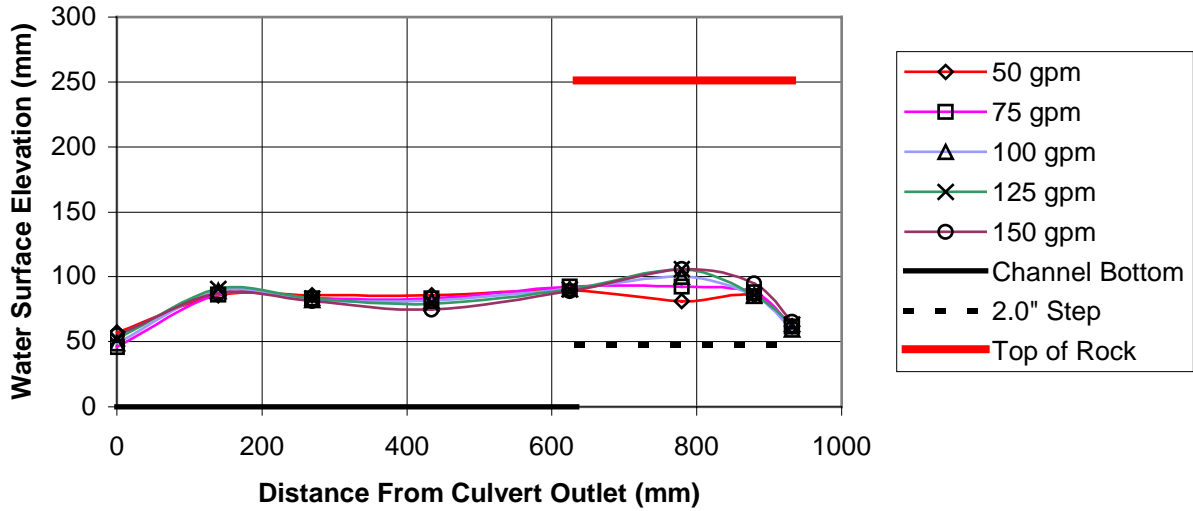


Figure 5.44 Plot of Water Surface Elevation for 2.0-inch Equivalent Riprap Step at 4% Culvert Slope

**Rough - Water Surface Elevation for 2.0" Step @ 6% Slope**

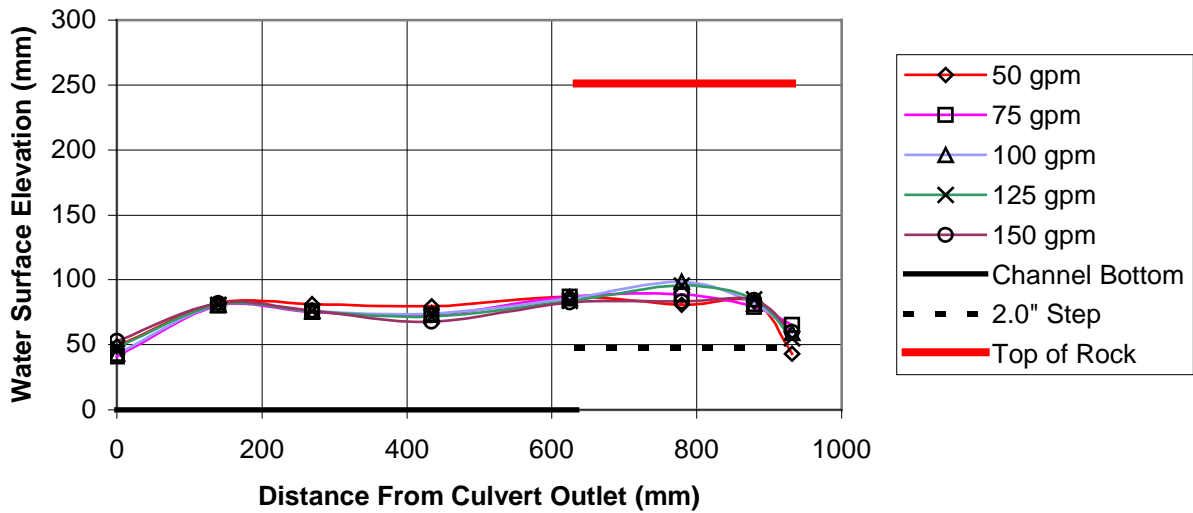


Figure 5.45 Plot of Water Surface Elevation for 2.0-inch Equivalent Riprap Step at 6% Culvert Slope

**Rough - Water Surface Elevation for 2.0" Step @ 8% Slope**

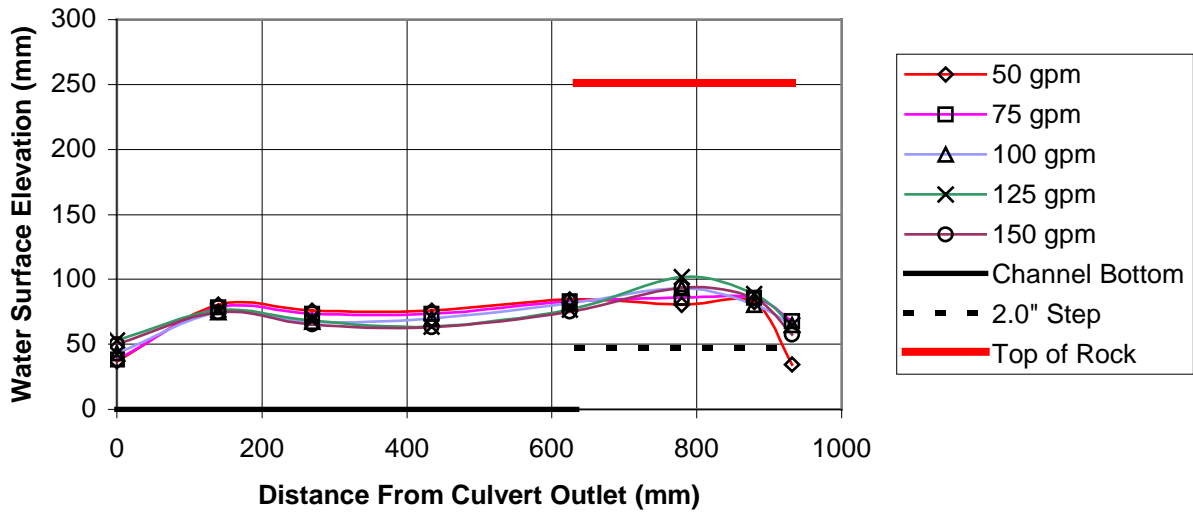


Figure 5.46 Plot of Water Surface Elevation for 2.0-inch Equivalent Riprap Step at 8% Culvert Slope

Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0359	0.0148	0.213	2.31	0.359	107	84.2	0.215
75	0.0428	0.0177	0.268	2.38	0.413	139	92.7	0.329
100	0.0426	0.0176	0.359	2.38	0.555	163	95.2	0.417
125	0.0492	0.0203	0.388	2.45	0.559	194	103	0.454
150	0.0568	0.0235	0.404	2.54	0.541	222	112	0.497

Table 5.45 Energy Calculations for 2.0-inch Equivalent Riprap Step @ 4% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0375	0.0155	0.204	2.97	0.337	134	85.6	0.357
75	0.0438	0.0181	0.262	3.00	0.399	170	93.6	0.438
100	0.0464	0.0192	0.329	3.02	0.488	197	98.3	0.511
125	0.0495	0.0205	0.386	3.03	0.554	230	103	0.551
150	0.0541	0.0223	0.424	3.02	0.583	260	110	0.560

Table 5.46 Energy Calculations for 2.0-inch Equivalent Riprap Step @ 6% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0361	0.0149	0.212	3.71	0.356	166	84.4	0.507
75	0.0379	0.0157	0.302	3.79	0.496	214	88.6	0.587
100	0.0439	0.0181	0.349	3.73	0.531	247	96.2	0.611
125	0.0445	0.0184	0.429	3.67	0.650	270	100	0.646
150	0.0499	0.0206	0.460	3.70	0.658	311	107	0.662

Table 5.47 Energy Calculations for 2.0-inch Equivalent Riprap Step @ 8% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non- Dimensional Energy Difference
50	0.0355	0.0146	0.216	3.95	0.365	183	83.9	0.537
75	0.0396	0.0164	0.289	4.09	0.464	230	90.0	0.619
100	0.0407	0.0168	0.376	4.06	0.594	273	94.0	0.656
125	0.0488	0.0201	0.392	3.90	0.567	301	103	0.651
150	0.0431	0.0178	0.532	3.87	0.818	326	104	0.685

### 5.18 2.5-inch Equivalent Riprap Step

Graphs of the water surface elevation for tests conducted at 2, 4, 6, and 8% slopes are shown in Figures 5.47, 5.48, 5.49, and 5.50. After the water surface elevation was established, average flow depth was determined. From the flow depth and the results from Section 5.5, the aforementioned volumetric displacement tests and energy calculations were conducted. The results for the energy calculations for the 2.5-inch equivalent riprap step are shown in Tables 5.48, 5.49, 5.50, and 5.51.

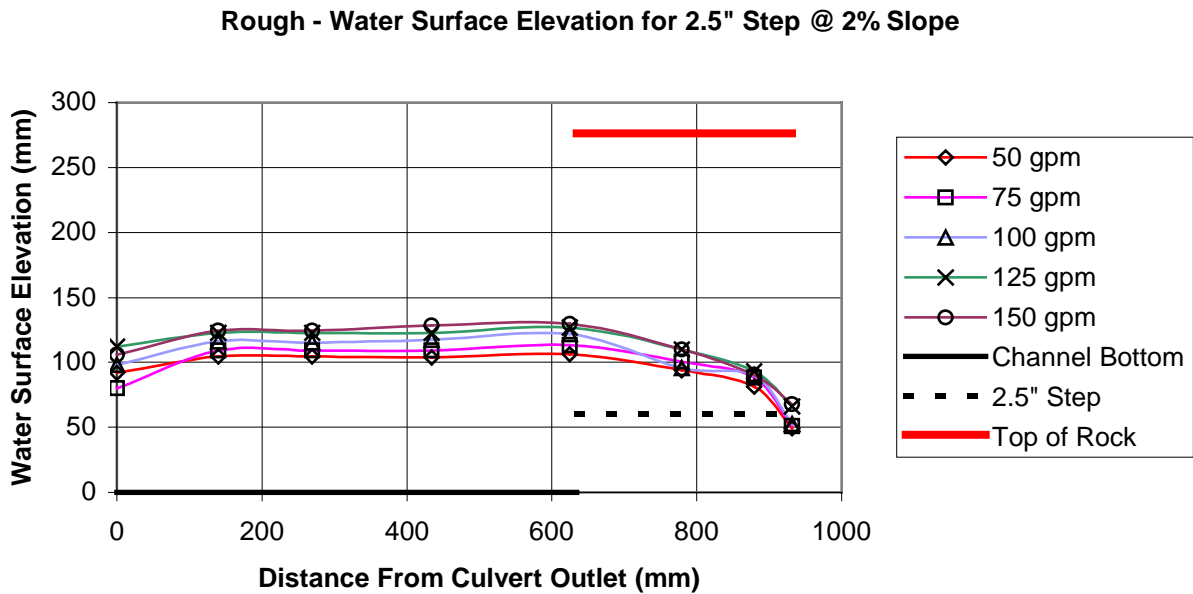


Figure 5.47 Plot of Water Surface Elevation for 2.5-inch Equivalent Riprap Step at 2% Culvert Slope

**Rough - Water Surface Elevation for 2.5" Step @ 4% Slope**

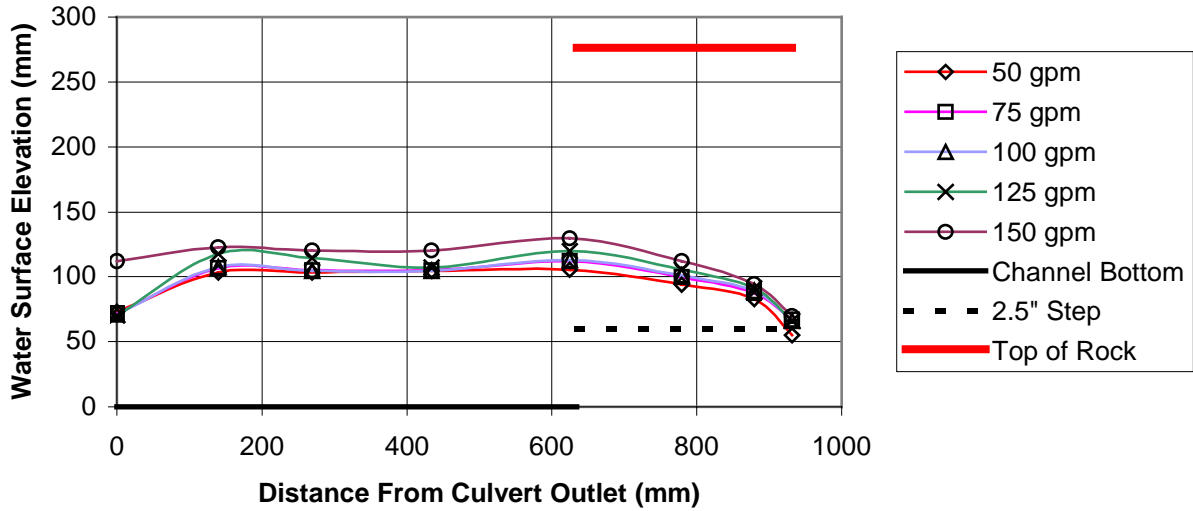


Figure 5.48 Plot of Water Surface Elevation for 2.5-inch Equivalent Riprap Step at 4% Culvert Slope

**Rough - Water Surface Elevation for 2.5" Step @ 6% Slope**

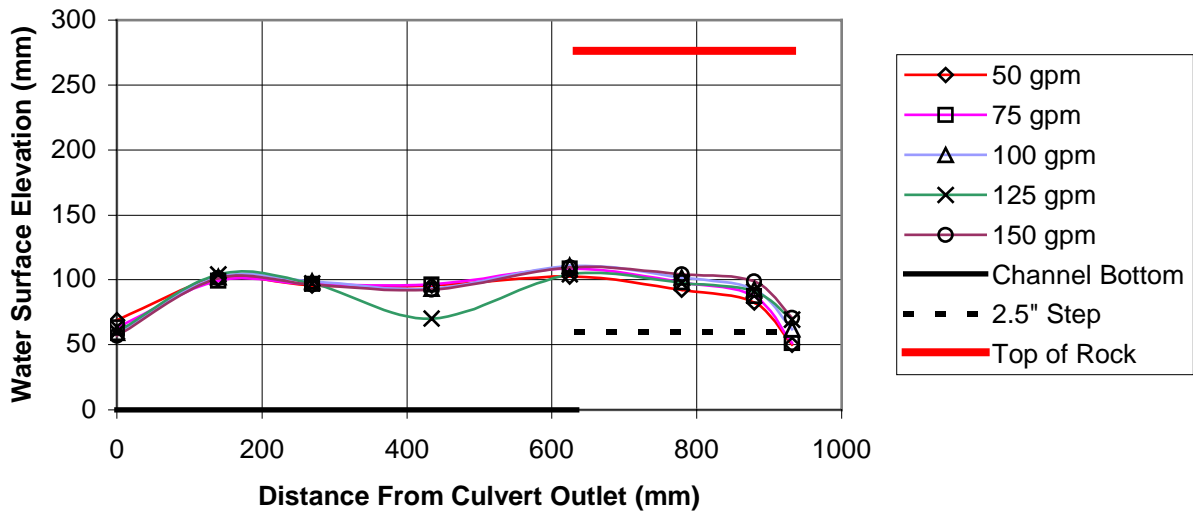


Figure 5.49 Plot of Water Surface Elevation for 2.5-inch Equivalent Riprap Step at 6% Culvert Slope



