PLAN B REPORT

Alphabet Weirs Physical Modeling

Submitted by

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

d_{50}	median diameter
d_s	median grain size (m)
h_n	normal depth
H	height
k_u	0.0428 (Richardson *et al*. 1990; Anderson, HIRE, p. 204)
n	Manning's roughness coefficient
Q	discharge (cfs)
S_f	friction slope (ft/ft)
W	width
W_b	bottom width (ft)
Φ	1.486 (conversion coefficient)

Abbreviations

%	percent
®	registered
3-D	three-dimensional
ADV	Acoustic Doppler Velocimeter
BOR	Bureau of Reclamation
cfs	cubic feet per second

CSU	Colorado State University
ERC	Engineering Research Center
ft	feet
ft/ft	feet per foot
hr(s)	hour(s)
Hz	Hertz
in.	inch(es)
m	meter(s)
mm	millimeter(s)
N/A	not available
PVC	polyvinyl chloride
™	trademark
X, Y	flume axes

CHAPTER 1

INTRODUCTION

1.1 Project Background

In-stream rock weirs can provide energy dissipation, increase aquatic habitat, allow fish passage, and relieve pressure on failing banks. Information on the design and performance of these structures is largely anecdotal based on empirical professional experience without the engineering rigor required for duplicability. Site-specific design requires a substantial design effort that in some cases can consume more resources than construction. There is little systematic information on how well these structures meet project goals. The Pacific Northwest Region of the Bureau of Reclamation (BOR) designs and constructs numerous structures every year for fish passage and habitat restoration as part of the Salmon Recovery Project. The Middle Rio Grande River Maintenance Project is exploring alternate means to stabilize banks by reducing flow velocity along eroding banks. A research proposal by the Technical Service Center of the BOR seeks to streamline the design process, increase understanding of the performance of the in-stream rock weirs, and improve the chances for successfully meeting management objectives. In response to the proposal, Colorado State University (CSU) was contracted, through the BOR, to investigate the performance of in-stream weirs through physical modeling.

1.2 Scope of Work

The research program was conducted at the Hydraulics Laboratory located at the Engineering Research Center (ERC) of CSU. Physical modeling was conducted on two types of in-stream rock structures, U- and W-weirs. Tasks for the project included constructing the physical model, testing them, and collecting data that include bed and water-surface elevations and three-dimensional (3-D) velocities. Three different gradations of bed material (5 mm, 9.8 mm, and 15 mm) and three different discharges (one-third, two-third, and bankfull discharges) were tested for the U-weirs. At this time, only one W-weir has been tested with 15-mm bed material at one-third, two-third, and bankfull discharges.

1.3 Research Objectives

The objectives of this study included:

- Quantifying dimensions of the scour pools downstream of weirs.
- Measuring bed and water-surface elevations to develop water-surface profiles.
- Collecting 3-D velocity measurements to analyze velocity and shear stress distributions in the model.

This report documents the construction process, testing procedure, and provides a summary of the data collected during testing.

CHAPTER 2

MODEL CONSTRUCTION

Physical modeling involved the construction of a scaled model with a unique Froude scale for each selected bed material. The appropriately scaled models were built using an existing flume at the ERC Hydraulics Laboratory with some modifications. Modifications included the addition of a head box, tail box, grate cover, stop logs, and data-collection cart. Different configurations of bed material, weir shape, and bed slope were constructed. Construction included building the weir and leveling the bed material. A total of nine configurations were constructed, each configuration having a unique combination of weir shape, bed slope, and bed material.

2.1 Flume Modifications

A flume 16-ft wide by 50-ft long and 4-ft deep, with a pump and head-box system capable of discharges up to 40.0 cubic feet per second (cfs) was selected for this study. A pond liner was placed inside the flume to aid in waterproofing. Firestone® water block sealant was used to adhere the pond liner to the floor. A cart spanning the width of the flume was added for data acquisition.

Flow was supplied with 40- and 75-horsepower pumps that recirculate water from an underground sump system. The 40-horsepower pump is capable of delivering discharges up to

10.0 cfs, while the 75-horsepower pump can deliver up to 30.6 cfs. Collectively, the pumps are capable of supplying flows greater than 40.0 cfs to the flume floor.

2.2 Construction Overview

Two different weirs were constructed, U- and W-weirs, with three different bed materials: 5 mm, 9.8 mm, and 15 mm. The corresponding Froude scales for the 5-mm, 9.8-mm, and 15-mm bed material are 1:4.36, 1:4.61, 1:5.75, respectively. Only the 15-mm bed material has been tested with the W-weir.

River left and *river right* were defined as left and right looking downstream, respectively, and are used accordingly throughout this report. The X-axis of the flume is defined in the downstream direction and referred to as the *station*, starting at 6 ft and ending at 48 ft. The Y-axis is defined in the direction of the cross section and is referred to as the *position*, starting at 50 ft and ending at 66 ft. Figure 2.1 presents a plan-view schematic of the flume, while Figure 2.2 presents a profile view.

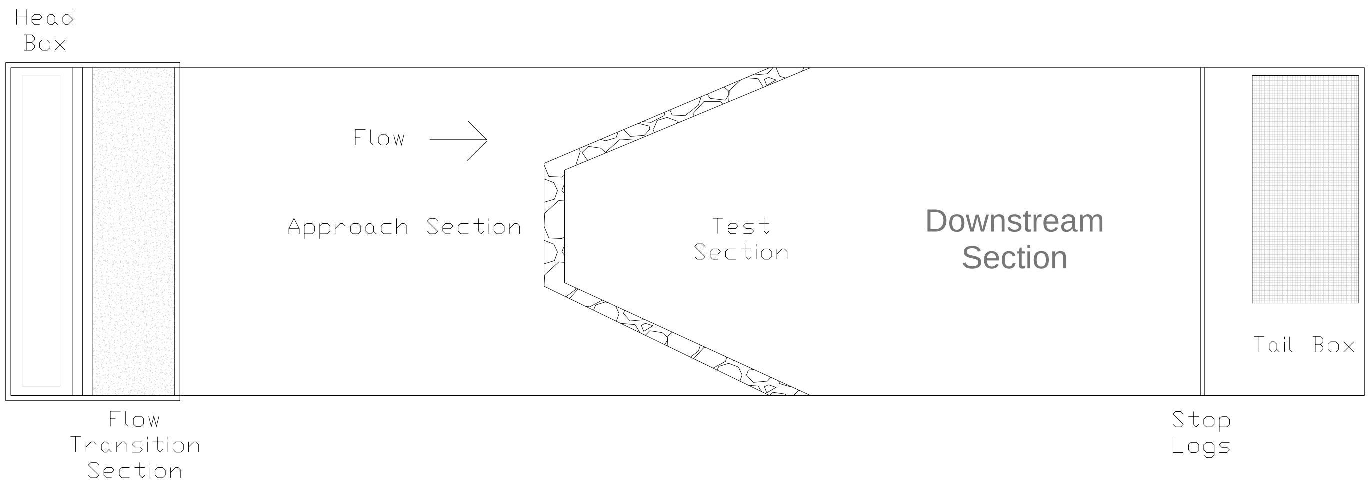


Figure 2.1. Plan-view Schematic of Flume

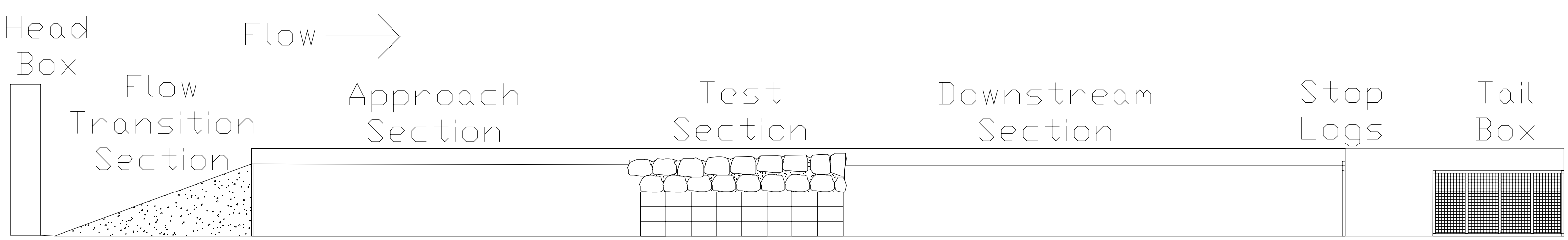


Figure 2.2. Profile-view Schematic of Flume

2.2.1 Head Box

An inlet pipe baffle, drain, and transition ramp comprised the head box. The baffle was 6-ft high with a filter wall filled with small cobble. A drain was constructed that consisted of a threaded plate with a 6-ft high threaded polyvinyl chloride (PVC) pipe that acted as a plug. A concrete approach ramp was built to aid in flow transition from the head box to the test reach. It was constructed using sand as the base filler material overlaid with a 3-in. layer of concrete reinforced with a 1/2-in. wire mesh. A 16-ft wide retaining wall supported the approach ramp. Figure 2.3 presents a photograph of the approach section.

Figure 2.3. Photograph of Baffle and Upstream Transition

2.2.2 Tail Box

An 8.5-ft long by 16-ft wide and 4-ft high tail box was constructed at the downstream end of the flume to direct flow into the sump. Tail-box walls consisted of 2-by-4 wooden frames and sheeted with 1/2-in. thick plywood that was painted with epoxy paint. Walls were secured to the floor with 1/2-in. concrete drop anchors as well as kickers that braced the wall approximately two-thirds of the distance up the wall. Walls were then sealed to the laboratory floor using PuriFoam™ waterfall foam.

A grate cover was constructed to reduce the amount of sediment going into the sump. The cover initially consisted of 1/2-in. wire mesh wired to the grate. Catch walls were installed upstream of the grate to reduce the amount of sediment that could actually reach the grate. The catch walls were later removed and the grate cover was changed to a box-style grate cover consisting of a 3-ft high wooden frame outside of the perimeter of the grates with 1/4-in. wire mesh nailed to the frame. A photograph of the grate cover is presented in Figure 2.4.

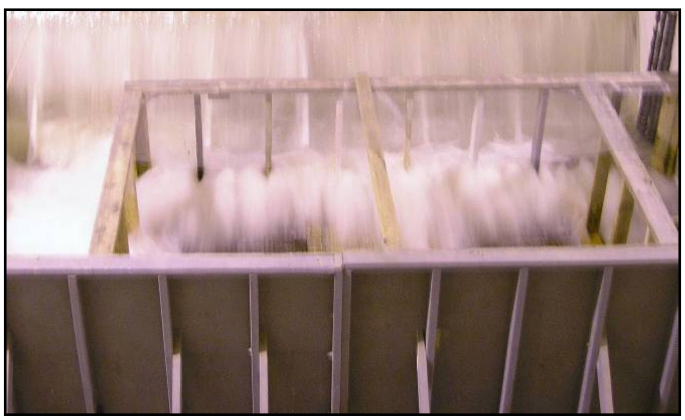


Figure 2.4. Photograph of the Grate Cover

2.2.3 Stop Logs

A system of stop logs was constructed at the downstream end of the model to control the water-surface elevation in the test section. Boards were bolted to the downstream retaining wall to provide downstream control. Backwater was adjusted by increasing or decreasing the number of boards or shims. Figure 2.5 presents a photograph of the completed stop-log system.

Figure 2.5. Photograph of Stop Logs

2.2.4   Weir Construction

Weirs were constructed following designs specified by Rosgen (2001), this study concentrated on U- and W-weirs. Arms extended from each side of the sill at a 20- to 30-degree angle (plan angle) with the bank and rose upwards 2 to 7 degrees (profile angle) and intersected the sides of the channel at the overbank elevation. Prototype sill elevation was 0.8 ft greater than the elevation of the bed, as prescribed by the Pacific Northwest Region of the BOR, creating a drop immediately downstream of the crest rocks. Outer arms of the weirs tied into the banks at bankfull elevation.

Modeled U-weirs consisted of a horizontal sill constructed perpendicular to the flow, centered in the lateral dimension and spanning one-third of the total channel width. Figure 2.6 presents a conceptual design of a U-weir.

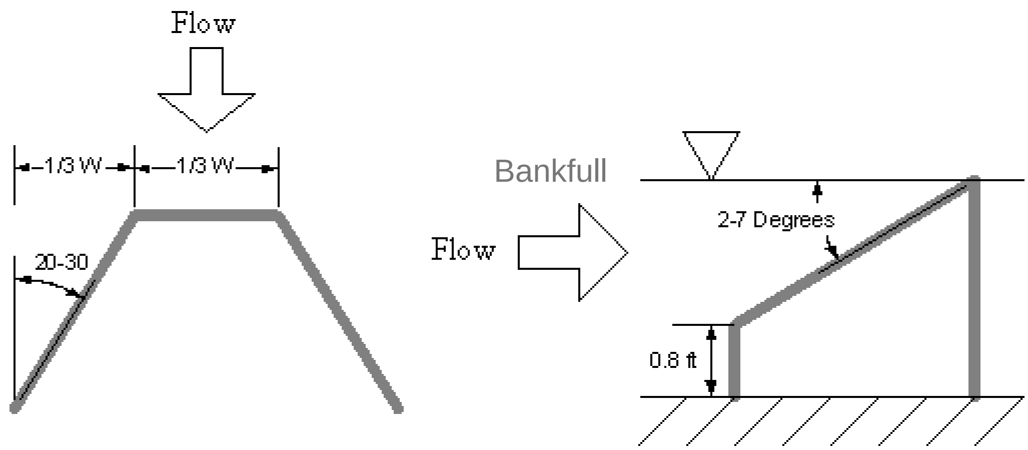


Figure 2.6. U-weir Conceptual Design (BOR 2005)

The modeled W-weir consisted of four sill segments with the center point facing downstream. For W-weir construction, the outer arms tied into the stream bank at bankfull elevation, while the inner arms reach to one-half bankfull elevation. Figure 2.7 presents a conceptual design of a W-weir.

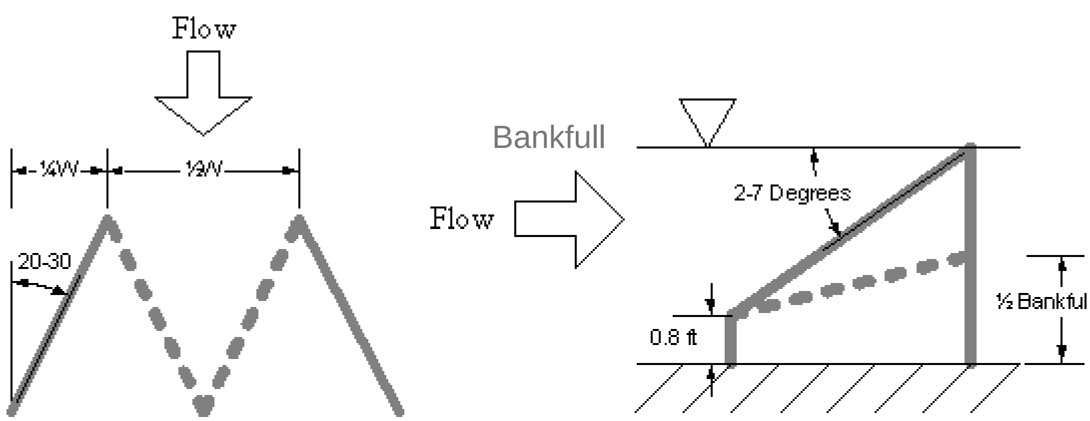


Figure 2.7. W-weir Conceptual Design (BOR 2005)

Weirs were constructed using predetermined rock sizes. Rocks were stacked two high with header rocks being placed on top of footer rocks. For Configurations 1 through 4, the rocks were just set on top of one another to reach the proper height requirement. For Configuration 5, a wooden step was retro-fitted onto the weir tested in Configuration 4 to create a step in the weir. The purpose of this step was to test the effects of a step on downstream scour-hole development. Figure 2.8 presents a photograph of the installed wooden step.

Figure 2.8. Photograph of Installed Wooden Step

After testing Configuration 5, it was observed that a step did have an effect on scour development downstream of the weir, particularly at low flows. Because of this observation, subsequent configurations incorporated footer rocks offset downstream from the header rocks by approximately one third of the intermediate axis of the rock. Figure 2.9 illustrates the header and footer rock design.

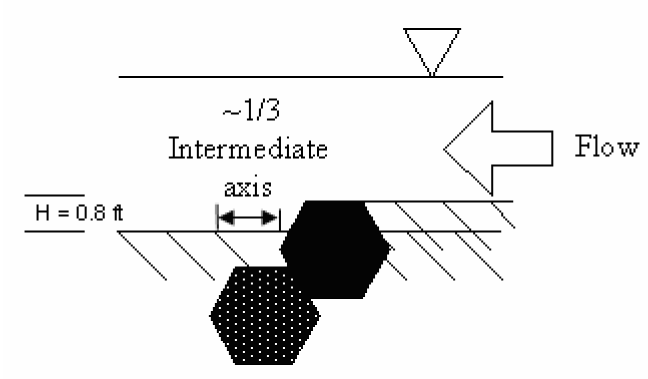


Figure 2.9. Schematic of Offset Header and Footer Rocks (BOR 2005)

For Configuration 1, the weir was constructed without cementing any of the rocks. As determined by the BOR, subsequent configurations were conducted using weirs with crest rocks grouted together and supported with an anchor wall designed to minimize subsurface and interstitial flow underneath and through the weir. Figure 2.10 presents an example of a grouted weir.

Figure 2.10. Photograph of a Grouted Weir and Anchor Wall

2.2.5 Leveling the Flume

Leveling of the bed material consisted of inserting stakes at strategic locations along the length of the flume. Typically, the locations started at Station 8 and proceeded to Station 44 in 4-ft increments, at Positions 54, 58, and 62 for each of the stations. Marking flags were used to indicate stake locations.

After the stakes were inserted, the flume was then leveled to the height of the stakes using hard-toothed and landscaping rakes. Following the initial leveling, the flume was surveyed using a rod and level, typically at 4- to 8-ft intervals along the length of the flume and at Positions 54, 58, and 62. Bed slopes for the left, right, and center of the flume were compared to the desired bed slope. If the actual bed slope deviated more than 10% from the desired bed slope, the bed was re-leveled and re-surveyed. These steps were repeated until the bed was within an acceptable tolerance.

2.3 Construction Specifics for Weir Configurations

2.3.1 Bed Material

Bed-material sizing for each of the tests was designated by the BOR and found using Shields scaling. The median diameters (d_{50}) of the prescribed bed materials were 5 mm, 9.8 mm, and 15 mm, while the actual d_{50s} achieved were approximately 4.14 mm, 9.81 mm, and 15.36 mm, respectively. A mixture of 50% 3/8-in. washed rock and 50% 3/8-in. "Laramie chip" was used for the 5-mm bed material. A mixture of approximately 80% 3/4-in. unwashed rock and 20% 3/8-in. washed rock was used for the 9.8-mm bed material. Three-quarter inch unwashed rock from Lafarge was used for the 15-mm bed material. A plot of the grain size distributions for all bed materials is presented in Figure 2.11.

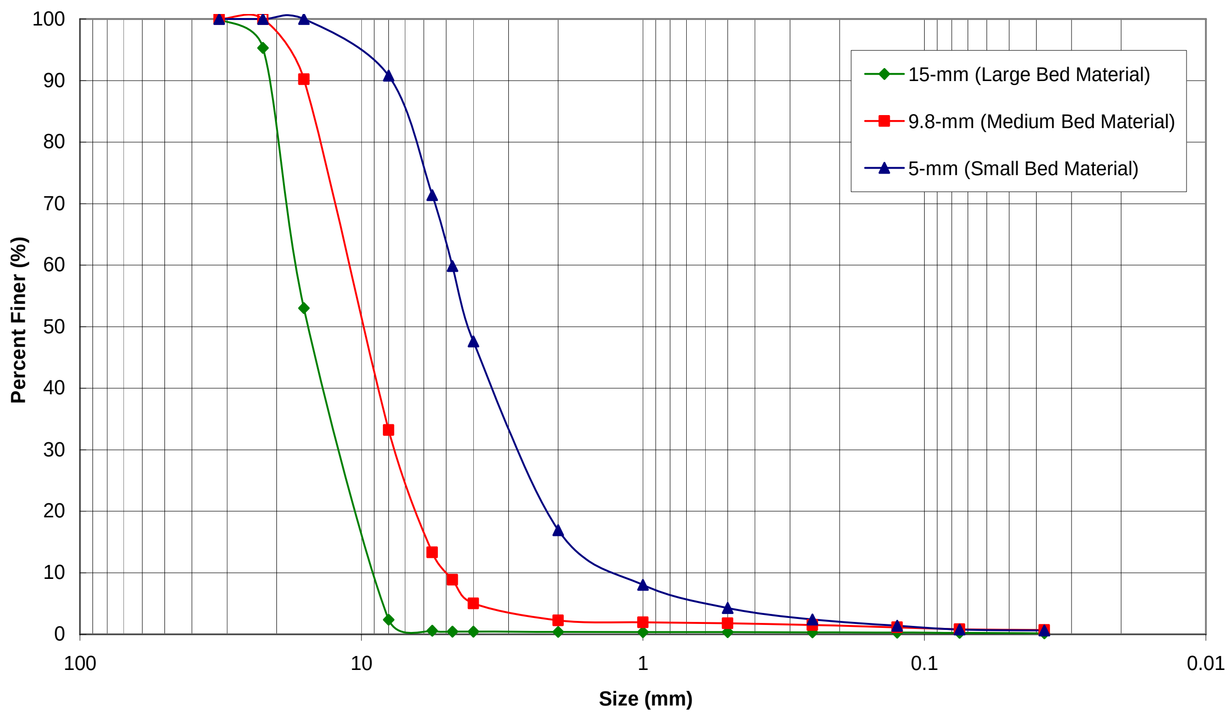


Figure 2.11. Grain Size Distribution of Bed Materials

2.3.2 Weir-rock Size and Drop Height

Weir-rock sizes were prescribed by the BOR. Rock sizes were 10 in., 8.8 in., and 6.87 in. which correspond to the 5-mm, 9.8-mm, and 15-mm bed material, respectively. Drop heights were determined by dividing the prototype crest height (0.8 ft) by the Froude scaling ratios, 1:4.36, 1:4.61, and 1:5.75 using Froude scaling corresponding to the 5-mm, 9.8-mm, and 15-mm bed materials, respectively. The drop heights were 0.14 ft, 0.17 ft, and 0.18 ft for the 6.87-in., 8.8-in., and 10-in. rock sizes, respectively.