**Rough - Water Surface Elevation for 2.5" Step @ 8% Slope**

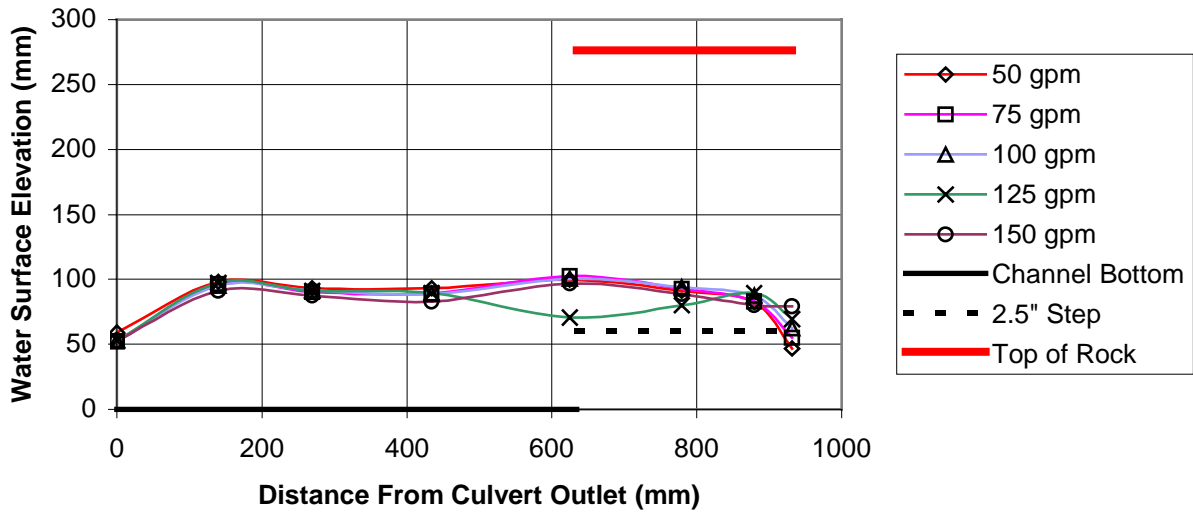


Figure 5.50 Plot of Water Surface Elevation for 2.5-inch Equivalent Riprap Step at 8% Culvert Slope

Flowrate (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth (m)	Average Flow Area (m <sup>2</sup> )	Average Flow Velocity (m/s)	Fr # Based on Circular Cross-Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet (mm)	Average Energy in Zone 2 (mm)	Non-Dimensional Energy Difference
50	0.0509	0.0210	0.150	2.31	0.212	107	102	0.0146
75	0.0576	0.0238	0.199	2.38	0.265	139	109	0.202
100	0.0428	0.0177	0.357	2.38	0.552	163	99.4	0.391
125	0.0644	0.0266	0.297	2.45	0.373	194	119	0.371
150	0.0631	0.0261	0.364	2.54	0.462	222	120	0.474

Table 5.49 Energy Calculations for 2.5-inch Equivalent Riprap Step @ 4% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0518	0.0214	0.148	2.97	0.207	134	102	0.170
75	0.0567	0.0234	0.202	3.00	0.271	170	109	0.353
100	0.0580	0.0239	0.264	3.02	0.350	197	111	0.446
125	0.0614	0.0253	0.311	3.03	0.401	230	116	0.493
150	0.0659	0.0272	0.348	3.02	0.433	260	122	0.530

Table 5.50 Energy Calculations for 2.5-inch Equivalent Riprap Step @ 6% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0508	0.0210	0.150	3.71	0.213	166	101	0.416
75	0.0558	0.0231	0.205	3.79	0.277	214	108	0.498
100	0.0601	0.0248	0.255	3.73	0.332	247	113	0.553
125	0.0574	0.0237	0.333	3.67	0.444	270	113	0.599
150	0.0638	0.0263	0.360	3.70	0.455	311	121	0.616

Table 5.51 Energy Calculations for 2.5-inch Equivalent Riprap Step @ 8% Slope

Flowrate  (gpm)	Testing Channel Data - Zone 2			Froude # Calculations		Energy Calculations		
	Average Flow Depth  (m)	Average Flow Area  (m <sup>2</sup> )	Average Flow Velocity  (m/s)	Fr # Based on Circular Cross- Section	Fr # Based on Average Zone 2 Values	Energy at Culvert Outlet  (mm)	Average Energy in Zone 2  (mm)	Non- Dimensional Energy Difference
50	0.0499	0.0206	0.153	3.95	0.219	183	101	0.404
75	0.0510	0.0211	0.225	4.09	0.318	230	103	0.564
100	0.0538	0.0222	0.284	4.06	0.391	273	108	0.609
125	0.0478	0.0197	0.400	3.90	0.584	301	106	0.641
150	0.0488	0.0202	0.470	3.87	0.679	326	96.0	0.715

### 5.19 Comparison to “Natural” Energy Grade Line

As stated in the beginning of this chapter, one criterion that needed to be met was to re-establish natural flow conditions downstream of the outlet. In order for this parameter to be examined, the headwater elevations above the invert of the culvert inlet, for the tested flowrates, were used to establish the “natural” energy grade line. The headwater elevation was taken as the location of the energy grade line above the culvert inlet and was extended parallel to the culvert (at the respective slope setting). A representation of the physical setting for this calculation is shown in Figure 5.51.

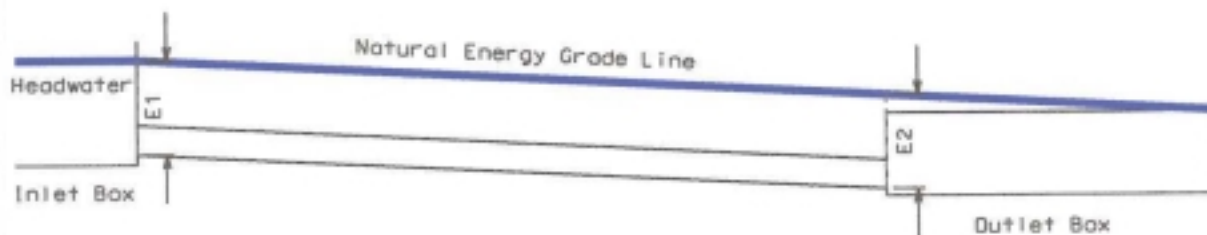


Figure 5.51 Energy Grade Line Establishment

Notice that the height of the energy grade line above the invert at the culvert inlet,  $E_1$ , is equal to the height of the energy grade line above the invert at the culvert outlet,  $E_2$ . Since  $E_1$  and  $E_2$  were equal, the calculations to find the elevation of the energy grade line at a point in the testing channel could be determined from simple trigonometry. The point selected to perform the comparison between the natural energy grade line and the total energy grade calculated from the three-point gage data was the center point of Zone 2. Following the selection of the point for comparison, the elevation of the natural energy grade line was calculated based on trigonometric relationships. The values for the elevation of the natural energy grade line, shown in red in Tables 5.52 and 5.53, were then compared to the values for total average energy in Zone 2 of the testing channel. The values for the elevation of the total average energy in Zone 2 of the testing channel shown in blue represent those cases where the energy remaining in the flow over Zone 2 exceeds that estimated for the so-called “natural condition”. The ‘smooth’ cast acrylic steps are compared in Table 5.52 and the ‘rough’ riprap steps are compared in Table 5.53.

Table 5.52 Comparison Between "Natural" and Calculated Energy in Zone 2 for 'Smooth' Steps							
Cast Acrylic Steps							
Slope (%)	Flowrate (gpm)	"Natural" Energy Grade Line (mm)	0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
			Total Average Energy In Zone 2 of Testing Channel (mm)				
2	50	65.3	41.5	53.2	61.3	75.7	88.9
2	75	84.3	48.5	61.2	73.1	98.5	98.5
2	100	108	55.7	73.5	78.5	93.9	108
2	125	137	66.2	77.0	86.6	103	114
2	150	171	74.6	85.1	95.7	109	122
4	50	65.3	52.6	52.8	61.1	76.9	88.3
4	75	85.3	47.7	60.4	72.8	98.0	98.0
4	100	108	57.3	68.4	78.9	95.5	116
4	125	136	72.7	76.9	84.5	116	133
4	150	172	93.8	95.1	91.8	131	135
6	50	64.3	41.5	53.7	64.8	83.0	89.2
6	75	85.3	51.2	60.2	69.6	103	103
6	100	108	67.2	68.6	77.0	106	112
6	125	136	77.4	77.1	85.7	105	122
6	150	172	107	95.8	106	108	120
8	50	63.3	57.0	56.3	62.9	78.5	88.0
8	75	83.3	86.6	77.1	71.5	104	104
8	100	108	92.5	91.1	83.1	92.3	118
8	125	135	105	108	105	97.4	125
8	150	170	143	122	117	109	125

Equivalent Riprap Steps								
Slope (%)	Flowrate (gpm)	"Natural" Energy Grade Line (mm)	0.0-inch	0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
			Total	Average	Energy	In Zone 2 of Testing Channel		
2	50	65.3	29.2	37.6	50.1	65.2	84.2	102
2	75	84.3	36.3	46.7	59.6	72.4	92.7	109
2	100	108	43.2	54.0	66.9	78.3	95.2	99.0
2	125	137	50.1	62.0	73.8	84.6	103	119
2	150	171	56.6	68.8	80.6	89.9	112	120
4	50	65.3	29.1	39.4	50.5	69.5	85.6	102
4	75	85.3	36.0	46.9	59.7	75.7	93.6	109
4	100	108	43.3	55.3	66.7	77.8	98.3	111
4	125	136	50.1	62.5	73.8	87.3	103	116
4	150	172	57.1	69.4	80.8	89.5	110	122
6	50	64.3	28.6	38.6	50.7	69.9	84.4	101
6	75	85.3	35.6	46.2	59.1	74.3	88.6	108
6	100	108	43.2	53.9	67.5	77.1	96.2	113
6	125	136	50.5	61.7	76.0	83.0	100	113
6	150	172	57.5	68.8	91.9	89.4	107	121
8	50	63.3	28.1	38.5	51.5	66.5	83.9	101
8	75	83.3	35.7	45.9	59.3	71.4	90.0	103
8	100	108	43.6	53.6	67.3	76.6	94.0	108
8	125	135	53.3	60.7	74.4	83.3	103	106
8	150	170	64.5	74.1	84.8	88.9	104	96.0

From Tables 5.52 and 5.53, one can see that the effectiveness of the step increases with the increase in flowrate. It appears that the low riprap steps are providing better energy dissipation than the higher riprap steps due partially to the low flow depths.

## 5.20 Flow Characteristics

The flow from each experimental test run was characterized in Tables 5.54 and 5.55 as discussed in Section 5.3

Where:

R = Reverse flow

J0 = No jump

X = Not fully expanded jet

J1 = Weak jump

P = Spurting flow

J2 = Oscillating jump

W = Swirling flow

^ = Jump in test channel

S = Slashing flow

\* = Jump in test culvert

L = Pooling

Flowrate (gpm)	Slope (%)	Flow Types				
		0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
50	2	RXJ0	RXJ0	RXJ0	RXLJ0	RXLJ0
75	2	RXJ0	RXJ0	RXJ0	RXLJ0	RXLJ0
100	2	RXPJ0	RXJ0	RXJ0	RXLJ0	RXLJ0
125	2	RXPJ0	RXPJ0	RXJ0	RXLJ0	RXLJ0
150	2	RXJ0	RXPJ0	RXJ0	RXLJ0	RXLJ0
50	4	RXJ0	RXJ0	RXJ0	RXLJ0	RXLJ0
75	4	RXJ0	RXJ0	RXJ0	RXLJ0	RXLJ0
100	4	RXPJ0	RXJ0	RXJ0	RXLJ0	RXLJ0
125	4	RXJ0	RXJ0	RXJ0	RXLJ0	RXLJ0
150	4	RXPJ2^	RXPJ2^	RXJ2^	RXLJ0	RXLJ0
50	6	RXPJ2^	RXJ2^	RXJ0	RXJ0	RXLJ0
75	6	RXPJ2^	RXJ2^	RXJ0	RXLJ0	RXLJ0
100	6	RXPJ2^	RXJ2^	RXJ2^	RXLJ0	RXLJ0
125	6	RXPJ2^	RXPJ2^	RXPJ2^	RXLJ0	RXLJ0
150	6	RXPJ2^	RXPJ2^	RXPJ2^	RXLJ0	RXLJ0
50	8	RXPJ2^	RXPJ2^	RXJ0	RXJ0	RXLJ0
75	8	RXPJ2^	RXPJ2^	RXJ2^	RXJ0	RXLJ0
100	8	RXPJ2^	RXPJ2^	RXPJ2^	RXLJ0	RXLJ0
125	8	RXPJ2^	RXPJ2^	RXPJ2^	RXLJ0	RXLJ0
150	8	RXPJ2^	RXPJ2^	RXPJ2^	RXPLJ0	RXLJ0

Table 5.55 Flow Characteristics for Riprap Steps							
Flowrate (gpm)	Slope (%)	Flow Types					
		0.0-inch	0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
50	2	RXJ1^	RXJ1^	RXJ1^	RXSLJ1*	RXSLJ1*	RXSLJ1*
75	2	RXJ1^	RXJ1^	RXJ1^	RXSLJ1*	RXSLJ1*	RXSLJ1*
100	2	RXJ0	RXJ1^	RXJ1^	RXSLJ1^	RXSLJ1*	RXSLJ1*
125	2	RXJ0	RXJ1^	RXJ0	RXSLJ1^	RXSLJ1*	RXSLJ1*
150	2	RXJ0	RXJ0	RXJ0	RXSLJ1^	RXSLJ2*	RXSLJ2*
50	4	RXJ2^	RXJ2^	RXJ2^	RXSLJ2*	RXSLJ2*	RXSLJ2*
75	4	RXJ2^	RXJ2^	RXJ2^	RXSLJ2*	RXSLJ2*	RXSLJ2*
100	4	RXJ2^	RXJ2^	RXJ0	RXSLJ2^	RXSLJ2*	RXSLJ2*
125	4	RXJ0	RXJ2^	RXJ2^	RXSLJ2^	RXSLJ2^	RXSLJ2*
150	4	RXJ0	RXJ2^	RXJ0	RXSLJ2^	RXSLJ2*	RXSLJ2*
50	6	RXJ2^	RXJ2^	RXJ0	RXSLJ2*	RXSLJ2*	RXSLJ2*
75	6	RXJ2^	RXJ2^	RXJ0	RXSLJ2^	RXSLJ2*	RXSLJ2*
100	6	RXJ0	RXJ2^	RXJ2^	RXSLJ2^	RXSLJ2*	RXSLJ2*
125	6	RXJ0	RXJ2^	RXJ0	RXSLJ2^	RXSLJ2*	RXSLJ2*
150	6	RXJ0	RXJ0	RXJ0	RXSLJ2^	RXSLJ2*	RXSLJ2*
50	8	RXJ2^	RXJ2^	RXJ2^	RXSJ2*	RXSLJ2*	RXSLJ2*
75	8	RXJ2^	RXJ2^	RXJ0	RXSJ2*	RXSLJ2*	RXSLJ2*
100	8	RXJ0	RXJ2^	RXJ0	RXSJ2*	RXSLJ2*	RXSLJ2*
125	8	RXJ0	RXJ0	RXJ0	RXSJ2*	RXSLJ2*	RXSLJ2*
150	8	RXJ0	RXJ0	RXJ0	RXSLJ0*	RXSLJ2*	RXSLJ2*

## 5.21 Error Analysis

A unique design for the testing flume was necessary in order to satisfy the requirements of research. Several modifications were made throughout the process of experimentation; therefore it was difficult to perform an error analysis. There were several reasons that made an in-depth error analysis impractical. The number of significant changes that occurred in design and in methods of calculation during the course of the research made it difficult to follow the propagation of error to the final results. As this research was a preliminary investigation, an in-depth error analysis should be performed in follow-up research experiments with the testing flume. The raw depth measurements taken in the testing channel were influenced by waves, turbulence, and aeration. These influences created the greatest source of error in the various experiments. Also, due to the time restraints of the project, establishing repeatability in depth measurements for a specific situation was not feasible. However, trends in the data can easily be seen and explained.

The primary measuring devices used in experiments performed with the testing flume include the following:

- Metric scales
  - Headwater depth
  - Longitudinal distance along testing channel
  - Piezometer depth
  - Pitot tube readings
  - Slope adjustment
- Digital Scales
  - Flowmeter
- Vernier Scale
  - Depth in testing channel

All of the metric scales were read to the nearest millimeter, based on the convention of best estimate. The Vernier scale was accurate to 0.001-ft and measurements were taken accordingly. Three significant figures applied for all measures of length. The flowmeter had a range of 40-450 gpm with a plus or minus of 2.0% full-scale linearity and a plus or minus of 1.0% full-scale repeatability. Expected values of uncertainty for several variables measured in the experiments are shown in Table 5.56.



Table 5.56	Expected Error For Various Calculated Values
Value	Expected Error (%)
Area (Culvert)	3.40
Area (Channel)	8.40
Depth (Culvert)	3.30
Depth (Channel)	8.30
Energy (Culvert)	9.00
Energy (Channel)	21.3
Froude Number (Culvert)	5.65
Froude Number (Channel)	11.2
Velocity (Culvert)	5.40
Velocity (Channel)	10.4

## Chapter 6

### Results

#### 6.1 Non-Dimensional Comparison of Cast Acrylic and Riprap Step

In order to compare the performance of each step type and height, the values of NDED (Equation 5.8) for each slope and discharge were compiled into two tables. NDED with respect to total energy will be referred to as EDT. Tables 6.1 and 6.2 summarize the data in terms of EDT with respect to cast acrylic steps and riprap steps, respectively. By only examining the non-dimensional energy difference in terms of total energy, a possible misinterpretation could occur. For example, if a higher riprap step was tested and the energy difference was less than that of a smaller step, a possible conclusion would be that the higher riprap step was not as effective in attenuating energy in the test channel as the smaller step. When a higher riprap step is placed in the channel, not only does the step height increase, but the ‘pooling’ of water at Zone 2 increases the height of the energy grade line as well. A closer examination of the NDED in terms of velocity head, EDV, in Tables 6.3 and 6.4, was necessary. EDV is defined in Equation 6.1.

$$EDV = \frac{\left(\frac{V^2}{2g}\right)_{CulvertOutlet} - \left(\frac{V^2}{2g}\right)_{TestChannel}}{TotalEnergyAtCulvertOutlet} \quad (6.1)$$

Where:

$V$  = Flow velocity

$g$  = Acceleration due to gravity

$$TotalEnergyAtCulvertOutlet = \frac{V^2}{2g} + y + z$$

Where:

$y$  = Depth of flow

$z$  = Distance from zero datum

Flowrate (gpm)	Slope (%)	NDED				
		0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
50	2	0.612	0.504	0.428	0.294	0.137
75		0.640	0.557	0.467	0.281	0.281
100		0.659	0.550	0.519	0.425	0.340
125		0.659	0.603	0.542	0.456	0.395
150		0.664	0.607	0.569	0.510	0.462
50	4	0.607	0.611	0.550	0.422	0.284
75		0.719	0.640	0.562	0.416	0.416
100		0.709	0.659	0.607	0.525	0.424
125		0.685	0.666	0.633	0.498	0.422
150		0.640	0.631	0.644	0.475	0.483
50	6	0.750	0.669	0.615	0.515	0.487
75		0.761	0.719	0.675	0.519	0.519
100		0.728	0.722	0.688	0.572	0.559
125		0.713	0.720	0.696	0.629	0.567
150		0.656	0.697	0.663	0.659	0.620
50	8	0.688	0.692	0.653	0.567	0.479
75		0.623	0.671	0.698	0.559	0.559
100		0.661	0.666	0.695	0.662	0.573
125		0.651	0.640	0.646	0.669	0.577
150		0.562	0.627	0.645	0.668	0.628

Table 6.2		Comparison of Values for EDT for Riprap Steps					
Flowrate (gpm)	Slope (%)	NDED					
		0.0-inch	0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
50	2	0.728	0.649	0.532	0.392	0.215	0.01463
75	2	0.738	0.653	0.569	0.472	0.329	0.202
100	2	0.736	0.669	0.591	0.521	0.417	0.391
125	2	0.742	0.681	0.620	0.553	0.454	0.371
150	2	0.745	0.690	0.628	0.595	0.497	0.474
50	4	0.785	0.705	0.628	0.488	0.357	0.170
75	4	0.788	0.723	0.644	0.545	0.438	0.353
100	4	0.785	0.719	0.668	0.613	0.511	0.446
125	4	0.783	0.729	0.680	0.621	0.551	0.493
150	4	0.779	0.734	0.686	0.653	0.560	0.530
50	6	0.824	0.767	0.687	0.585	0.507	0.416
75	6	0.834	0.785	0.725	0.653	0.587	0.498
100	6	0.825	0.782	0.727	0.688	0.611	0.553
125	6	0.821	0.771	0.725	0.706	0.646	0.599
150	6	0.815	0.779	0.709	0.717	0.662	0.616
50	8	0.844	0.790	0.718	0.633	0.537	0.404
75	8	0.843	0.800	0.747	0.698	0.619	0.564
100	8	0.840	0.803	0.753	0.719	0.656	0.609
125	8	0.823	0.798	0.751	0.719	0.651	0.641
150	8	0.806	0.773	0.740	0.730	0.685	0.715

Flowrate (gpm)	Slope (%)	NDED				
		0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
50	2	0.507	0.522	0.536	0.529	0.541
75	2	0.572	0.553	0.516	0.516	0.534
100	2	0.576	0.511	0.553	0.536	0.525
125	2	0.547	0.563	0.570	0.550	0.560
150	2	0.567	0.597	0.569	0.577	0.555
50	4	0.525	0.643	0.652	0.638	0.710
75	4	0.681	0.682	0.641	0.605	0.654
100	4	0.675	0.678	0.659	0.636	0.584
125	4	0.611	0.669	0.682	0.567	0.549
150	4	0.756	0.756	0.732	0.556	0.575
50	6	0.809	0.825	0.711	0.667	0.711
75	6	0.811	0.792	0.765	0.707	0.711
100	6	0.822	0.799	0.795	0.672	0.690
125	6	0.845	0.808	0.789	0.707	0.682
150	6	0.839	0.816	0.817	0.737	0.740
50	8	0.823	0.811	0.751	0.737	0.827
75	8	0.866	0.844	0.818	0.717	0.724
100	8	0.853	0.849	0.837	0.781	0.705
125	8	0.835	0.837	0.842	0.800	0.711
150	8	0.857	0.853	0.840	0.823	0.720

Flowrate (gpm)	Slope (%)	NDED					
		0.0-inch	0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
50	2	0.607	0.605	0.586	0.627	0.634	0.671
75	2	0.609	0.634	0.589	0.619	0.349	0.666
100	2	0.599	0.613	0.605	0.636	0.647	0.648
125	2	0.607	0.616	0.604	0.654	0.674	0.690
150	2	0.634	0.630	0.653	0.653	0.668	0.677
50	4	0.708	0.722	0.679	0.726	0.742	0.809
75	4	0.703	0.714	0.713	0.748	0.754	0.756
100	4	0.707	0.733	0.699	0.728	0.745	0.754
125	4	0.704	0.717	0.711	0.734	0.747	0.763
150	4	0.694	0.701	0.701	0.716	0.771	0.749
50	6	0.821	0.809	0.774	0.810	0.798	0.792
75	6	0.785	0.800	0.769	0.817	0.817	0.829
100	6	0.778	0.791	0.795	0.803	0.816	0.806
125	6	0.755	0.805	0.755	0.779	0.793	0.806
150	6	0.771	0.769	0.698	0.781	0.802	0.815
50	8	0.808	0.804	0.797	0.824	0.826	0.893
75	8	0.832	0.834	0.785	0.822	0.829	0.836
100	8	0.796	0.814	0.788	0.825	0.834	0.837
125	8	0.752	0.775	0.776	0.811	0.833	0.832
150	8	0.730	0.742	0.762	0.795	0.809	0.802

Several conclusions can be drawn from the comparison of these results. Generally, the value for NDED, both EDT and EDV, increases with the increase of culvert slope. This trend seems plausible since the velocity head at the culvert outlet increases with slope more rapidly than the corresponding value in the testing channel. The difference between the energy at the outlet and channel must increase to account for the divergence of the velocity heads. Examination of the EDV from left to right in the table for all of the tested configurations shows an increase in the value of non-dimensional energy loss in most cases. The opposite occurs with the EDT in terms of total energy. Therefore, progressively increasing the riprap steps heights effectively increased the attenuation of dynamic energy. By inspecting only the EDT, the ‘pooling’ effect disguised the increase in step height efficiency. The values for average flow depths in Zone 2 and at the culvert outlet are displayed in Tables 6.5 and 6.6, cast acrylic steps and riprap steps, respectively. The first value for the test culvert was obtained from Section 5.5 and is the depth at the outlet. The depths for each configuration are the average depths, established in the testing channel over the stone bed in Zone 2. Performance judgments cannot be based solely on the basis of non-dimensional energy difference. The effect of entire rock bed, including geometry and rock mobility plays a large role in energy attenuation of flows.

In the field however, the downstream rock would not be held in place rigidly, as in the laboratory model, and incipient motion and failure of the supporting bed material would likely occur under high velocity flows. The mobility of the rock in the field would significantly effect the energy attenuation and maintenance and should be investigated in future studies.

Flowrate (gpm)	Slope (%)	Average Flow Depth (mm)					
		Culvert Outlet	Zone 2 of Test Channel				
			0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
50	2	36.2	13.6	14.4	15.2	14.8	14.3
75	2	43.9	20.3	19.9	17.2	17.2	18.2
100	2	51.0	25.6	20.3	23.3	21.9	21.2
125	2	56.5	25.4	26.9	26.1	24.5	25.3
150	2	61.0	27.7	29.2	27.8	28.6	27.9
50	4	31.5	9.83	14.8	15.5	13.6	14.9
75	4	39.0	22.4	21.4	17.4	15.6	18.7
100	4	45.1	23.2	25.1	22.9	20.9	17.8
125	4	50.5	21.9	27.1	28.7	19.5	18.6
150	4	55.8	77.5	64.2	45.8	20.7	22.8
50	6	28.4	24.7	24.2	12.5	11.0	14.0
75	6	34.5	33.3	25.7	20.6	15.4	15.6
100	6	40.5	50.7	33.8	32.6	16.9	19.1
125	6	45.8	60.4	42.4	41.8	23.5	21.4
150	6	50.2	91.9	65.1	67.4	29.3	29.7
50	8	27.3	43.6	28.2	13.6	12.6	15.5
75	8	33.2	73.5	50.0	31.5	14.8	15.2
100	8	38.7	78.6	63.8	43.7	23.5	17.1
125	8	44.3	90.8	80.6	67.7	32.5	20.6
150	8	49.1	129.1	94.1	79.4	52.1	26.3

Table 6.6 Flow Depth at Culvert Outlet and Testing Channel - Riprap Steps								
Flowrate (gpm)	Slope (%)	Average Flow Depth (mm)						
		Culvert Outlet	Zone 2 of Test Channel					
			0.0-inch	0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
50	2	36.2	24.0	23.3	20.0	31.2	35.9	50.9
75	2	43.9	27.4	29.1	23.7	37.5	42.8	57.6
100	2	51.0	28.7	31.4	29.7	37.5	42.6	42.8
125	2	56.5	32.8	34.7	32.3	40.4	49.2	64.4
150	2	61.0	36.5	35.7	37.1	41.0	56.8	63.1
50	4	31.5	23.9	25.8	18.5	35.2	37.5	51.8
75	4	39.0	26.4	29.4	26.8	38.6	43.8	56.7
100	4	45.1	30.1	33.4	28.4	36.6	46.4	58.0
125	4	50.5	32.8	36.0	34.4	42.0	49.5	61.4
150	4	55.8	34.4	37.8	35.9	39.9	54.1	65.9
50	6	28.4	22.9	24.9	15.0	35.6	36.1	50.8
75	6	34.5	23.9	28.3	21.1	37.3	37.9	55.8
100	6	40.5	27.7	31.1	32.6	35.8	43.9	60.1
125	6	45.8	30.5	34.4	27.3	37.3	44.5	57.4
150	6	50.2	33.2	32.7	24.8	39.4	49.9	63.8
50	8	27.3	21.9	24.6	21.9	32.5	35.5	49.9
75	8	33.2	24.9	28.0	20.2	33.9	39.6	51.0
100	8	38.7	26.1	30.7	24.6	35.1	40.7	53.8
125	8	44.3	26.2	30.3	29.8	37.7	48.8	47.8
150	8	49.1	26.6	26.2	28.7	37.6	43.1	48.8



## 6.2 Froude Number and Non-Dimensional Energy Difference

Graphical representation of hydraulic performance measurements were desired to support further understanding of the test results obtained. The plots were made non-dimensional to provide the best comparative presentation of the experiments formed. Froude number is plotted versus non-dimensional energy difference, (EDT). At first, the plots seemed inconclusive but once the data was separated by slope, several interesting conclusions could be made. For the following discussion, refer to the Figures listed below:

- Figure 6.1 Froude Number at Culvert Outlet vs. EDT for 0.5-inch Cast Acrylic Step
- Figure 6.2 Froude Number at Culvert Outlet vs. EDT for 1.0-inch Cast Acrylic Step
- Figure 6.3 Froude Number at Culvert Outlet vs. EDT for 1.5-inch Cast Acrylic Step
- Figure 6.4 Froude Number at Culvert Outlet vs. EDT for 2.0-inch Cast Acrylic Step
- Figure 6.5 Froude Number at Culvert Outlet vs. EDT for 2.5-inch Cast Acrylic Step
- Figure 6.6 Froude Number at Culvert Outlet vs. EDT for 0.0-inch Riprap Step
- Figure 6.7 Froude Number at Culvert Outlet vs. EDT for 0.5-inch Riprap Step
- Figure 6.8 Froude Number at Culvert Outlet vs. EDT for 1.0-inch Riprap Step
- Figure 6.9 Froude Number at Culvert Outlet vs. EDT for 1.5-inch Riprap Step
- Figure 6.10 Froude Number at Culvert Outlet vs. EDT for 2.0-inch Riprap Step
- Figure 6.11 Froude Number at Culvert Outlet vs. EDT for 2.5-inch Riprap Step

Simply allowing the flowing water to expand and collect, or pool, in an area is one form of energy dissipation. The high velocity flow from the culvert outlet enters an area of low velocity flow. Due to complex flow characteristics including reversed flow, re-circulation, etc, energy is dissipated and exits at a lower velocity flow. Under conditions of supercritical flow upstream, a hydraulic jump may be forced by the pooling flow, adding to the energy dissipation. By introducing steps, smooth cast acrylic or rough riprap, into the path of the flow, Zone 1 becomes a pooling area.

The majority of the energy attenuation in Figures 6.1 through 6.5 was due to the impact of the flow on the step, causing turbulence. After having observed the plotted data pattern for each particular culvert slope and step height in Figures 6.1 through 6.11, one may or may not have distinguished a defined 'arc' shape or trend depending on the degree of energy dissipation in that instance. A more defined, compact 'arc' pattern indicated less energy. A less defined or less compact 'arc' indicated more energy dissipation. In Figures 6.1 and 6.2, four less visible, more compact, arcs are formed. The higher cast acrylic step heights, in Figures 6.4 and 6.5, produced more visible and less compact arcs. Expansion of the exit jet from the outlet of the culvert onto the apron floor, across Zone 1, and then impacting against the step of Zone 2 helped reduce the energy in the flow. As the step height increased,

pooling disguised the increase in energy dissipation and gave the appearance of the lower steps having the greatest amount of energy dissipation and the higher steps producing the lowest amount of energy dissipation.

In Figures 6.6 through 6.11, energy attenuation was due to the impact of the flow on the step as well as the additional turbulence created by the roughened riprap surface. The flow was greatly affected by the addition of the roughened test channel surface. Regarding riprap steps, the greatest energy difference was seen in Figure 6.6 with the 0.0-inch equivalent riprap step and regressing to the least energy difference as seen in Figure 6.11 with the 2.5-inch equivalent riprap step. The effect of pooling in Zone 1 decreased dramatically due to the wave action created by the roughened test channel surface. The 0.5-inch equivalent riprap step produced a less visible arc whereas the 2.5-inch equivalent riprap step produced a more visible arc.

Overall, the riprap steps produced the greatest range of energy difference.