2.3.3 Weir Dimensions

Weir dimensions were based on parameters prescribed by Rosgen (2001). The height was determined from the bankfull depth, which was found by calculating the normal depth of the flume given grain size, bed slope, and discharge. Normal depth was calculated using:

$$h_n = \left(\frac{nQ}{W_b S_f^{1/2} \Phi} \right)^{3/5}$$ **Equation (2.1)**

where:

n = Manning's roughness coefficient;

Q = discharge (cfs);

W_b = bottom width (ft);

S_f = friction slope (ft/ft); and

Φ = 1.486 (conversion coefficient).

Manning's n was calculated using an empirical equation from *Highways in the River Environment* (Richardson *et al*. 1990):

$$n = k_u * d_s^{1/6}$$ **Equation (2.2)**

where

k_u = 0.0428 (Richardson *et al*. 1990; Anderson, HIRE, p. 204); and

d_s = median grain size (m).

From Rosgen's recommendations of plan angles between 20 to 30 degrees and profile angles between 2 to 7 degrees, the BOR created a program that used the calculated normal depth to optimize the length of the weir arms to best fit Rosgen's criteria. Target angles were 25 degrees for plan angles and 4.5 degrees for profile angles. Figure 2.12 presents a plan-view sketch of a U-weir, Figure 2.13 presents a plan-view sketch of a W-weir, and Figure 2.14 presents a profile sketch of a weir. Table 2.1 gives the specific dimensions for each of the weirs for the different configurations.

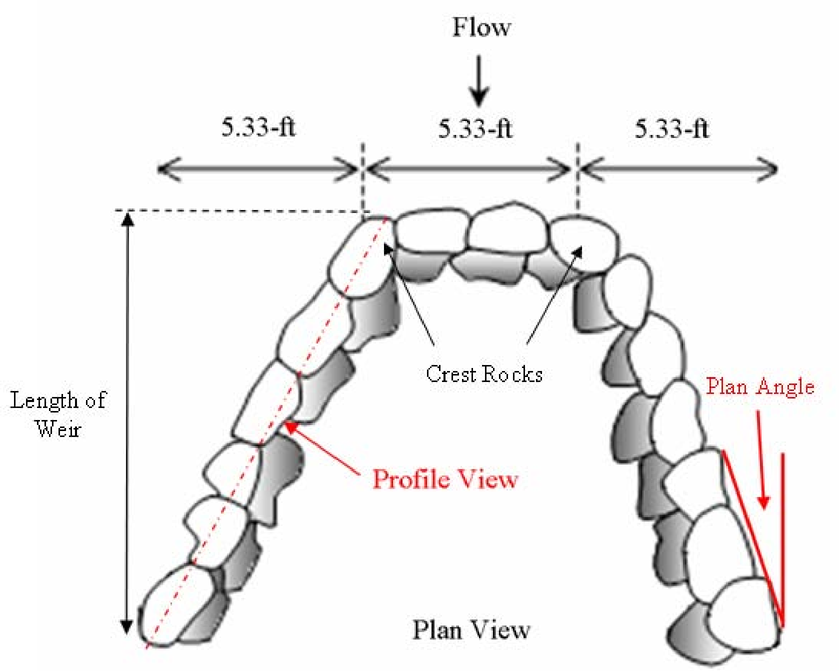


Figure 2.12. Plan-view schematic of a U-weir (adapted from Rosgen (2001))

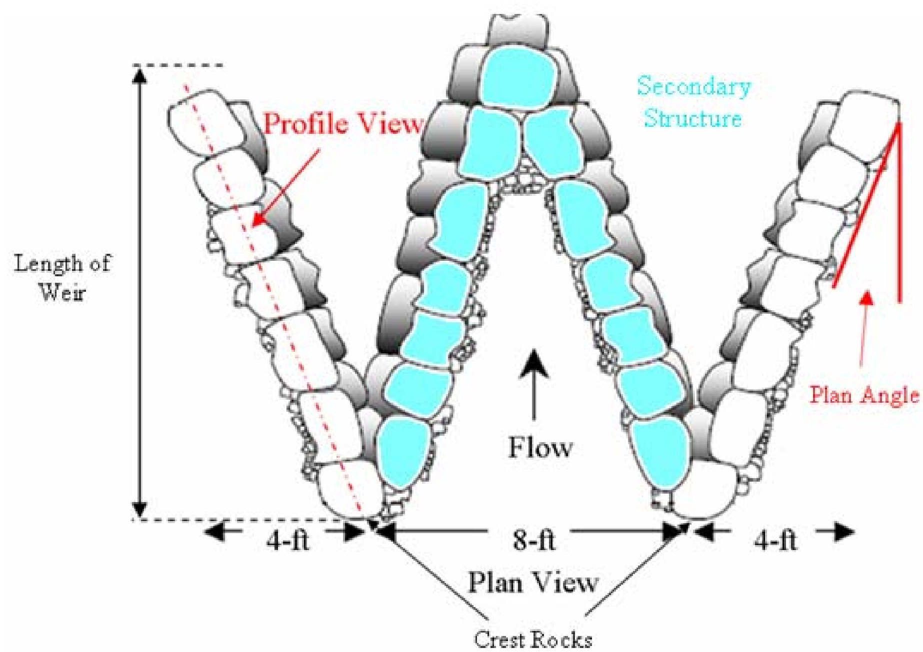


Figure 2.13. Plan-view schematic of a W-weir (adapted from Rosgen (2001))

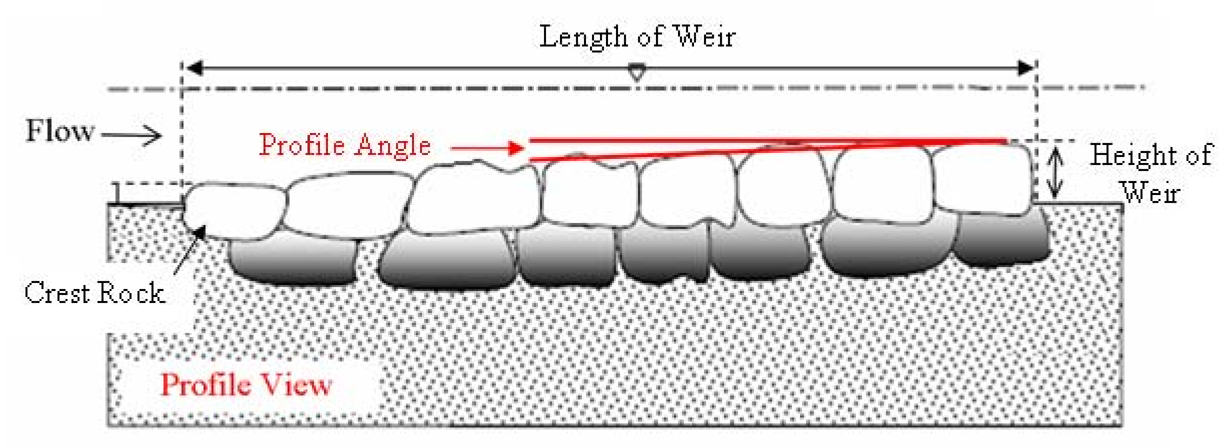


Figure 2.14. Profile-view Schematic of a Weir (adapted from Rosgen (2001))

Table 2.1. Weir Specifications

Configu-ration	Test Number	Weir Type	Length of Weir (ft)	Height of Weir (ft)	Secondary Structure Elevation (ft)	Drop Height (ft)	Plan Angle of Arms (degrees)	Profile Angle of Arms (degrees)	Weir Rock Size (in.)
1	1 - 4	W	11.00	1.10	0.55	0.00	20.00	5.40	6.87
2	5 - 7	U	11.44	0.90	N/A	0.00	24.98	4.09	6.87
3 - 5	8 - 14	U	11.44	1.04	N/A	0.14	24.98	4.73	6.87
6	15 - 17	U	9.25	0.73	N/A	0.18	29.95	3.92	10.00
7 - 8	18 - 23	U	9.83	0.92	N/A	0.17	28.47	4.72	8.80
9	24 - 26	U	11.24	0.73	N/A	0.18	25.39	3.37	10.00

N/A – not available

CHAPTER 3

TEST MATRIX

3.1 Configurations

A total of nine configurations were tested. Each configuration consisted of a combination of bed slopes, drop heights, three different bed-material sizes (5 mm, 9.8 mm, and 15 mm), and two different weir shapes (U- and W-weirs). A test matrix was developed to examine the effects of structure geometry, bed-material size, and discharge on flow conditions and local scour potential. A total of twenty-six tests were conducted during this phase of the project. Table 3.1 presents the test matrix.