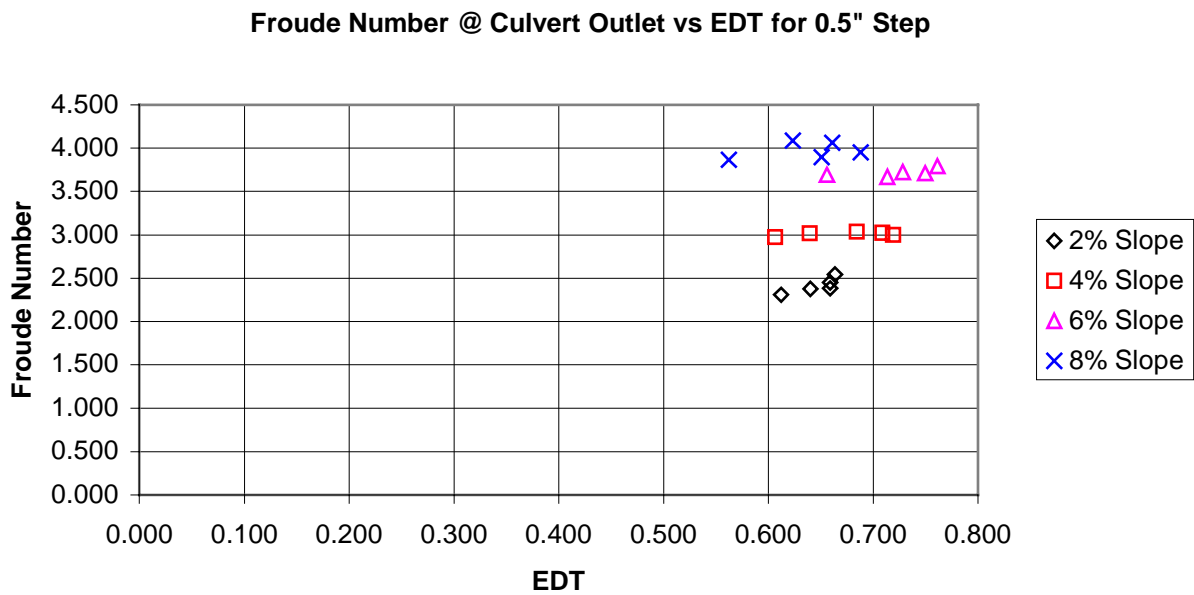


Figure 6.1 Froude Number at Culvert Outlet vs. EDT for 0.5-inch Cast Acrylic Step

**Froude Number @ Culvert Outlet vs EDT for 1.0" Step**

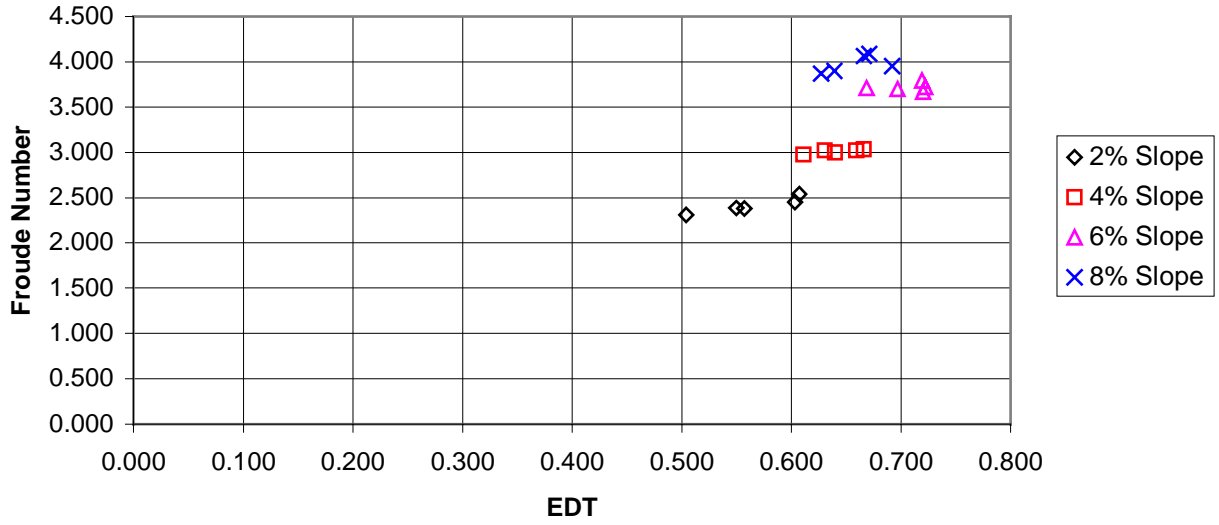


Figure 6.2 Froude Number at Culvert Outlet vs. EDT for 1.0-inch Cast Acrylic Step

**Froude Number @ Culvert Outlet vs EDT for 1.5" Step**

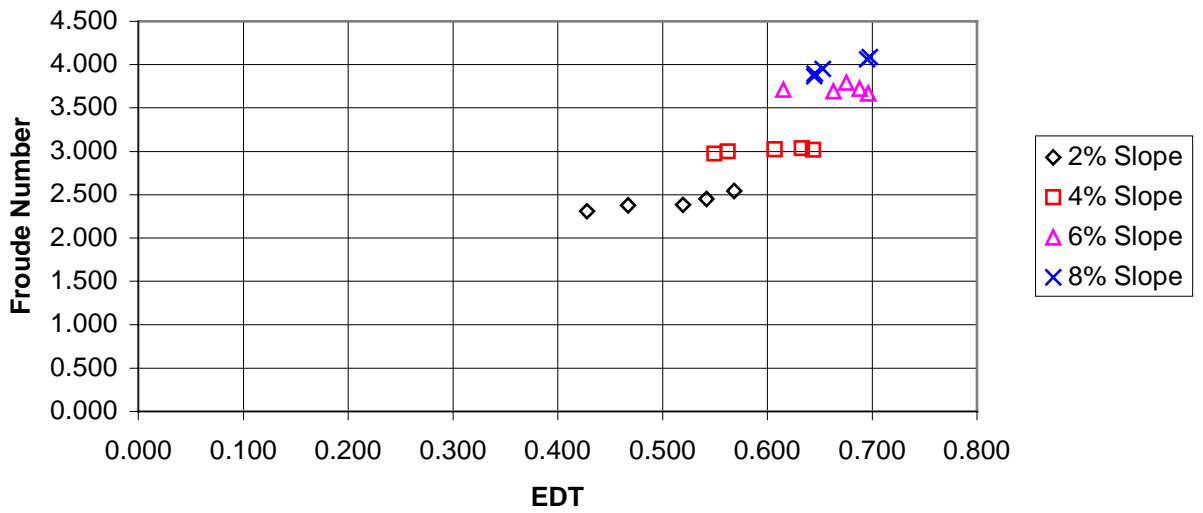


Figure 6.3 Froude Number at Culvert Outlet vs. EDT for 1.5-inch Cast Acrylic Step

**Froude Number @ Culvert Outlet vs EDT for 2.0" Step**

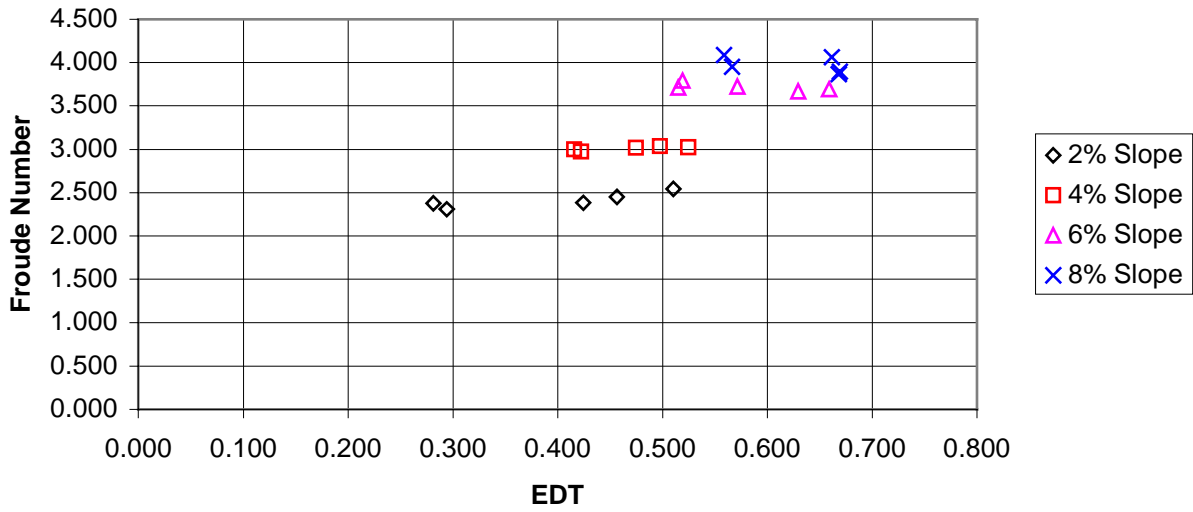


Figure 6.4 Froude Number at Culvert Outlet vs. EDT for 2.0-inch Cast Acrylic Step

**Froude Number @ Culvert Outlet vs EDT for 2.5" Step**

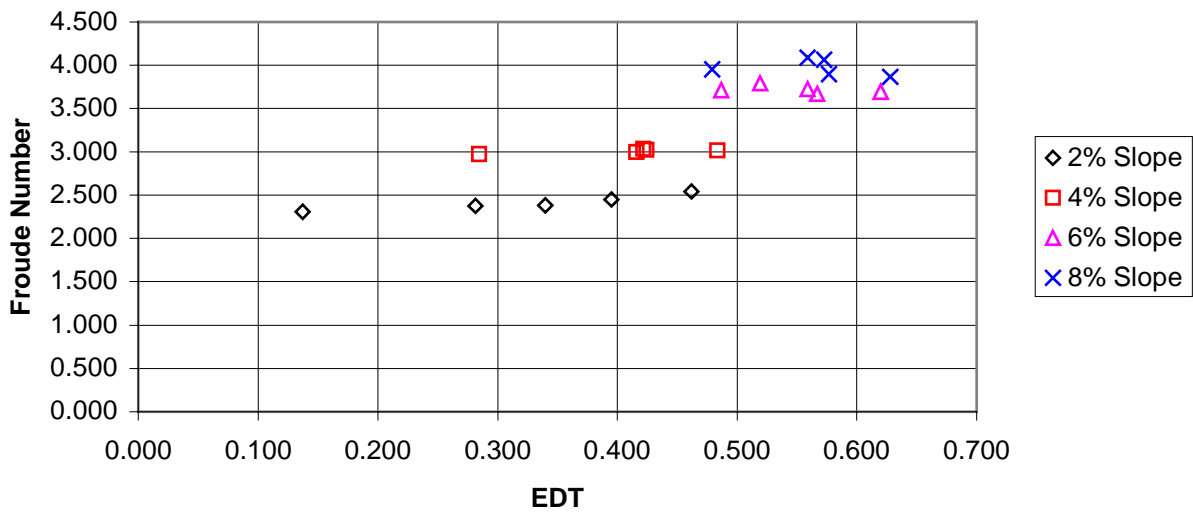


Figure 6.5 Froude Number at Culvert Outlet vs. EDT for 2.5-inch Cast Acrylic Step

Froude Number @ Culvert Outlet vs EDT for 0.0" Riprap Step

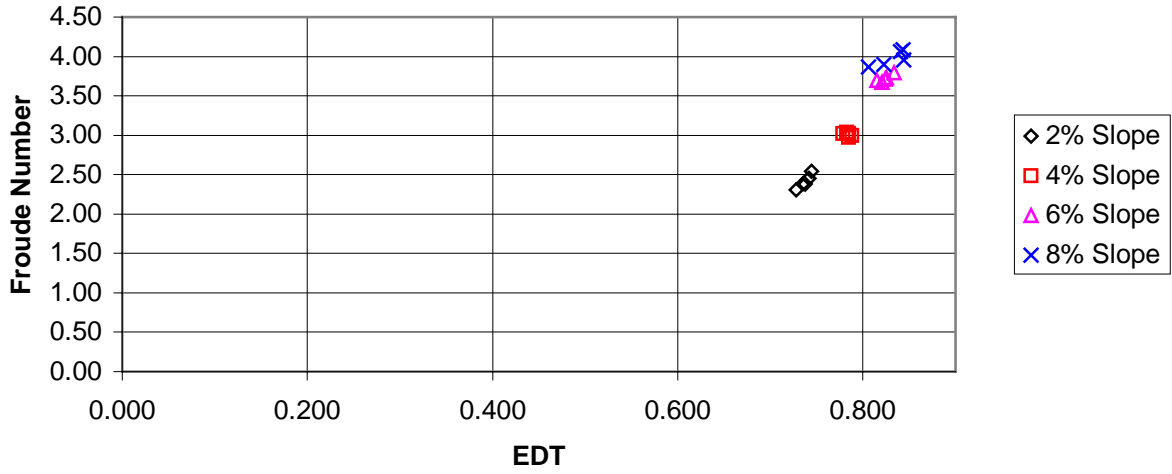


Figure 6.6 Froude Number at Culvert Outlet vs. EDT for 0.0-inch Riprap Step

Froude Number @ Culvert Outlet vs EDT for 0.5" Riprap Step

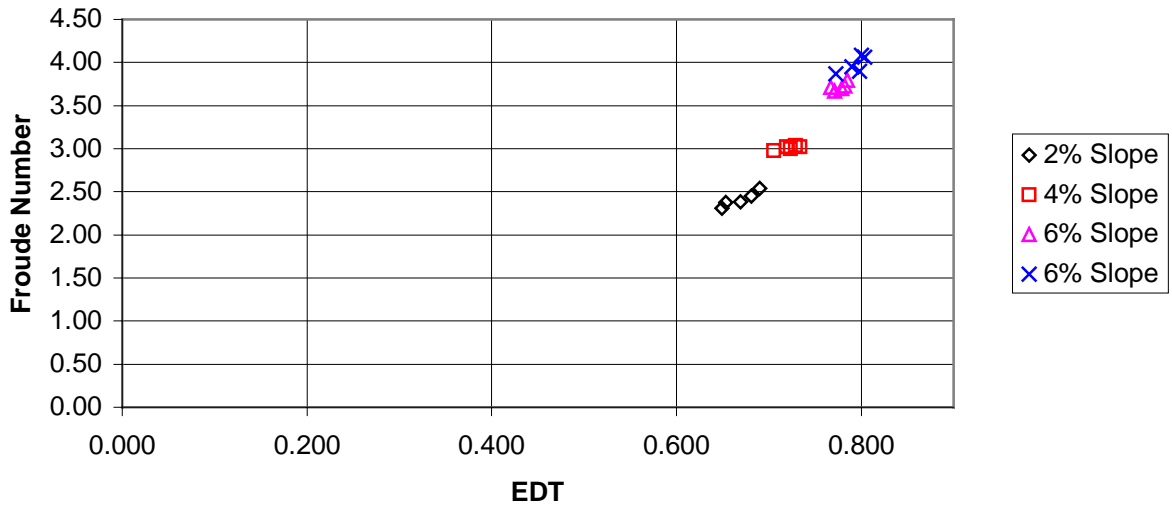


Figure 6.7 Froude Number at Culvert Outlet vs. EDT for 0.5-inch Riprap Step

Froude Number @ Culvert Outlet vs EDT for 1.0" Riprap Step

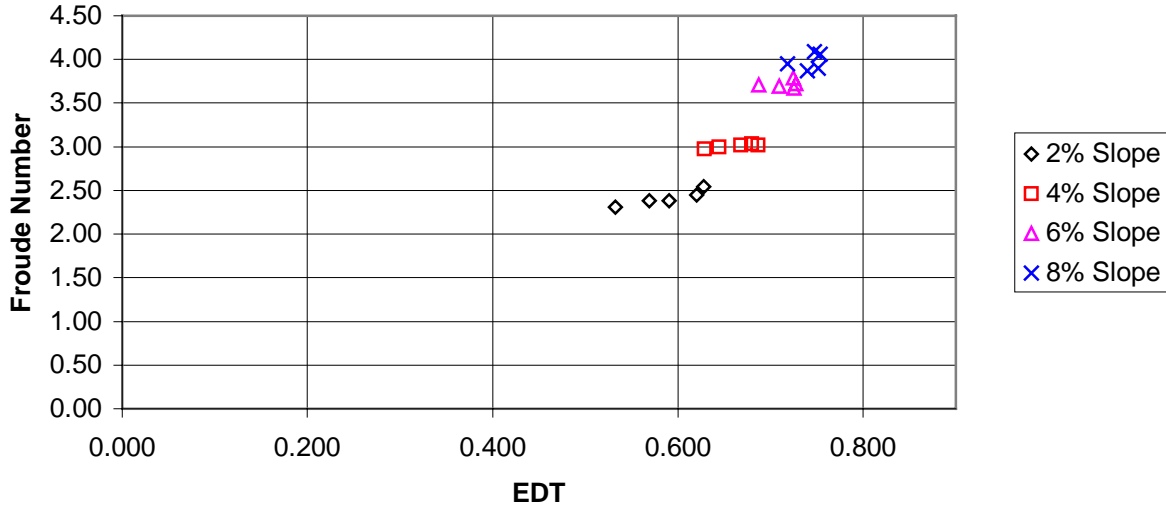


Figure 6.8 Froude Number at Culvert Outlet vs. EDT for 1.0-inch Riprap Step

Froude Number @ Culvert Outlet vs EDT for 1.5" Riprap Step

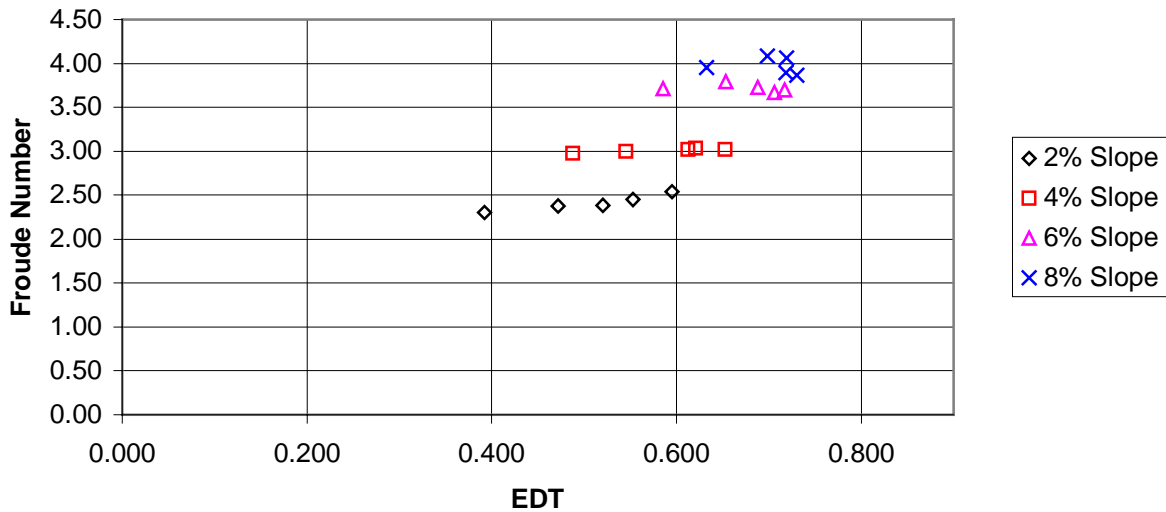


Figure 6.9 Froude Number at Culvert Outlet vs. EDT for 1.5-inch Riprap Step

Froude Number @ Culvert Outlet vs EDT for 2.0" Riprap Step

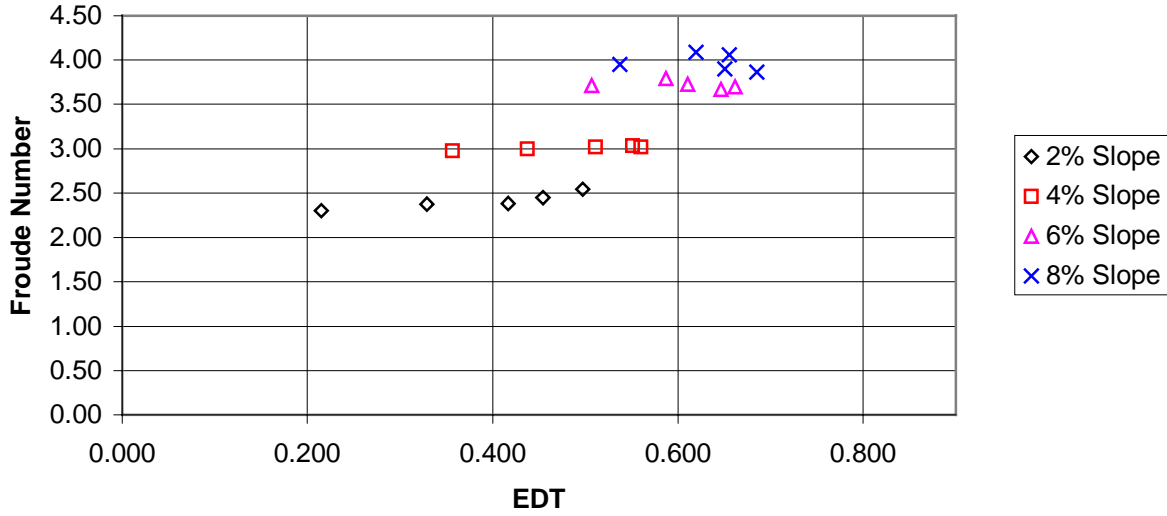


Figure 6.10 Froude Number at Culvert Outlet vs. EDT for 2.0-inch Riprap Step

Froude Number @ Culvert Outlet vs EDT for 2.5" Riprap Step

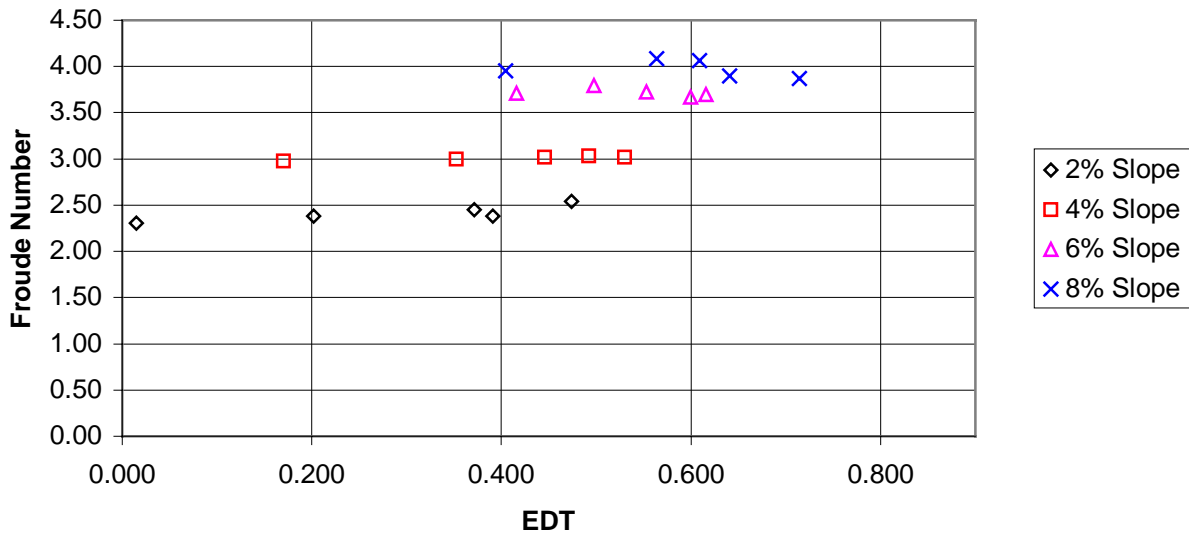


Figure 6.11 Froude Number at Culvert Outlet vs. EDT for 2.5-inch Riprap Step

### 6.3 Energy Dissipation Performance Parameter

The next conclusion, drawn from the experimental data in evaluation of the various step types and heights was based on the deviation from the natural energy grade line, established in Section 5.19. It was decided to present the data in graphical and tabular form in order to draw conclusions about the performance of each step. The difference between the elevation of the natural energy grade line and the total energy, calculated in the testing channel, was non-dimensionalized and termed the energy difference performance parameter (EDPP). One variable used to create this non-dimensional parameter was the magnitude of the natural energy grade line deviation from the horizontal at the culvert outlet, shown as E3 in Zone 2 in Figure 6.12 (not to scale). The values for E3 are shown for each culvert slope in Table 6.7.

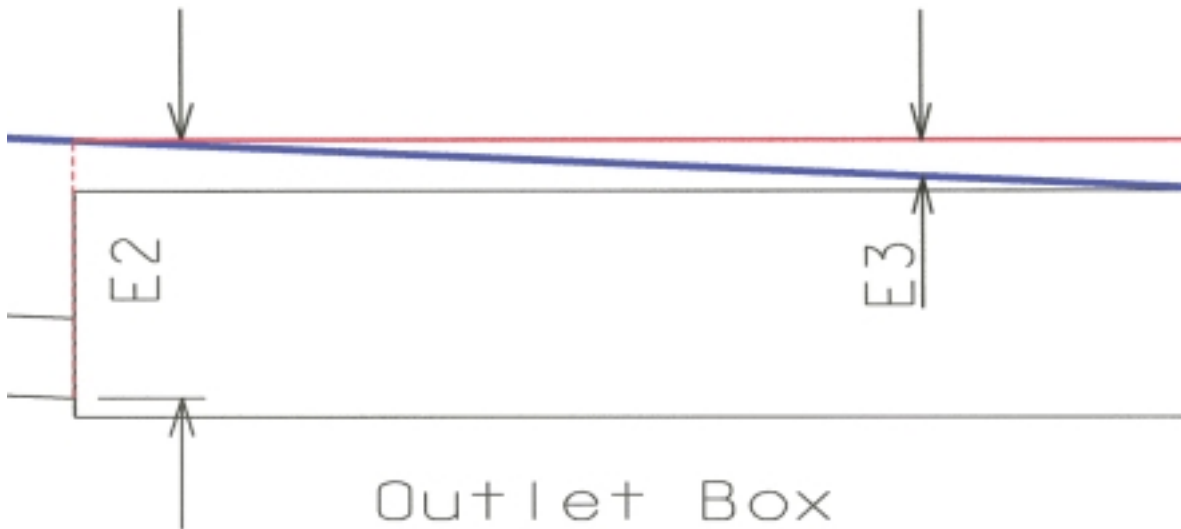


Figure 6.12 Schematic of E3, Value for Establishing the Energy Dissipation Performance Parameter

Slope (%)	E3 (mm)
2	15.7
4	31.4
6	47.1
8	62.9



The following expression was used to determine the values for the energy dissipation performance parameter.

$$EDPP = \frac{E2 - E_f}{E3} \quad (6.1)$$

Where:

*EDPP* = Energy Dissipation Performance Parameter

*E2* = Elevation of the natural energy grade line at the culvert outlet

*E<sub>f</sub>* = Total average energy from the three-point gage at the center of Zone 2 (EGL)

*E3* = Values from Table 6.7 calculated for the center of Zone 2

The values of EDPP were then organized for comparison. Their values are shown in Table 6.8 for cast acrylic and in Table 6.9 for riprap steps. Positive values indicate that the energy in the flow has been decreased below the natural energy grade line assumption established at the culvert inlet. Negative values, in blue, indicate no effect in decreasing the energy of the flow below the assumed natural value at the culvert outlet.

Cast Acrylic Steps						
Slope (%)	Flowrate (gpm)	0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
		EDPP				
2	50	2.51	1.77	1.25	0.337	-0.507
2	75	3.28	2.47	1.71	0.094	0.094
2	100	4.35	3.22	2.90	1.91	1.03
2	125	5.53	4.84	4.23	3.20	2.46
2	150	7.16	6.50	5.82	4.99	4.11
4	50	0.905	0.897	0.631	0.129	-0.236
4	75	1.70	1.29	0.897	0.095	0.095
4	100	2.13	1.77	1.44	0.908	0.266
4	125	2.53	2.39	2.15	1.16	0.619
4	150	3.00	2.96	3.06	1.82	1.70
6	50	0.817	0.558	0.322	-0.064	-0.197
6	75	1.06	0.865	0.665	-0.047	-0.047
6	100	1.20	1.17	1.00	0.385	0.255
6	125	1.58	1.59	1.41	1.01	0.634
6	150	1.72	1.96	1.73	1.70	1.44
8	50	0.349	0.360	0.256	0.007	-0.144
8	75	0.197	0.348	0.437	-0.086	-0.086
8	100	0.501	0.523	0.649	0.504	0.099
8	125	0.731	0.685	0.732	0.852	0.419
8	150	0.690	1.03	1.10	1.22	0.967

Equivalent Riprap Steps							
Slope (%)	Flowrate (gpm)	0.0-inch	0.5-inch	1.0-inch	1.5-inch	2.0-inch	2.5-inch
		EDPP					
2	50	3.30	2.76	1.96	1.007	-0.204	-1.31
2	75	4.06	3.39	2.57	1.76	0.460	-0.603
2	100	5.15	4.46	3.64	2.91	1.83	1.57
2	125	6.56	5.80	5.04	4.36	3.17	2.17
2	150	8.31	7.53	6.78	6.19	4.81	4.29
4	50	1.65	1.32	0.970	0.364	-0.149	-0.684
4	75	2.07	1.72	1.32	0.806	0.235	-0.242
4	100	2.57	2.19	1.82	1.47	0.819	0.402
4	125	3.25	2.85	2.49	2.06	1.55	1.137
4	150	4.17	3.78	3.41	3.14	2.50	2.09
6	50	1.091	0.879	0.622	0.214	-0.094	-0.457
6	75	1.387	1.163	0.889	0.565	0.262	-0.144
6	100	1.714	1.49	1.199	0.996	0.589	0.224
6	125	2.153	1.92	1.62	1.46	1.109	0.828
6	150	2.769	2.53	2.04	2.09	1.72	1.41
8	50	0.809	0.643	0.436	0.198	-0.078	-0.344
8	75	1.006	0.844	0.631	0.439	0.142	-0.066
8	100	1.279	1.119	0.901	0.753	0.477	0.259
8	125	1.553	1.44	1.218	1.077	0.764	0.718
8	150	1.932	1.78	1.61	1.54	1.31	1.43

Plots of the energy dissipation performance parameter were then made for each of the steps shown in Figures 6.13 through 6.23. Each plot shows the energy dissipation performance parameter versus flowrate. The effectiveness of all the steps increased with flowrate and decreased with increasing slope. In general, energy dissipation ‘appeared’ to decrease with increasing step heights. Efficiencies of the steps varied greatly with the highest efficiency at 2% culvert slope, 150 gpm, with a 0.0-inch equivalent riprap step and the lowest efficiency at 2% culvert slope, 50 gpm, with a 2.5-inch equivalent riprap step.