Table 3.1. Test Matrix

Configuration	Test Number	Date Completed	Run Time (hrs)	Discharge (cfs)	Weir Shape	Weir Rock Size (in.)	Drop (ft)	Fill/No Fill Upstream	Anchored	Grain Size (mm)	Slope (ft/ft)
1	1	8/16/2005	N/A	N/A	W	6.87	None	No	No	15	0.0047
	2	9/8/2005	17.00	13.3	W	6.87	None	No	No	15	0.0047
	3	9/13/2005	20.00	26.6	W	6.87	None	No	No	15	0.0047
	4	10/6/2005	12.00	40.0	W	6.87	None	No	No	15	0.0047
2	5	2/10/2006	8.00	13.3	U	6.87	None	No	Yes	15	0.0047
	6	2/17/2006	12.00	26.6	U	6.87	None	No	Yes	15	0.0047
	7	2/24/2006	10.00	40.0	U	6.87	None	No	Yes	15	0.0047
3	8	3/27/2006	9.00	13.3	U	6.87	0.14	No	Yes	15	0.0047
	9	3/29/2006	14.00	26.6	U	6.87	0.14	No	Yes	15	0.0047
	10	4/4/2006	13.00	40.0	U	6.87	0.14	No	Yes	15	0.0047
4	11	4/12/2006	14.00	13.3	U	6.87	0.14	Fill	Yes	15	0.0047
	12	4/14/2006	12.00	26.6	U	6.87	0.14	Fill	Yes	15	0.0047
5	13	5/1/2006	12.00	26.6	U	6.87	0.14	Fill	Yes	15	0.0047
	14	5/15/2006	14.00	34.0	U	6.87	0.14	Fill	Yes	15	0.0047
6	15	7/15/2006	11.00	6.5	U	10.0	0.18	No	Yes	5	0.0021
	16	7/25/2006	13.00	13.3	U	10.0	0.18	No	Yes	5	0.0021
	17	7/28/2006	13.00	20.0	U	10.0	0.18	No	Yes	5	0.0021
7	18	9/1/2006	11.00	10.0	U	8.8	0.17	No	Yes	9.8	0.0033
	19	10/19/2006	13.00	20.0	U	8.8	0.17	No	Yes	9.8	0.0033
	20	10/24/2006	13.00	30.0	U	8.8	0.17	No	Yes	9.8	0.0033
8	21	11/6/2006	12.25	10.0	U	8.8	0.17	No	Yes	9.8	0.0033
	22	11/9/2006	12.00	20.0	U	8.8	0.17	No	Yes	9.8	0.0033
	23	11/13/2006	12.00	30.0	U	8.8	0.17	No	Yes	9.8	0.0033
9	24	12/21/2006	11.50	6.7	U	10.0	0.18	No	Yes	5	0.0021
	25	1/5/2007	12.00	13.3	U	10.0	0.18	No	Yes	5	0.0021
	26	1/10/2007	12.00	20.0	U	10.0	0.18	No	Yes	5	0.0021

N/A – not available

3.1.1 Configuration 1

Construction of Configuration 1 (Tests 1 through 4) began on July 6, 2005 and involved the installation of an upstream transition (Figure 2.3) that was 2-ft tall with a 3:1 slope. Twenty-inch cut-off walls were used to minimize subsurface flow in the model. A 12-ft long test section, devoid of cut-off walls, was constructed in the flume where a W-weir was installed with 6.87-in. rock. Approximately 75 tons of road base and 25 tons of 3/4-in. unwashed rock were used for the bed material that was leveled to a slope of 0.0047 ft/ft. To construct the weir, stakes were surveyed for the upstream and downstream elevations and a surveyor's string was used as a guide for the rock heights. In this setup, rocks were installed at the mean elevation of the rock. The crest rocks were installed level with the bed.

Configuration 1 was used as a shakedown run to determine what modifications were needed in the testing procedure or the model itself. Figure 3.1 presents a photograph of the W-weir installation.

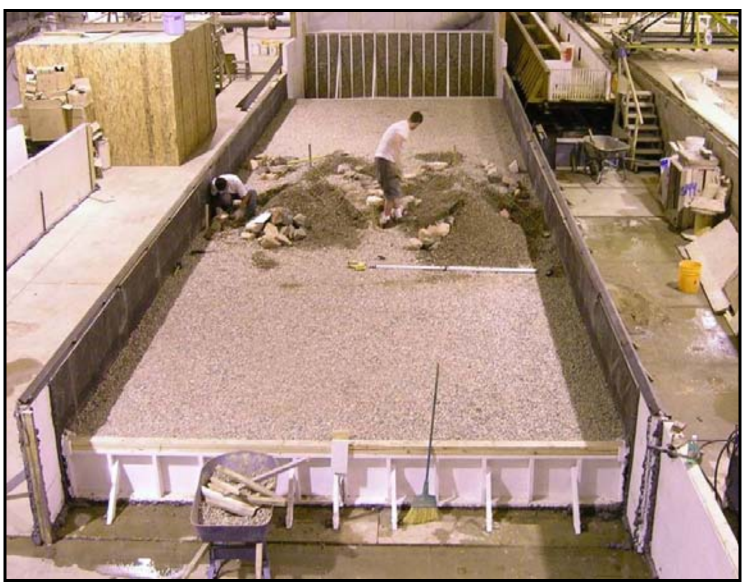


Figure 3.1. Photograph of the W-weir Installation

3.1.2 Configuration 2

Construction of Configuration 2 (Tests 5 through 7) began on September 10, 2005 and incorporated modifications identified during shakedown runs. Bed material and weir-rock size were maintained from Configuration 1. The weir was grouted and an anchor wall was added. Black tarpaulin was installed to prevent subsurface and interstitial flow through the weir. A new method of measuring the slope of the weir was implemented, which involved measuring the elevation of the highest point of each header rock and plotting the elevations to make sure that the slope of the weir arms was satisfactory. Figure 3.2 presents a photograph of the grouted weir construction.

Figure 3.2. Photograph of Anchor Wall and Grouted U-weir Construction

3.1.3 Configuration 3

Construction of Configuration 3 (Tests 8 through 10) began on March 2, 2006 and involved removing bed material to drop the bed elevation to a prescribed drop height of 0.14 ft with the weir. Bed material was removed for Configuration 3 to drop the elevation by 0.14 ft, while maintaining the same weir height. This created a drop downstream of the horizontal sill of the weir. Figure 3.3 presents an example of the downstream drop.

Figure 3.3. Photograph of the Flume After Lowering Bed by 0.14 ft

3.1.4 Configuration 4

Construction of Configuration 4 (Tests 11 and 12) began on March 31, 2006 and involved modifying the approach section's bed slope. The approach section of the flume was filled with bed material to reduce the bed slope in this section to 0.0023 ft/ft. The bed slope in the downstream section remained at 0.0047 ft/ft. This was done to see what effect the upstream had on velocities and scour evolution, while maintaining the same weir configuration and downstream conditions.

3.1.5 Configuration 5

Construction of Configuration 5 (Tests 13 and 14) began on April 5, 2006 and involved installation of a 2-by-8 beneath the header rocks to act as a step. After Configuration 4 testing was completed, it was determined that we would need to test the effects of a step on scour at lower discharges. For Configuration 5, a step was installed using a 2-by-8 anchored beneath the header rock and installed at bed elevation. The step was anchored into the cinder blocks using concrete lag screws, and then sealed to the weir using Purifoam® waterfall foam and Great Stuff®. Figure 3.4 presents a photograph of the wooden-step construction.

Figure 3.4. Photograph of Construction of Wooden Step

3.1.6 Configuration 6

Construction of Configuration 6 (Tests 15 through 17) began on April 19, 2006. Five-millimeter bed material was installed to a slope of 0.0021 ft/ft and a U-weir with 10-in. rock. The U-weir was constructed so that the header and footer rocks offset by one-third the intermediate axis of the rock. The upstream transition was raised by 1.4 ft to allow for an increased depth of bed material and correspondingly, the stop-log wall was raised 1.4 ft.

For Configuration 6, both the upstream transition and downstream flume wall were raised by 1.4 ft to increase bed-material depth. Figure 3.5 presents a photograph of the flow-transition wall addition. It was predicted that the bed-material depth would need to be increased because of the predicted increase in scour. The U-weir was constructed with the footer rocks offset by one-third the d_{50} of the weir rocks downstream of the header rocks. However, during the initial shakedown run, bowing was observed at the head-box walls and a few studs had broken along the flume wall.

Figure 3.5. Photographs of Flow-transition Wall Addition

3.1.7 Configuration 7

Construction of Configuration 7 (Tests 18 through 20) began on July 26, 2006 and involved installing 9.8-mm bed material to a slope of 0.0033 ft/ft and a U-weir with 8.8-in. rock. Both the flow-transition wall and stop-log wall were lowered by 0.5 ft to prevent overtopping at higher flows and improve approach conditions. Figure 3.6 presents a photograph of the modified upstream transition.

Figure 3.6. Photograph of Modified Upstream Transition

3.1.8 Configuration 8

Construction of Configuration 8 (Tests 21 through 23) began on September 25, 2006. Configuration 8 was an iteration of Configuration 7 with the bed material being re-leveled to a slope of 0.0033 ft/ft.

3.1.9 Configuration 9

Construction of Configuration 9 (Tests 24 through 26) began on November 14, 2006. For this configuration, 5-mm bed material was installed and the U-weir changed accordingly (10-in. rock). The bed material was also leveled to a slope of 0.0021 ft/ft.

3.2 Construction Summary

Construction of the physical model involved building a 16-ft by 50-ft flume to test two different types of weirs, U- and W-weirs, with three different bed materials: 5 mm, 9.8 mm, and 15 mm. Construction of the model involved building a transition ramp in the head box as well as downstream walls, sediment traps to reduce the amount of sediment going into the sump. For each configuration, a weir was built and the bed material was leveled to a prescribed bed slope. A total of nine configurations have been tested.

CHAPTER 4

TESTING

A testing schedule was developed by CSU in cooperation with the BOR. All testing was conducted on the premises of the Engineering Research Center by CSU personnel. Construction of Configuration 1 was completed on August 15, 2005 and testing began immediately after. Data collected during testing included bed elevation, water-surface elevation, and 3-D velocities.

4.1 Testing Platform

Data acquisition for the alphabet weir model was performed from a mobile test platform. A rope was installed above the cart to aid in moving the cart while testing. Rails for the cart were constructed the entire length of the flume. Point-gauge measurements of bed and water-surface elevations were taken from a rail attached to the upstream edge of the cart. Figure 4.1 presents a photograph of the cart and point gauge.

Figure 4.1. Photograph of Cart and Point Gauge

A tape measure was attached the length of the point-gauge rail on the platform to locate data-acquisition positions. A tape measure was also fastened to the flume wall along the length of the flume allowing station locations to be identified.

To establish laboratory elevations for elevations collected from the point gauge, a total station survey of the cart was completed. A coordinate system was established for the flume with stations and positions. *Stations* were along the X-axis, running the length of the flume. *Positions* were along the Y-axis, running across the flume perpendicular to the flume walls along the data-collection cart. Elevations were collected from a known location on the point gauge attached to the rail of the platform and surveyed every foot along the flume and platform starting at Station 6 and ending at 45. Surfer® was utilized to create an interpolated elevation grid between the surveyed points. This grid was set up in a reference table in Microsoft® Excel and allowed any elevation collected from the cart to be converted to laboratory elevation.