**Energy Dissipation Performance Parameter vs. Flowrate for 0.5-inch Cast Acrylic Step**

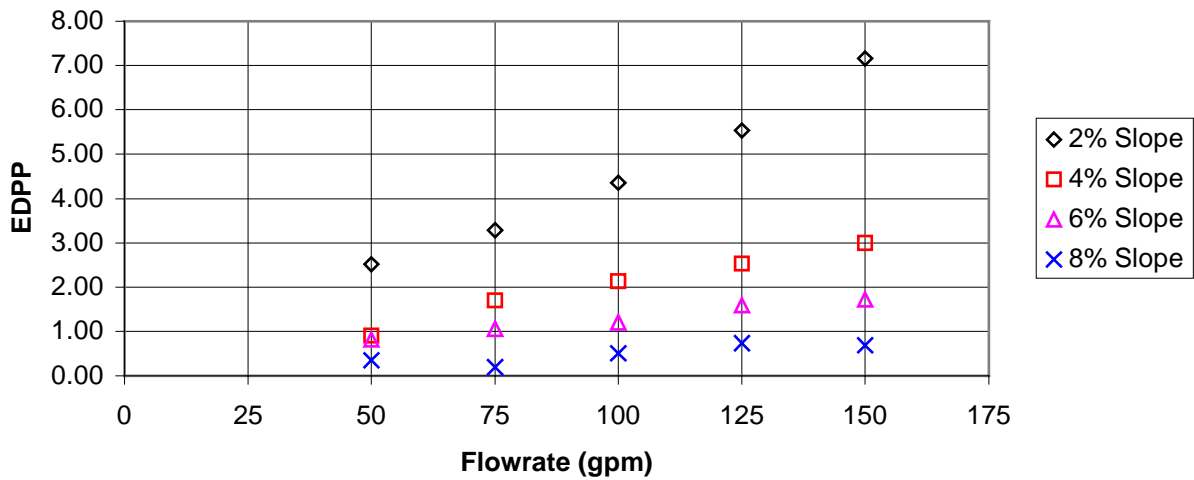


Figure 6.13 EDPP versus Flowrate for 0.5-inch Cast Acrylic Step

**Energy Dissipation Performance Parameter vs. Flowrate for 1.0-inch Cast Acrylic Step**

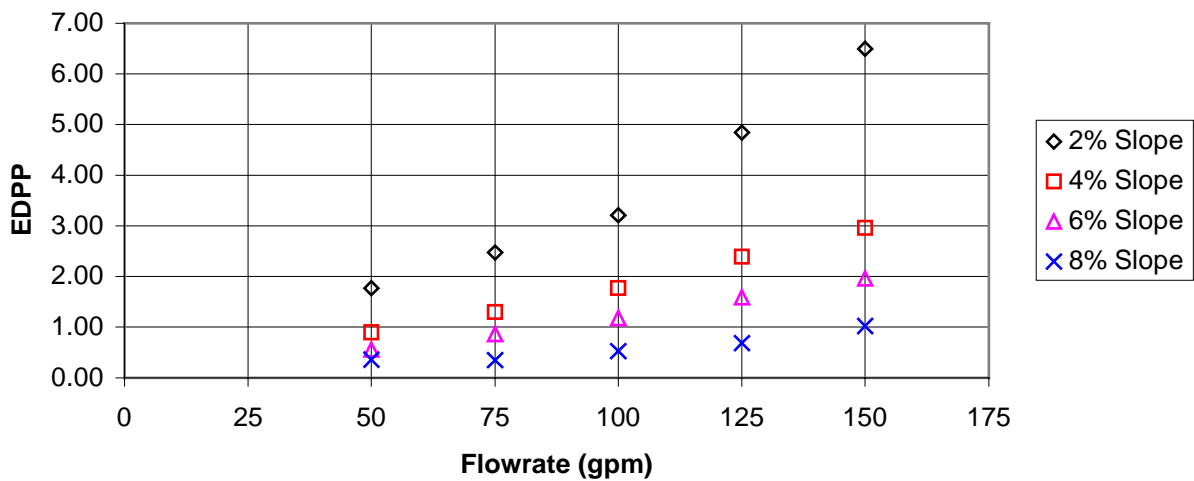


Figure 6.14 EDPP versus Flowrate for 1.0-inch Cast Acrylic Step

**Energy Dissipation Performance Parameter vs. Flowrate for 1.5-inch Cast Acrylic Step**

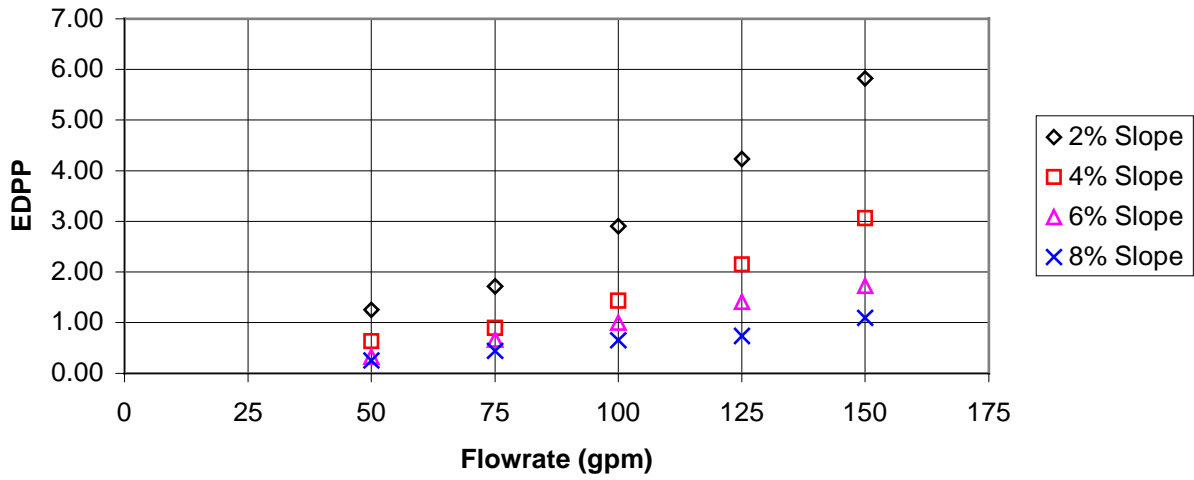


Figure 6.15 EDPP versus Flowrate for 1.5-inch Cast Acrylic Step

**Energy Dissipation Performance Parameter vs. Flowrate for 2.0-inch Cast Acrylic Step**

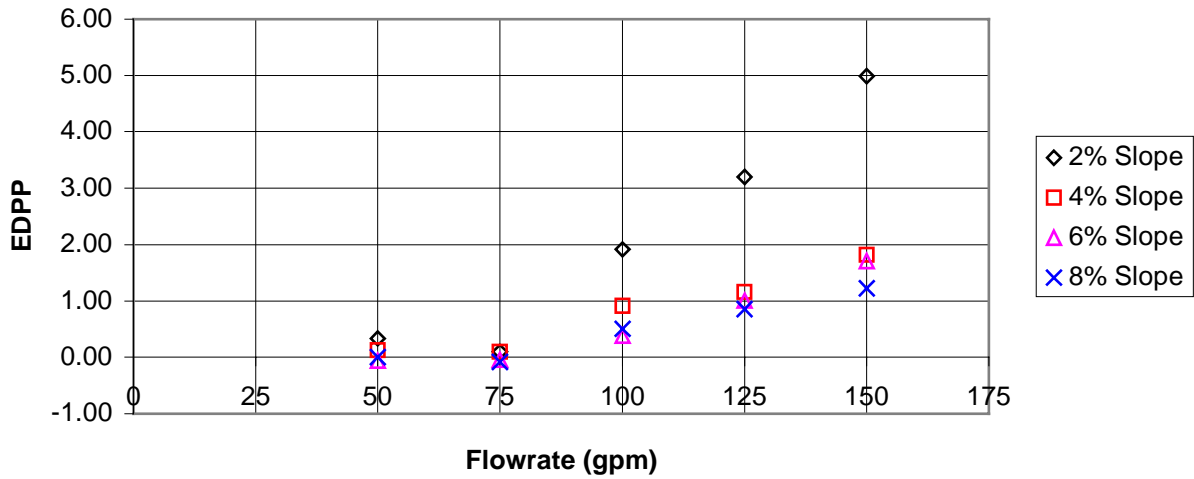


Figure 6.16 EDPP versus Flowrate for 2.0-inch Cast Acrylic Step

**Energy Dissipation Performance Parameter vs. Flowrate for 2.5-inch Cast Acrylic Step**

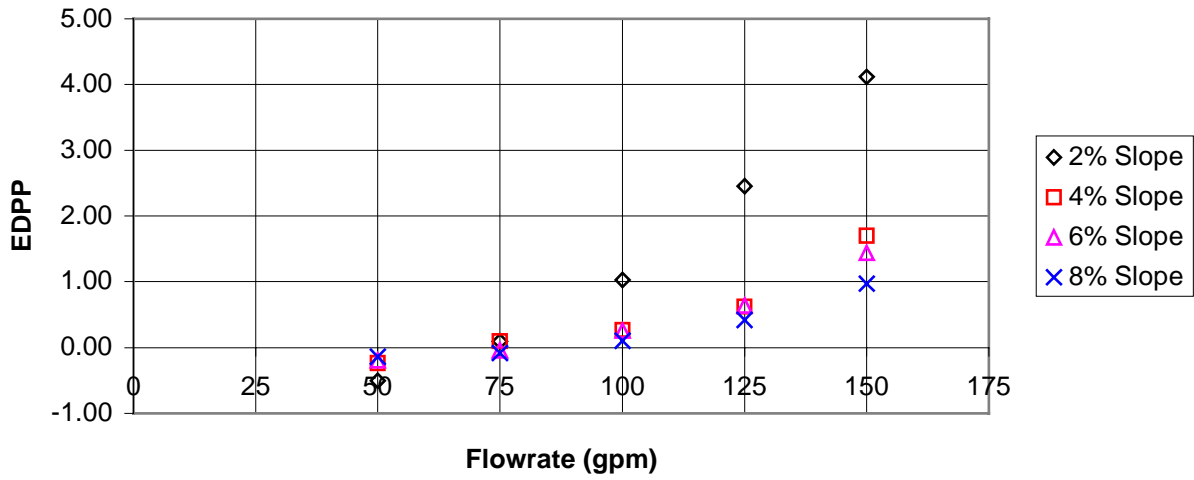


Figure 6.17 EDPP versus Flowrate for 2.5-inch Cast Acrylic Step

**Energy Dissipation Performance Parameter vs Flowrate for 0.0-inch Equivalent Riprap Step**

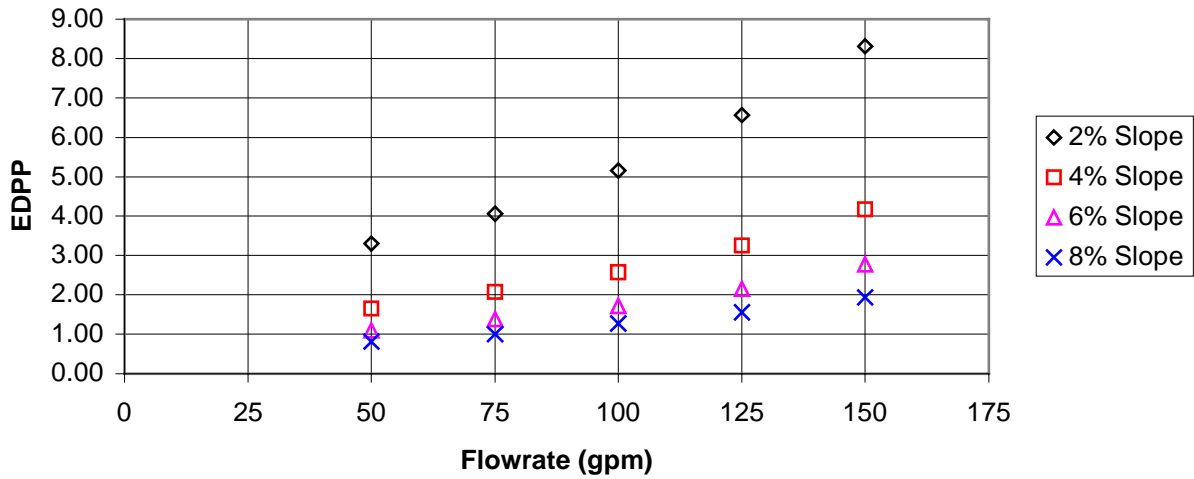


Figure 6.18 EDPP versus Flowrate for 0.0-inch Equivalent Riprap Step

**Energy Dissipation Performance Parameter vs. Flowrate for 0.5-inch Equivalent Riprap Step**

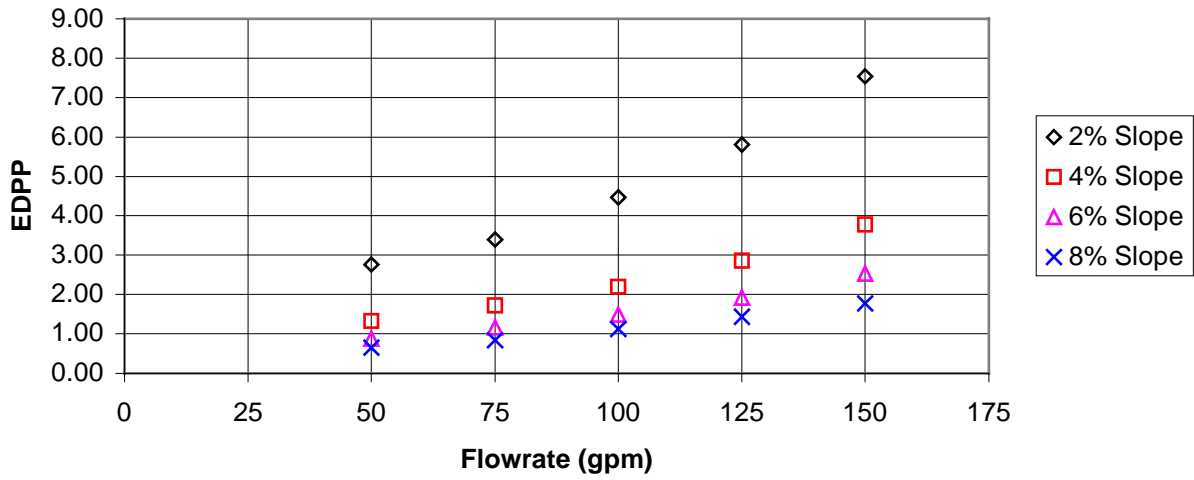


Figure 6.19 EDPP versus Flowrate for 0.5-inch Equivalent Riprap Step

**Energy Dissipation Performance Parameter vs. Flowrate for 0.5-inch Equivalent Riprap Step**

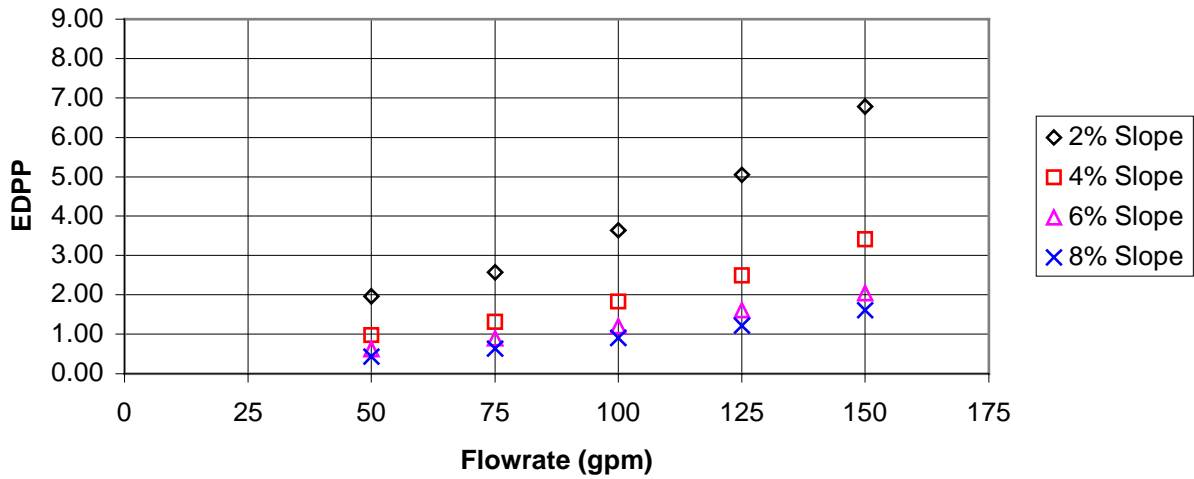


Figure 6.20 EDPP versus Flowrate for 1.0-inch Equivalent Riprap Step

**Energy Dissipation Performance Parameter vs. Flowrate for 1.5-inch Equivalent Riprap Step**

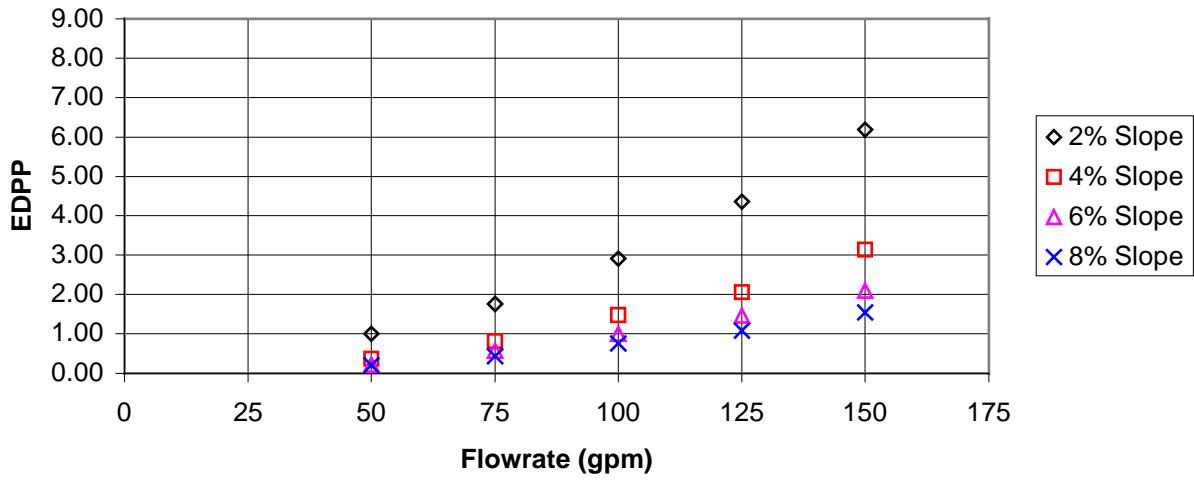


Figure 6.21 EDPP versus Flowrate for 1.5-inch Equivalent Riprap Step

**Energy Dissipation Performance Parameter vs. Flowrate for 2.0-inch Equivalent Riprap Step**

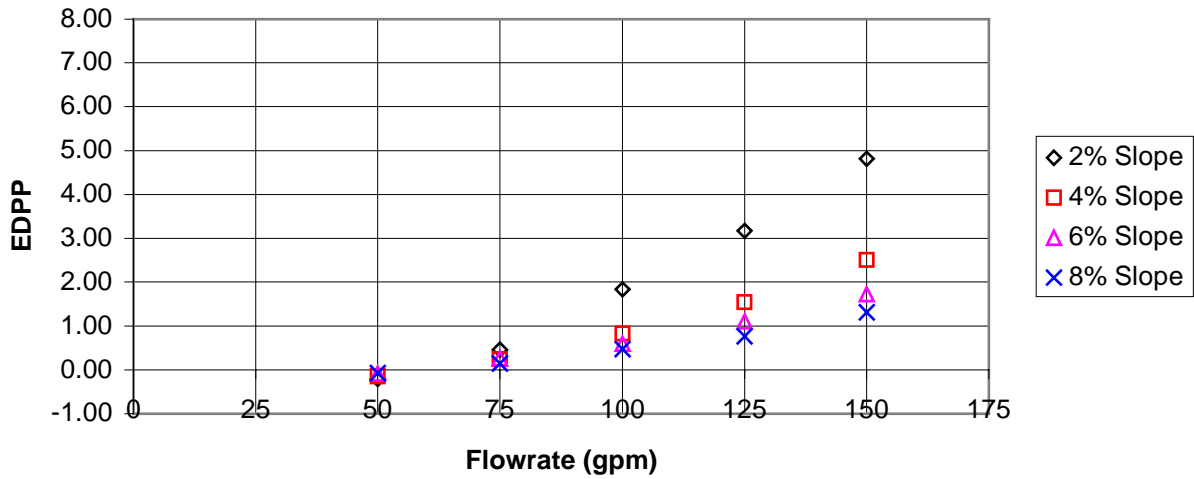


Figure 6.22 EDPP versus Flowrate for 2.0-inch Equivalent Riprap Step

### Energy Dissipation Performance Parameter vs. Flowrate for 2.5-inch Equivalent Riprap Step

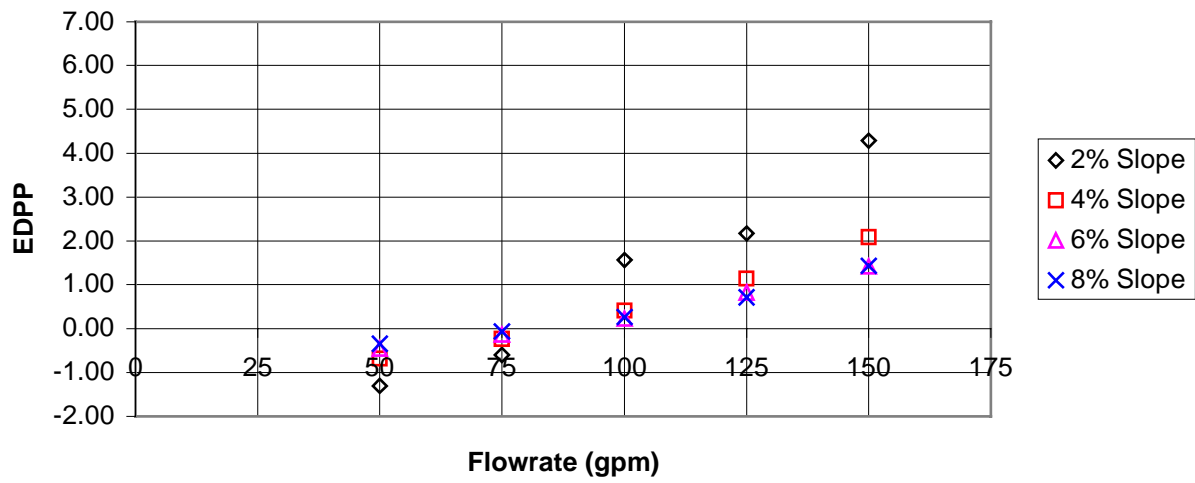


Figure 6.23 EDPP versus Flowrate for 2.5-inch Equivalent Riprap Step



### 6.4 Cast Acrylic and Riprap Step Comparison - EDPP

The purpose of creating two types of steps to be placed in the testing channel was to use the cast acrylic steps with uniform, even features as the standard and compare the riprap step results to the standard. In order to compare the results and prevent confusion, this section will focus on the ‘effective’ riprap step height and not the referenced ‘equivalent’ step height. Refer to Table 5.1 in Section 5.2. It was necessary to compare the energy attenuating efficiency of the riprap step to the standard cast acrylic step. First, plots were constructed for EDPP values for the range of step heights at culvert slopes of 2, 4, 6, and 8 %, at each flowrate in Figures 6.24 through 6.28. Then, plots were constructed for the percent difference between the riprap EDPP values and the cast acrylic EDPP values for three step heights, 0.5-inch (12.7-mm), 1.0-inch (25.4-mm), and 1.5-inch (38.1-mm) in Figures 6.29 through 6.33. As discussed previously in Section 5.2, actual ‘melted’ riprap step heights never actually reached 2.0-inch or 2.5-inch heights. Therefore, comparisons between the standard, cast acrylic steps, and the riprap steps were limited to only three step heights.

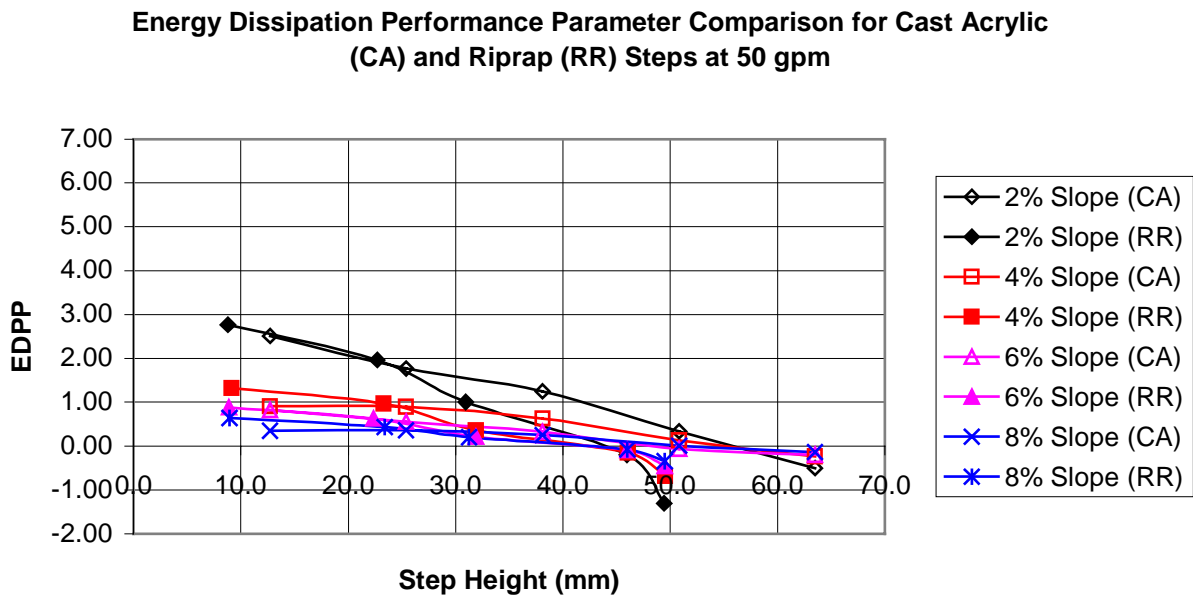


Figure 6.24 EDPP for Cast Acrylic and Riprap Steps at 50 gpm

**Energy Dissipation Performance Parameter Comparison for Cast Acrylic (CA) and Riprap (RR) Steps at 75 gpm**

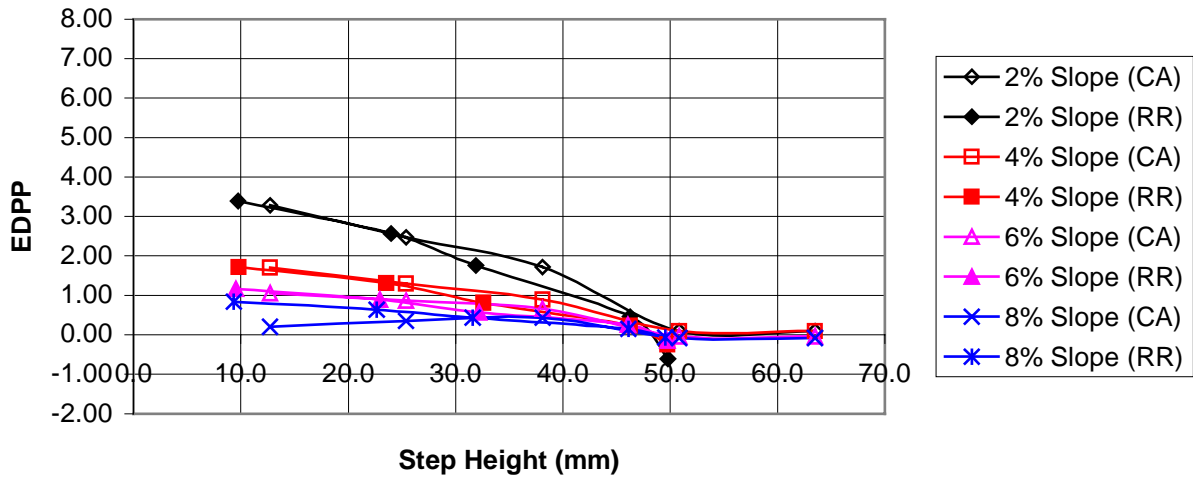


Figure 6.25 EDPP for Cast Acrylic and Riprap Steps at 75 gpm

**Energy Dissipation Performance Parameter Comparison for Cast Acrylic (CA) and Riprap (RR) Steps at 100 gpm**

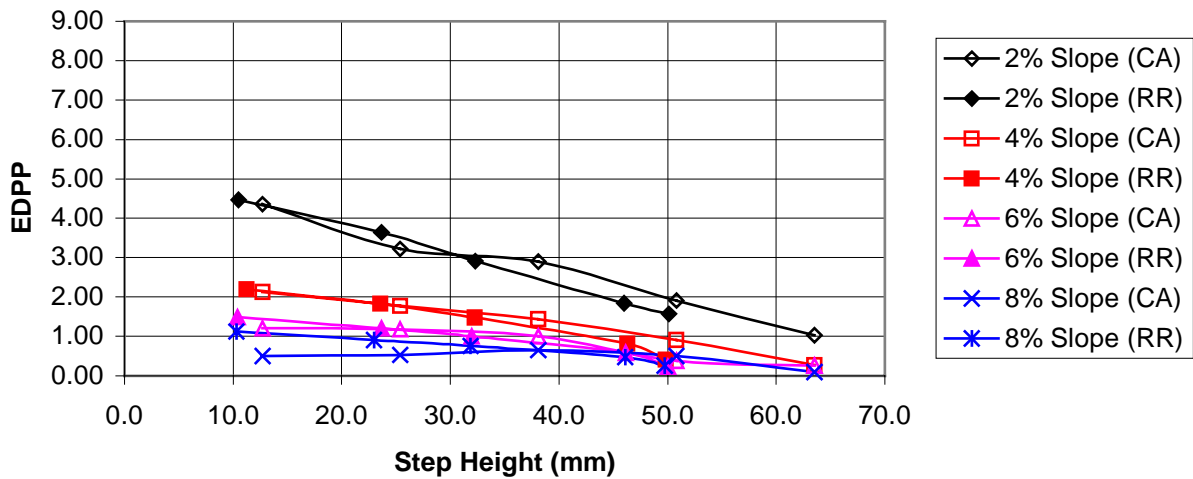


Figure 6.26 EDPP for Cast Acrylic and Riprap Steps at 100 gpm

**Energy Dissipation Performance Parameter Comparison for Cast Acrylic (CA) and Riprap (RR) Steps at 125 gpm**

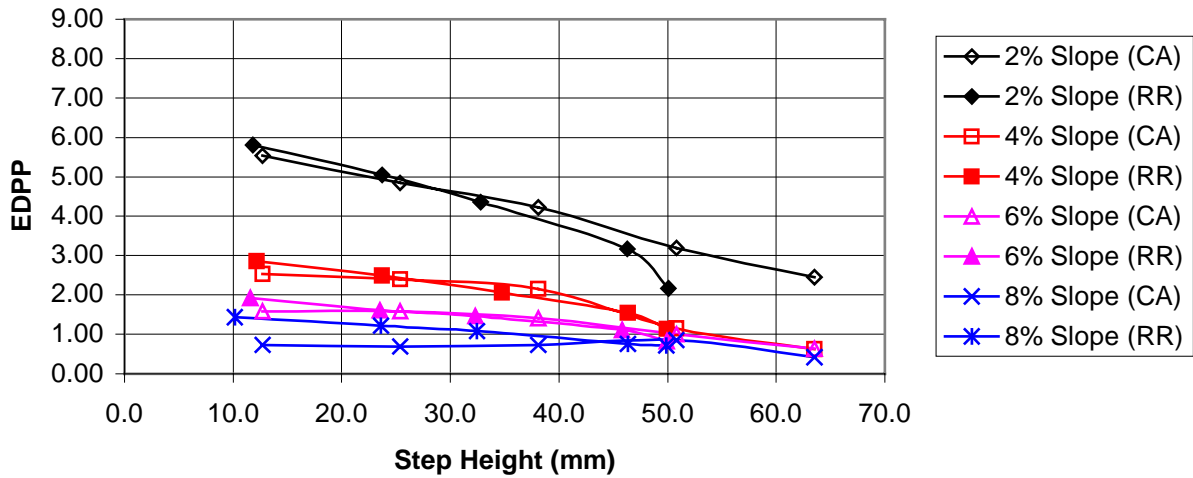


Figure 6.27 EDPP for Cast Acrylic and Riprap Steps at 125 gpm

**Energy Dissipation Performance Parameter Comparison for Cast Acrylic (CA) and Riprap (RR) Steps at 150 gpm**

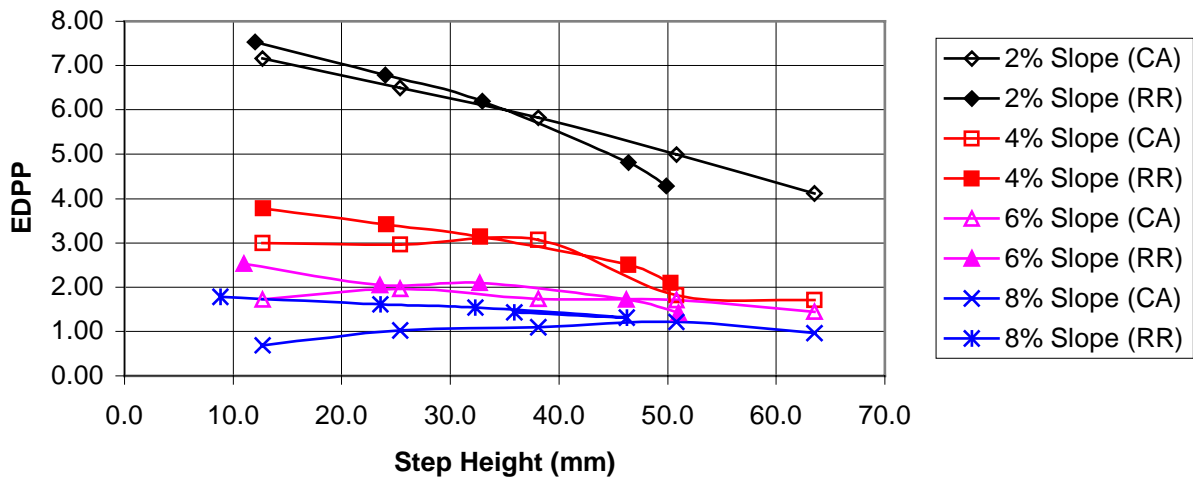


Figure 6.28 EDPP for Cast Acrylic and Riprap Steps at 150 gpm

Riprap Energy Dissipation Performance Parameter % Difference From Cast Acrylic at 50 gpm