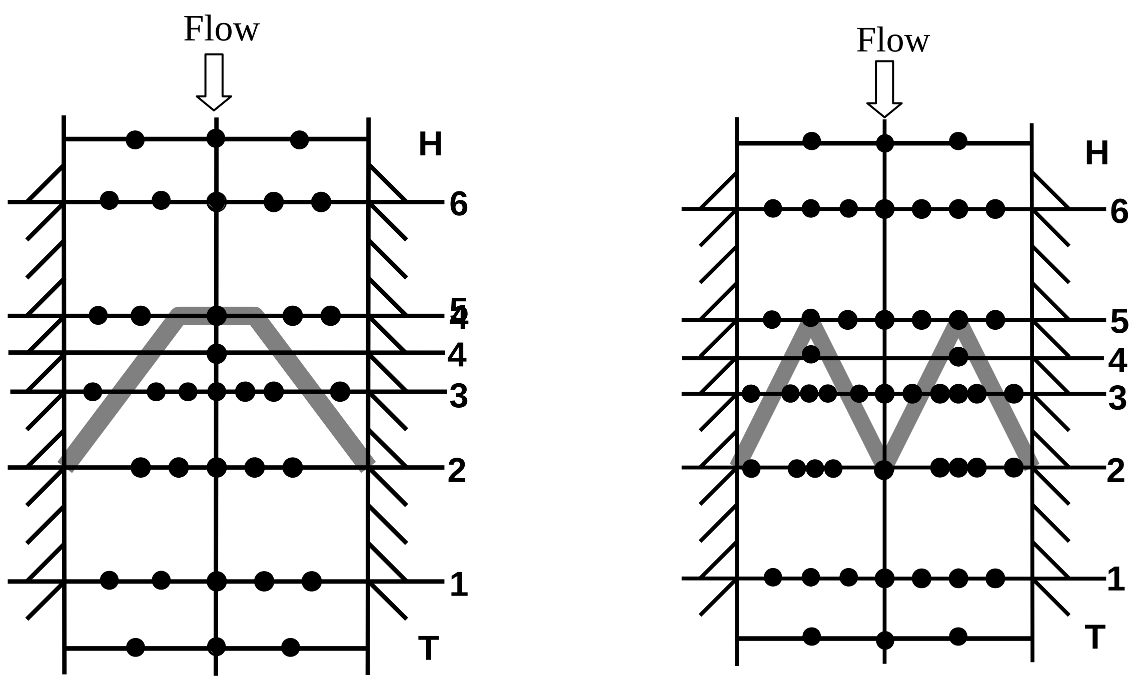
4.2 Data-acquisition Locations

Data-acquisition points were determined to best quantify the hydraulic and scour variables associated with each structure. At the data-acquisition locations, bed and water-surface readings, and 3-D velocities at 20%, 60%, and 80% depths were collected. In total, there were seven transects along the length of the flume where data were collected:

- Transect T was located at Station 42.00 to measure downstream tailwater conditions before reaching the downstream wall.
- Transect 1 was located 8.00 ft downstream of where the weir arms intersect the bank. This area was chosen because it was thought to be downstream of the influence of tailwater turbulence as well as the scour hole. U-weir sampling was distributed evenly across the channel, while W-weir sampling was distributed evenly across the halves of the channel.
- Transect 2 was located where the weir arms intersect the bank.
- Transect 3 was located at the midpoint along the weir arms. Sampling points were distributed evenly between the two arms for the U-weir, while the W-weir had three sampling points distributed between one side of the W with an additional point along the centerline and a point midway between the bank and the arm nearest the wall.
- Transect 4 was located halfway in-between Transects 3 and 5, approximately 1/4 of the weir length downstream of the crest rocks. Sampling points were collected in the middle of the vanes of both weirs.
- Transect 5 was located along the upstream-most edge of the weir crest. Sampling points matched those of Transect 3.

- Transect 6 was located 8.00 ft upstream of Transect 4. This transect was chosen because it was thought to be upstream of the draw-down curve over the weirs and to define entrance conditions. Sampling points matched those of Transect 1.
- Transect H was located at Station 8.00 to measure approach conditions.

Figure 4.2 presents examples of the data-acquisition points for U and W-weirs. Each test configuration has unique sampling locations.



(a) U-weir (b) W-weir

Figure 4.2. Schematic of Sampling Locations for U- and W-weirs (BOR 2005)

4.3 Surveying

Bed surveys were conducted before, during, and after each test. An initial bed survey of the predetermined sampling locations was conducted before each test configuration to act as a base line. Water-surface and bed surveys were conducted during testing to determine flow depths. A thorough bed survey (300 to 500 data points) was conducted after each test to map the bed contours. In addition to the bed surveys, a total station survey was conducted on each of the weirs.

4.4 Velocity Measurements

Three-dimensional flow velocities were collected at each of the sampling locations unique to each test configuration. Velocities were collected at 20%, 60%, and 80% flow depths using a wading rod and a SonTek hand-held Acoustic Doppler Velocimeter (ADV) with a sampling frequency of 25 Hz for 30 seconds. Accuracy of the device was $\pm$1% of the measured velocity. Figure 4.3 presents a schematic of the sampling depths.

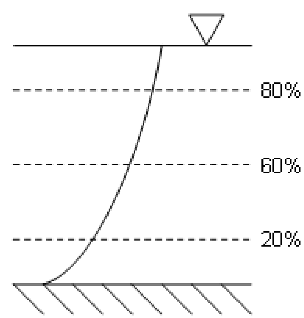


Figure 4.3. Schematic of Sampling Depths (BOR 2005)

4.5 Data Analysis

Topographic plots were generated in Surfer® to aid in the visualization of the bed. To make all of the plots comparable, the elevation of the crest rock of each weir was set at an elevation of 100, while the rest of the points were adjusted according. Contour and wire frame maps were generated for all of the tests that had bed surveys. WinADV software was used to analyze the velocity data acquired by the ADV. Since filtering parameters are still being analyzed, the data reported later in this report are unfiltered.

4.6 Testing Overview

A typical testing sequence consists of installing the weir and bed material, performing a shakedown run, and testing the configuration. Installation consisted of constructing the weir and installing the bed material to specification. A shakedown run was performed prior to testing to determine what, if any, modifications were needed on the flume. Testing involved setting the flume to a prescribed flow depth and letting the flume run for 12 hrs. Data collected included bed and water-surface elevations, and 3-D velocities. The following sections examine the tasks involved in each step.

4.6.1 Installation

After the flume was excavated, the proper sized bed material was installed upstream of the weir. Following the installation of the upstream bed material, the weir was then installed to the proper specifications and surveyed with a total station. Subsequently, the downstream section of the flume was filled with bed material. During the installation of the bed material, the flume was surveyed and leveled to meet the bed slope specifications. Finally, the stop-log walls were installed as well as the tail-box walls and grate covers.

4.6.2 Shakedown Runs

Shakedown runs were conducted after every installation to determine the integrity of the flume and weir. The discharge was increased sequentially, one-third, two-third, and bankfull discharges, to check for bed settling, leaks in the walls, and leaks in the weir. If any problems were discovered, they were addressed and another shakedown run was performed. If there were no problems, the bed was re-leveled and surveyed until it passed inspection.

4.6.3 Testing

Once the proper bed slope was obtained, the model was brought to the proper discharge for the first test run. After proper discharge was obtained, flow depths were measured at Station 46.5 at Positions 54, 58, and 64 to determine if the downstream flow depth corresponded to the theoretical normal depth. Flow depth was considered acceptable if it was within 10% of the normal depth, and ideally within 5%. If flow depths were not within the 10% specifications, the discharge was terminated and the stop logs were adjusted accordingly. This process was done until the flow depth was within an acceptable tolerance. The discharge was maintained for 4 to 6 hrs. During the next day, the model was run for 8 hrs and bed, water-surface, and velocity measurements were collected at the predetermined sample locations. This typically would take around 6 hrs and the flume was allowed to run for another 2 hrs. Run times for the tests ranged from 11 to 17 hrs, with the average run time being 12 hrs. Twelve hours was determined to be the optimal run time, allowing for quasi-equilibrium of the scour hole. Around the 6-hr mark, velocities were taken. After the discharge was terminated, the flume was allowed to drain overnight. When the bed was dry, elevation measurements were collected to create a topographic map of the features created by the flows. Photographs were taken before, during, and after each test and construction phase for documentation purposes.

4.7 Test Results

A total of nine configurations were tested. Specifics regarding construction and observations of each configuration are discussed. Approximate scour depths and Surfer® plots are provided for configurations where thorough bed readings were collected. The following sections discuss the results from the tests outlined in Table 3.1.

4.7.1 Configuration 1 – W-weir (15-mm bed material)

Testing for Configuration 1 began on August 15, 2005 and concluded on October 6, 2006. Configuration 1 corresponded to Tests 1 through 4 and consisted of a W-weir with 15-mm bed material, a bed slope of 0.0047 ft/ft, and a bankfull discharge of 40.0 cfs. Header and footer rocks had an intermediate axis of 6.87 in. and the crest of the weir was flush with the bed material. Figure 4.4 and Figure 4.5 present the plan and profile views of the Configuration 1 weir, respectively. Data-collection points for Configuration 6 are presented in a schematic shown in Figure 4.6.