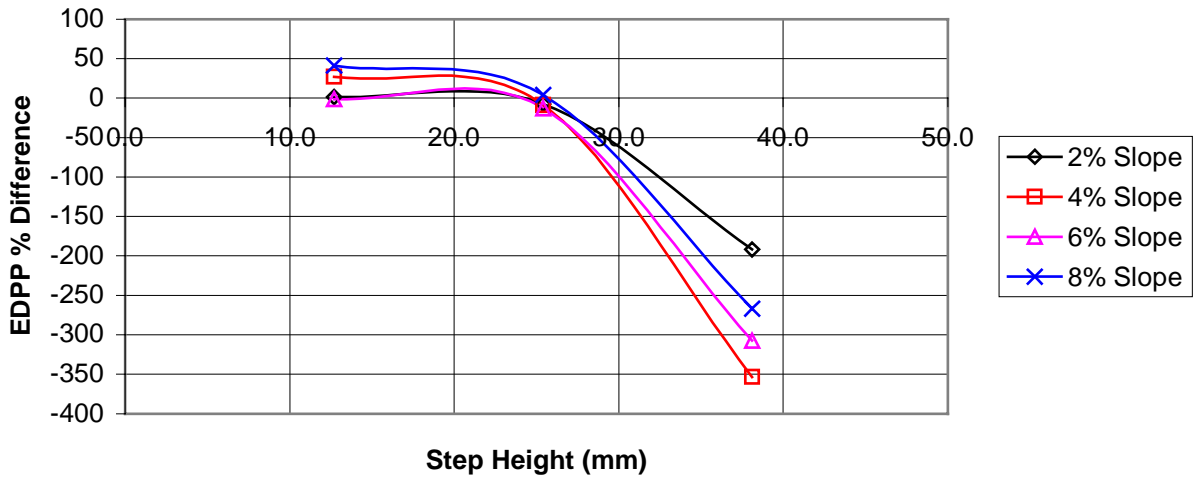


Figure 6.29 Riprap EDPP Percent Difference From Cast Acrylic at 50 gpm

Riprap Energy Dissipation Performance Parameter % Difference From Cast Acrylic at 75 gpm

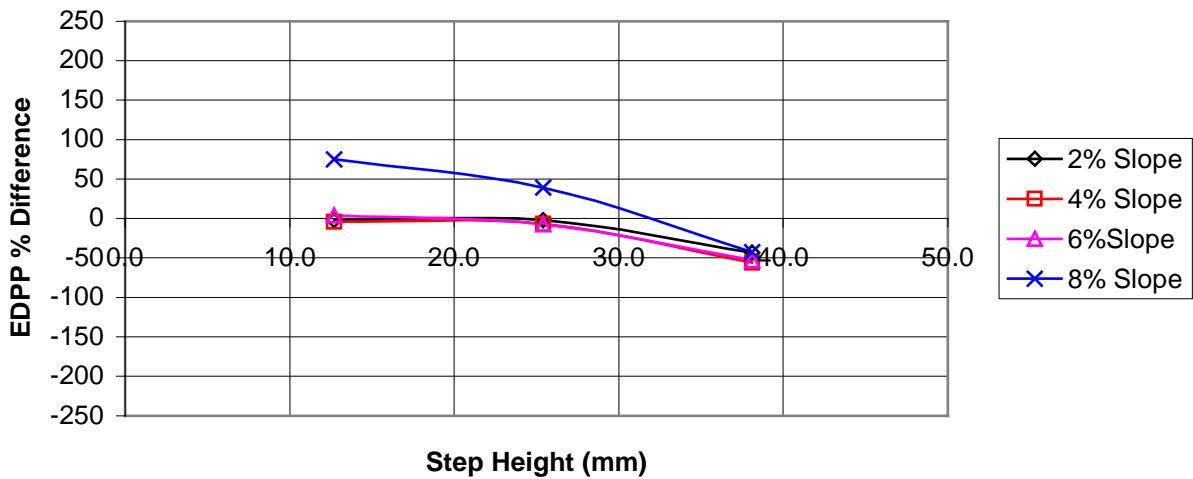


Figure 6.30 Riprap EDPP Percent Difference From Cast Acrylic at 75 gpm

**Riprap Energy Dissipation Performance Parameter % Difference From Cast Acrylic at 100 gpm**

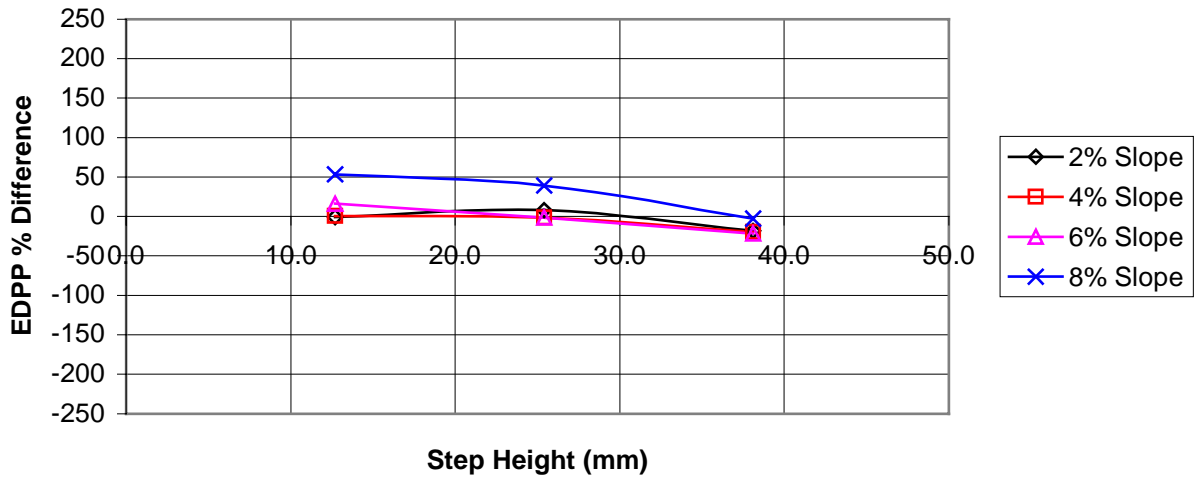


Figure 6.31 Riprap EDPP Percent Difference From Cast Acrylic at 100 gpm

**Riprap Energy Dissipation Performance Parameter % Difference From Cast Acrylic at 125 gpm**

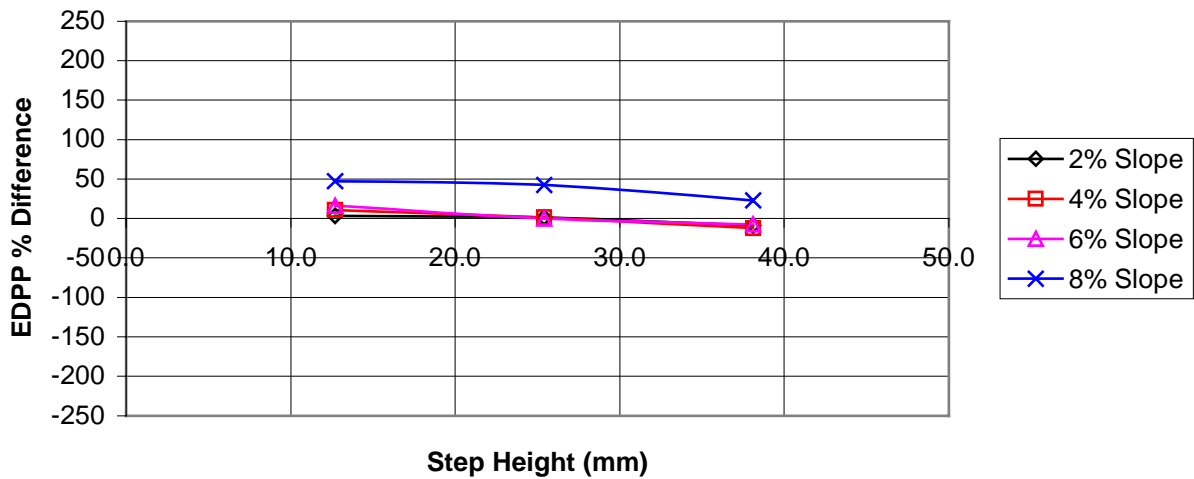


Figure 6.32 Riprap EDPP Percent Difference From Cast Acrylic at 125 gpm

**Riprap Energy Dissipation Performance Parameter % Difference From Cast Acrylic at 150 gpm**

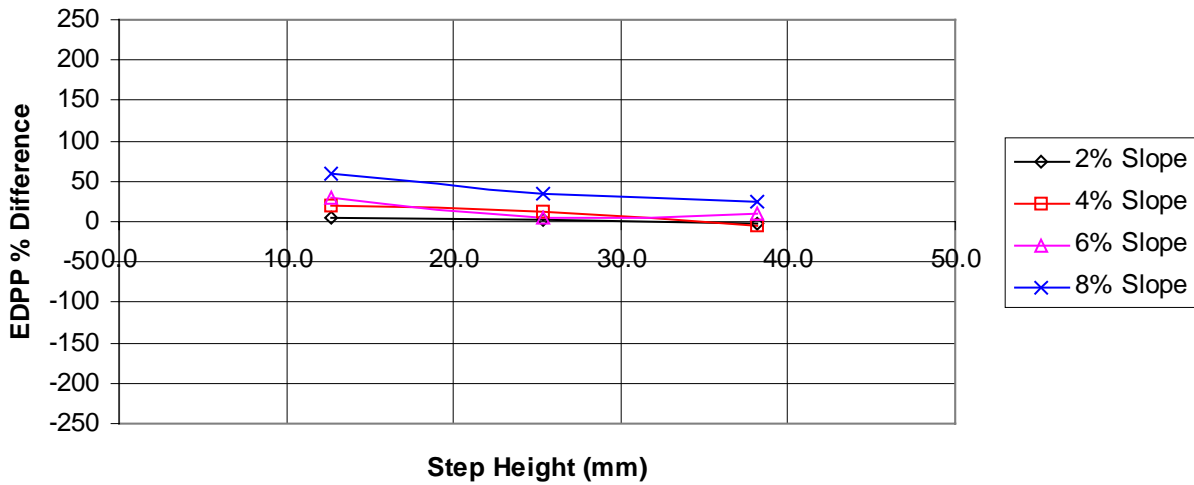


Figure 6.33 Riprap EDPP Percent Difference From Cast Acrylic at 150 gpm

In Figures 6.24 through 6.28, several EDPP culvert equivalent slope lines intersected. The intersection of these lines indicated a change of the more efficient energy dissipating step, either cast acrylic or riprap, becoming the least efficient or vice versa. The 8% culvert slope EDPP lines intersected at every flowrate except for the flowrate of 150 gpm. The 2%, 4% and 6% culvert slope EDPP lines intersected at all flowrates. The intersection point for the 2%, 4%, 6%, and 8% culvert slope EDPP lines occurred at increasingly higher steps as the flowrate increased. Once a flowrate of 150 gpm was obtained, all culvert slope EDPP lines intersected at a step height except for the 8% culvert slope EDPP. At the flowrate of 150 gpm, the riprap steps were more efficient energy dissipators than the cast acrylic steps at all three step heights. As the flowrate increased, riprap steps became increasingly more efficient than the standard cast acrylic steps at attenuating energy for a larger range of step heights. Overall, the smallest culvert slope promoted the highest energy dissipation efficiency whereas the largest culvert slope promoted the lowest efficiency.

For Figures 6.29 through 6.33, positive y-axis values indicated riprap steps were more efficient than the standard cast acrylic steps whereas negative values indicated riprap steps were less efficient. A greater positive EDPP percent difference value indicated a greater energy attenuating efficiency and a more negative EDPP percent difference value indicated a lesser energy attenuating efficiency. At the lowest flowrate, 50 gpm, the greatest range

of percent difference between the step heights was observed with the lowest step height being the most efficient at attenuating energy and the highest step height being the least efficient at attenuating energy. This trend gradually changed as the flowrate increased. Once the flowrate of 150 gpm was obtained, the percent difference between the step heights remained relatively constant.

## Chapter 7

### Conclusions and Recommendations

Based on the results presented in Sections 6.1 through 6.5, the riprap step is an effective method of energy attenuation. The riprap step forces a hydraulic jump to take place resulting in energy dissipation. The greatest efficiency for energy dissipation was observed with riprap step heights less than 25% of the culvert diameter at small culvert slopes. As the culvert slope and step height increased past the 25% culvert diameter, energy dissipation efficiency of the riprap step decreased. Construction of a full scale prototype model in the field is recommended with the following dimensions ( $D$  = culvert diameter):

- $0.235 D$  riprap  $D_{90}$
- Wingwall and apron configuration as described in the Introduction

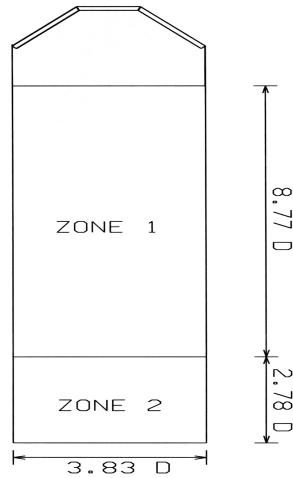


Figure 7.1 Prototype Model Design – Plan View

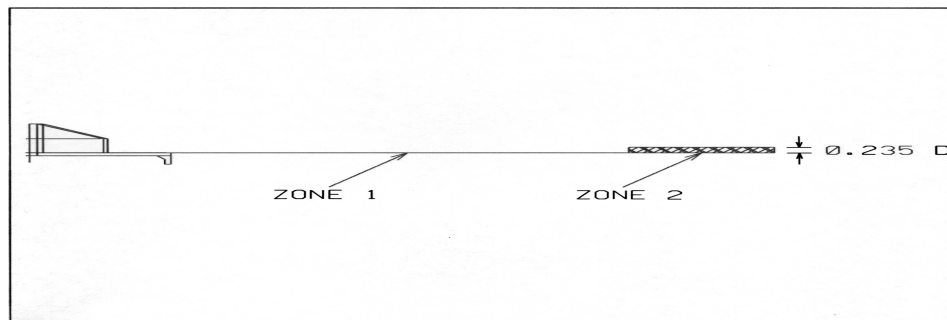


Figure 7.2 Prototype Model Design – Profile View



Since this research was a preliminary investigation of energy dissipation at culvert outlets using a riprap step, further research is needed to provide a better understanding of riprap steps. A large portion of the time available for this project was used to develop the testing flume. Significant additional time was required to determine the most effective approach to obtaining an effective riprap step design. Further investigation of the riprap step could include:

- Further analysis of error associated with the testing flume
- Larger range of culvert slopes
- Larger range of step heights tested
- Larger range of material gradations tested
- Greater accuracy measuring velocities and depths (Laser Doppler Anemometer)
- Longer testing channel to allow for better establishment of uniform flow
- Construction of non-rigid downstream bed to examine scour characteristics
- Test riprap step geometry, and other geometries, for sedimentation characteristics
- Examination of a full scale prototype in the field

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## VITA

Belinda M. Weikle was born in Union, West Virginia in 1972, but spent her entire childhood in Lewisburg, WV. She graduated from Greenbrier East High School in 1990 and entered college one year later.

Beginning at Bluefield State College, she majored in General Engineering and then transferred to West Virginia Institute of Technology into the Civil Engineering program where she received her Bachelors of Science in Civil Engineering in 1997. While at WVIT, she concentrated in the areas of fluid mechanics and water/wastewater.

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