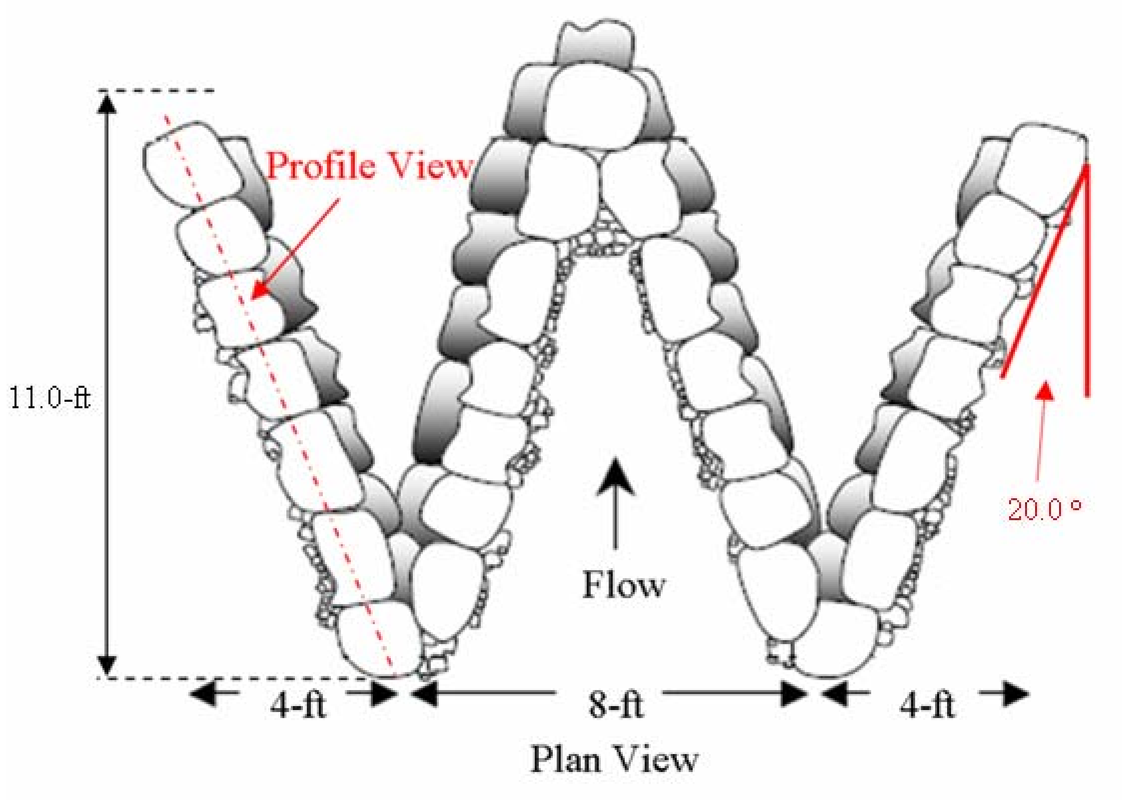


Figure 4.4. Plan View of W-weir for Configuration 1 (adapted from Rosgen (2001))

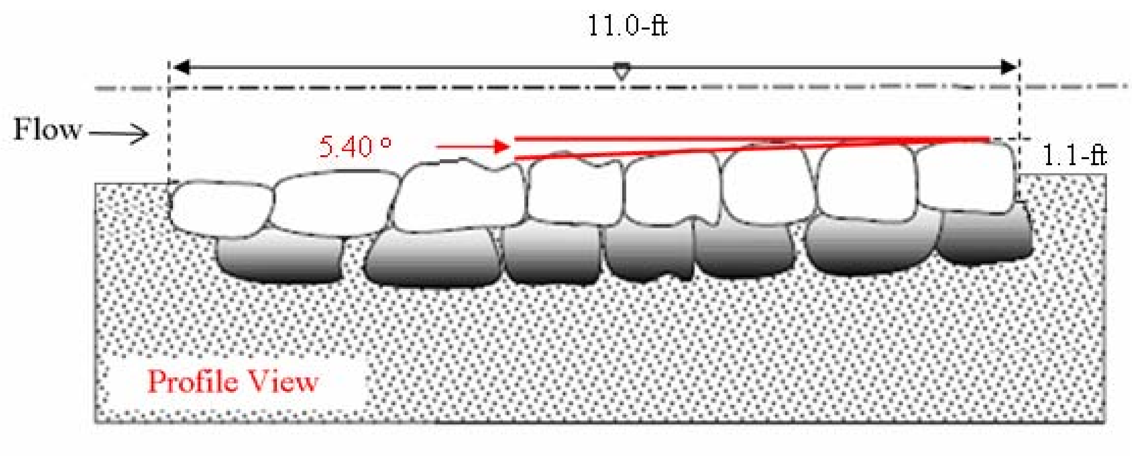


Figure 4.5. Profile View of W-weir for Configuration 1 (adapted from Rosgen (2001))

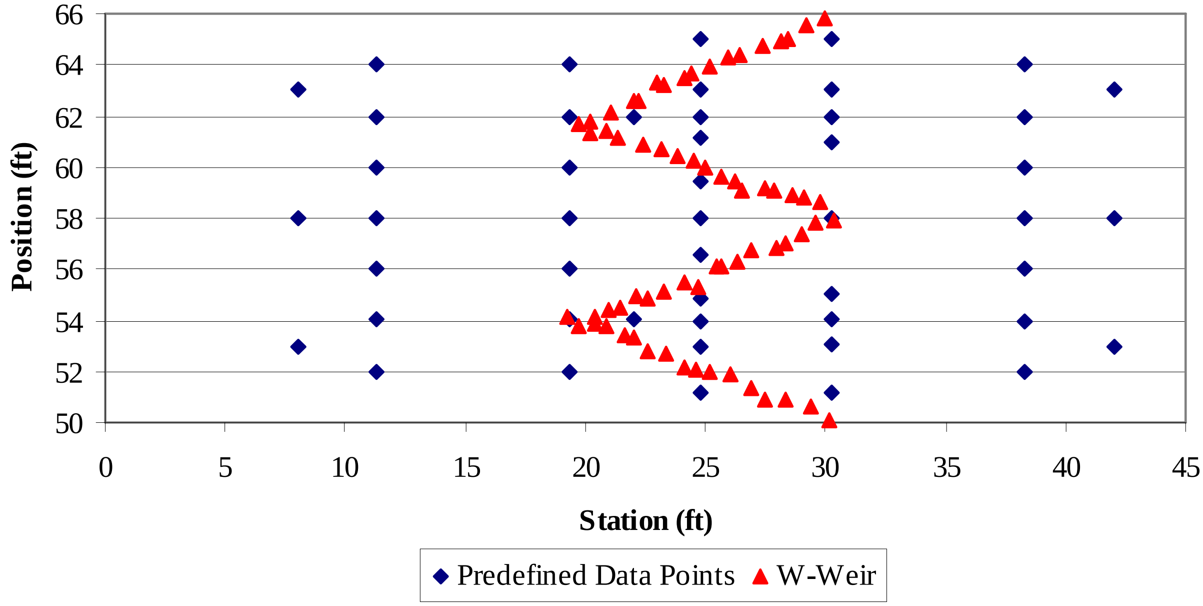


Figure 4.6. Data-collection Points for Configuration 1

Test 1 was a shakedown run to determine what modifications were needed on the flume and in the testing procedure. During Test 2, scour began to develop primarily on the stream left side of the weir. Weir failure was observed during Test 3, as one of the header rocks on the far right weir arm dropped downstream. Figure 4.7 illustrates the failure of the outer right weir arm. In addition, the rocks adjacent to the right wall began to pull away from the wall due to localized scour underneath the footer rocks. This was remedied by re-foaming the rocks to the wall and taking some of the downstream gravel on a depositional bar and putting it into the scour hole. It was observed during Test 4 that the localized scour along the outer edge of the weir arms increased. In addition, rocks along the left side of the weir began to fall upstream after 3 hrs of testing. Although the weir was considered failed at this point, testing continued for 9 more hours to determine if any appreciable movement of the weir rocks or significant localized scour of the bed would occur. No measurable change was observed after this time period. Figure 4.8 presents a photograph of the weir after Test 4.

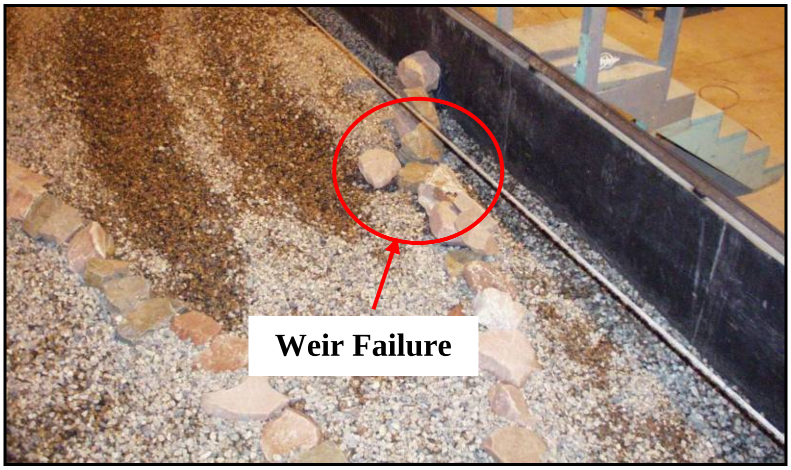


Figure 4.7. Photograph of Weir Failure During Test 3

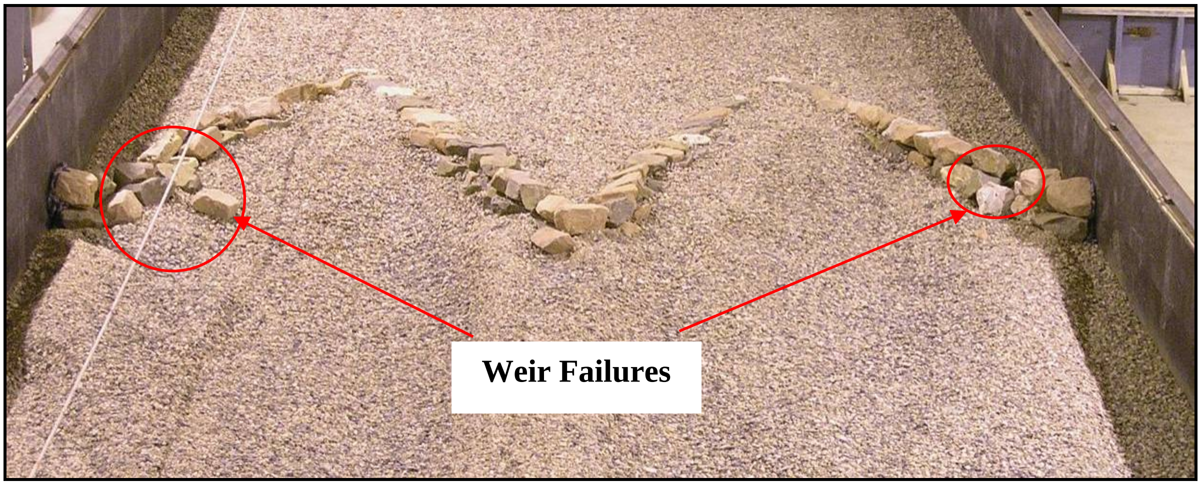


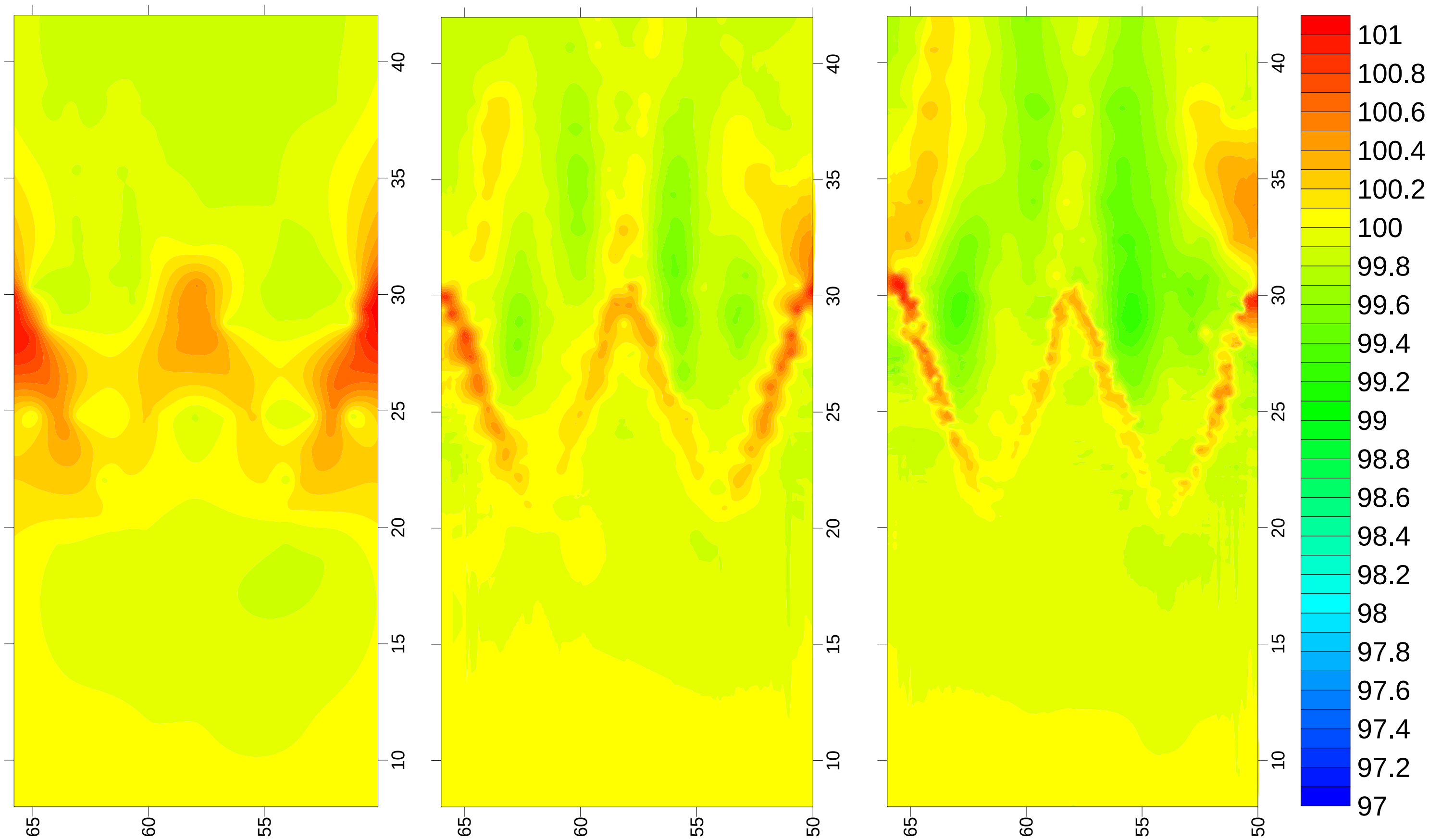
Figure 4.8. Photograph of Weir After Test 4 Exhibiting Weir Failure on Both of the Outside Arms

Two scour holes were observed on each side of the weir for a total of four scour holes. Scour holes were also asymmetrical, which is a result of the variations in the weir.

Table 4.1 summarizes the discharges and observed scour depths for each test. Bed contour plots generated with Surfer® illustrate the scour observed for each test and are presented in Figure 4.9.

Table 4.1. Approximate Scour Depths for the Tests in Configuration 1

Configuration	Test Number	Discharge (cfs)	Approx. Scour Depth (ft)
1	2	13.3	0.21
	3	26.6	0.54
	4	40.0	0.77



Test 3 (26.6 cfs)

Test 4 (40.0 cfs)

Figure 4.9. Contour Plots for Configuration 1 (W-weir, 15-mm Bed Material, Non-Anchored, No Drop)

Test 2 (13.3 cfs)

4.7.2 Configuration 2 – U-weir (15-mm bed material)

Testing for Configuration 2 began on February 8, 2006 and concluded on February 24, 2006. Configuration 2 corresponded to Tests 5 through 7 and consisted of a U-weir with 15-mm bed material, a bed slope of 0.0047 ft/ft, and a bankfull discharge of 40.0 cfs. For these tests, an anchor wall was constructed and the weir rocks were grouted together. There was no appreciable step along the weir arms. Header and footer rocks had an intermediate axis of 6.87 in. and the crest of the weir was also flush with the bed (no drop behind the cross sill). Figure 4.10 and Figure 4.11 present the plan and profile views of the Configuration 2 weir, respectively. Data-collection points for Configuration 2 are presented in a schematic shown in Figure 4.12.

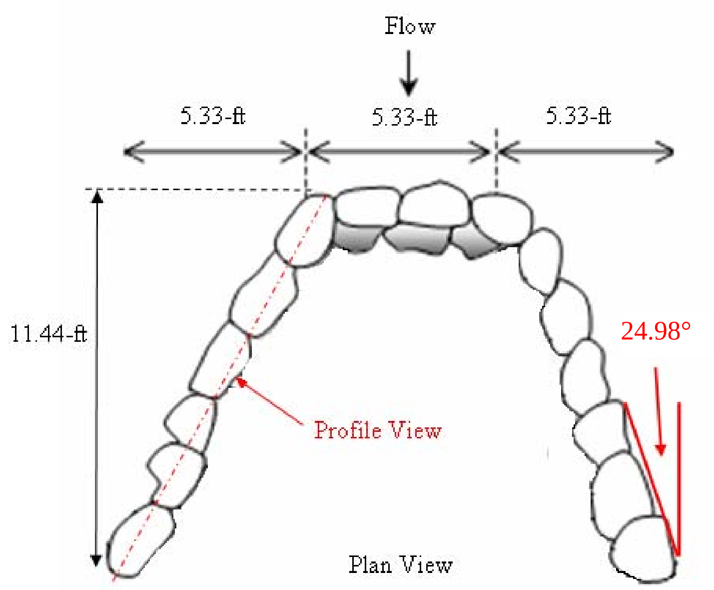


Figure 4.10. Plan View of U-weir for Configuration 2 (adapted from Rosgen (2001))

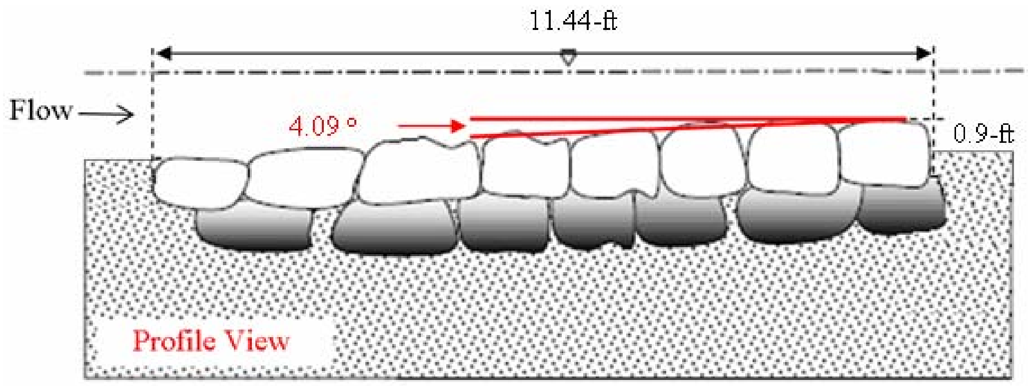


Figure 4.11. Profile View of U-weir for Configuration 2 (adapted from Rosgen (2001))

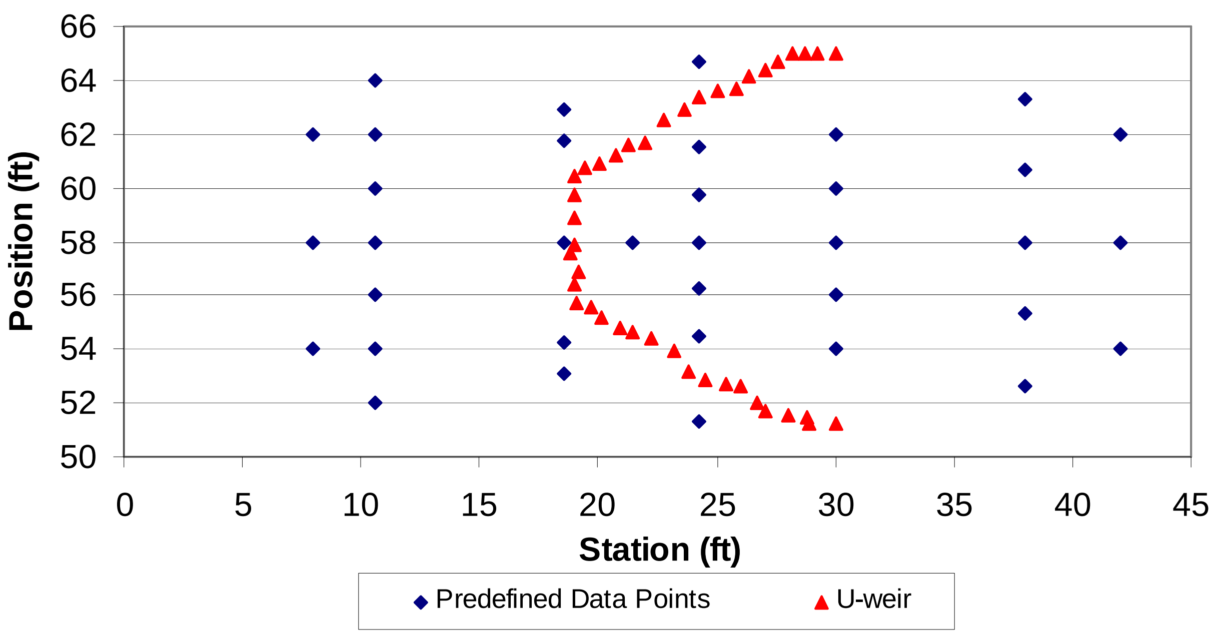


Figure 4.12. Data-collection Points for Configuration 2 (adapted from Rosgen (2001))

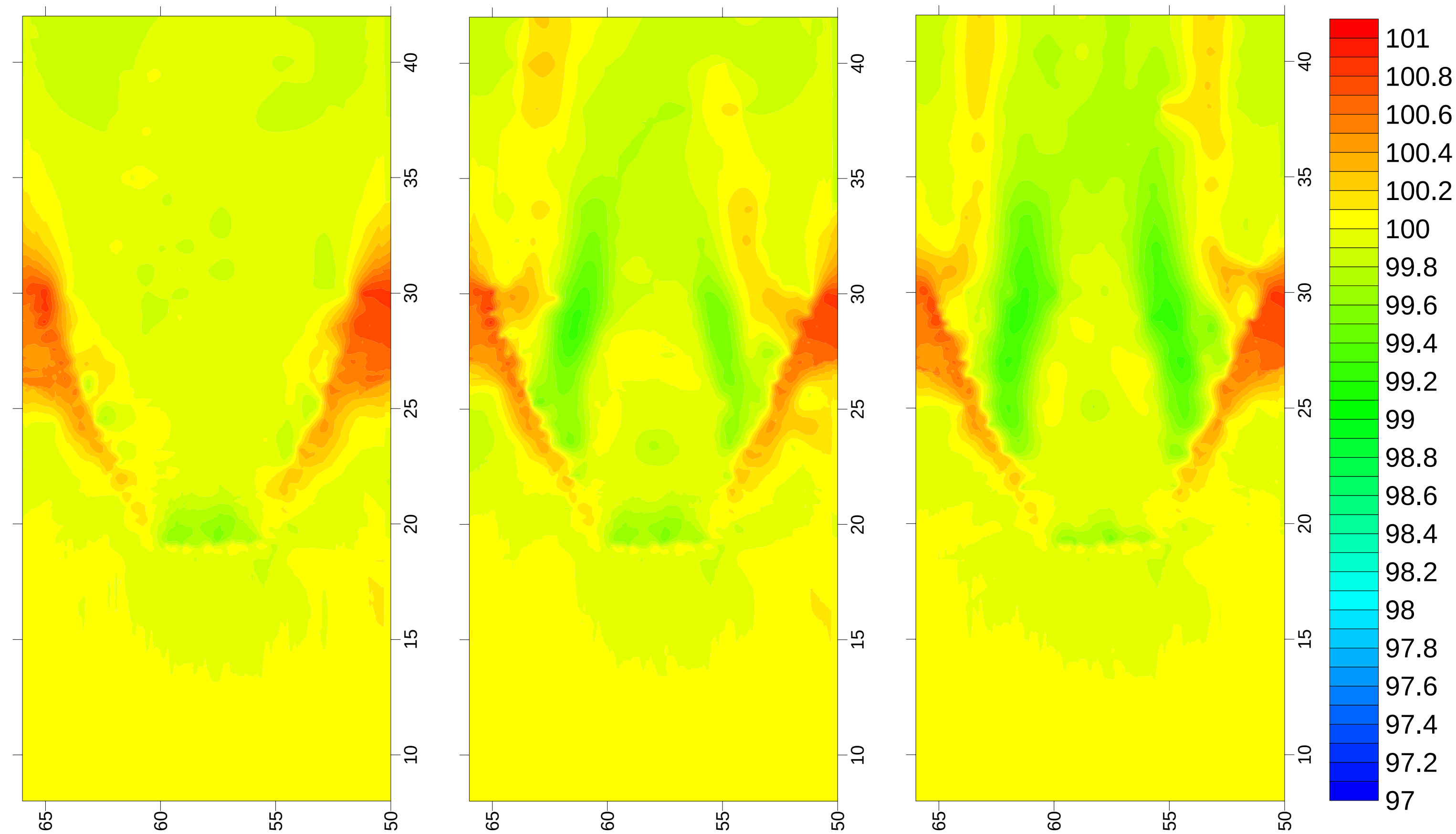
Two discernable scour holes developed as testing progressed with depositional bars along the outer edges. Figure 4.13 presents a photograph of the weir after Test 7. The scour holes looked to originate about one-third of the way down the weir downstream of the cross sill. The rate of scour also seemed to taper off between two-third and bankfull discharges.

Figure 4.13. Photograph of the Flume After Test 7

Table 4.2 summarizes the discharges and observed scour depths for each test. Bed contour plots generated with Surfer® illustrate the scour observed for each test and are presented in Figure 4.14.

Table 4.2. Approximate Scour Depths for the Tests in Configuration 2

Configuration	Test Number	Discharge (cfs)	Approx. Scour Depth (ft)
2	5	13.3	0.49
	6	26.6	0.74
	7	40.0	0.77



Test 6 (26.6 cfs)

Test 7 (40.0 cfs)

Figure 4.14. Contour Plots for Configuration 2 (U-weir, 15-mm Bed Material, Anchored, No Drop)

Test 5 (13.3 cfs)

4.7.3 Configuration 3 – U-weir (15-mm bed material)

Testing for Configuration 3 began on March 23, 2006 and concluded on April 4, 2006. Configuration 3 corresponded to Tests 8 through 10 and consisted of a U-weir with 15-mm bed material, a bed slope of 0.0047 ft/ft, and a bankfull discharge of 40.0 cfs. For these tests, an anchor wall was constructed and the weir rocks were grouted together with no appreciable step along the weir arms. Header and footer rocks had an intermediate axis of 6.87 in. and the drop height of the weir was 0.14 ft. For this configuration, the bed was lowered by 0.14 ft from the previous test. Figure 4.15 and Figure 4.16 present the plan and profile views of the Configuration 3 through 5 weirs, respectively. Data-collection points for Configurations 3 to 5 are presented in a schematic shown in Figure 4.17.

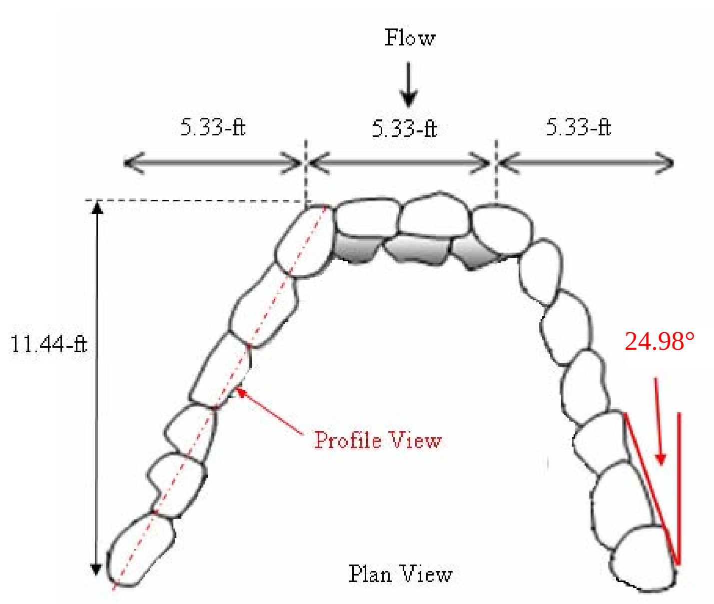


Figure 4.15. Plan View of U-weir for Configurations 3 through 5 (adapted from Rosgen (2001))

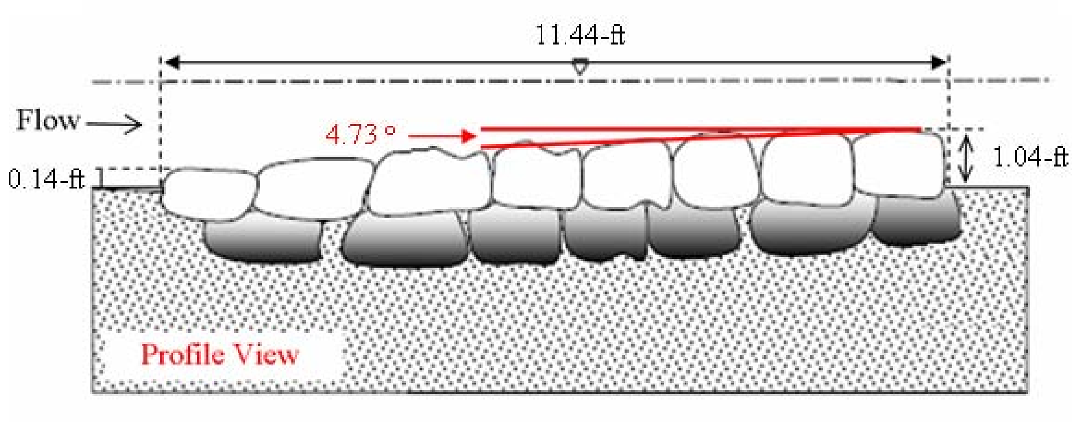


Figure 4.16. Profile View of U-weir for Configurations 3 through 5 (adapted from Rosgen (2001))

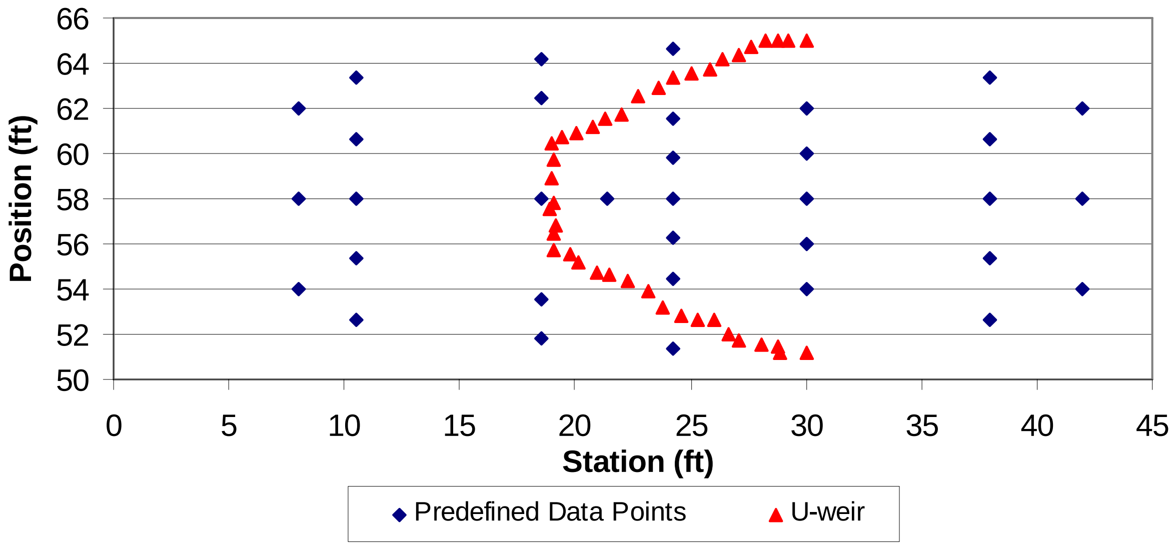


Figure 4.17. Data-collection Points for Configurations 3 through 5

Creating the drop increased scour at each discharge significantly. At one-third bankfull discharge (13.33 cfs), scour depths were greater than previously seen at bankfull discharge (40.0 cfs). Two distinct scour holes were observed at the lower discharge tests that eventually began to merge at bankfull discharge. Test 10 (bankfull discharge) exhibited so much scour that it reached the floor of the flume. Figure 4.18 presents a photograph of the scour hole after Test 10.

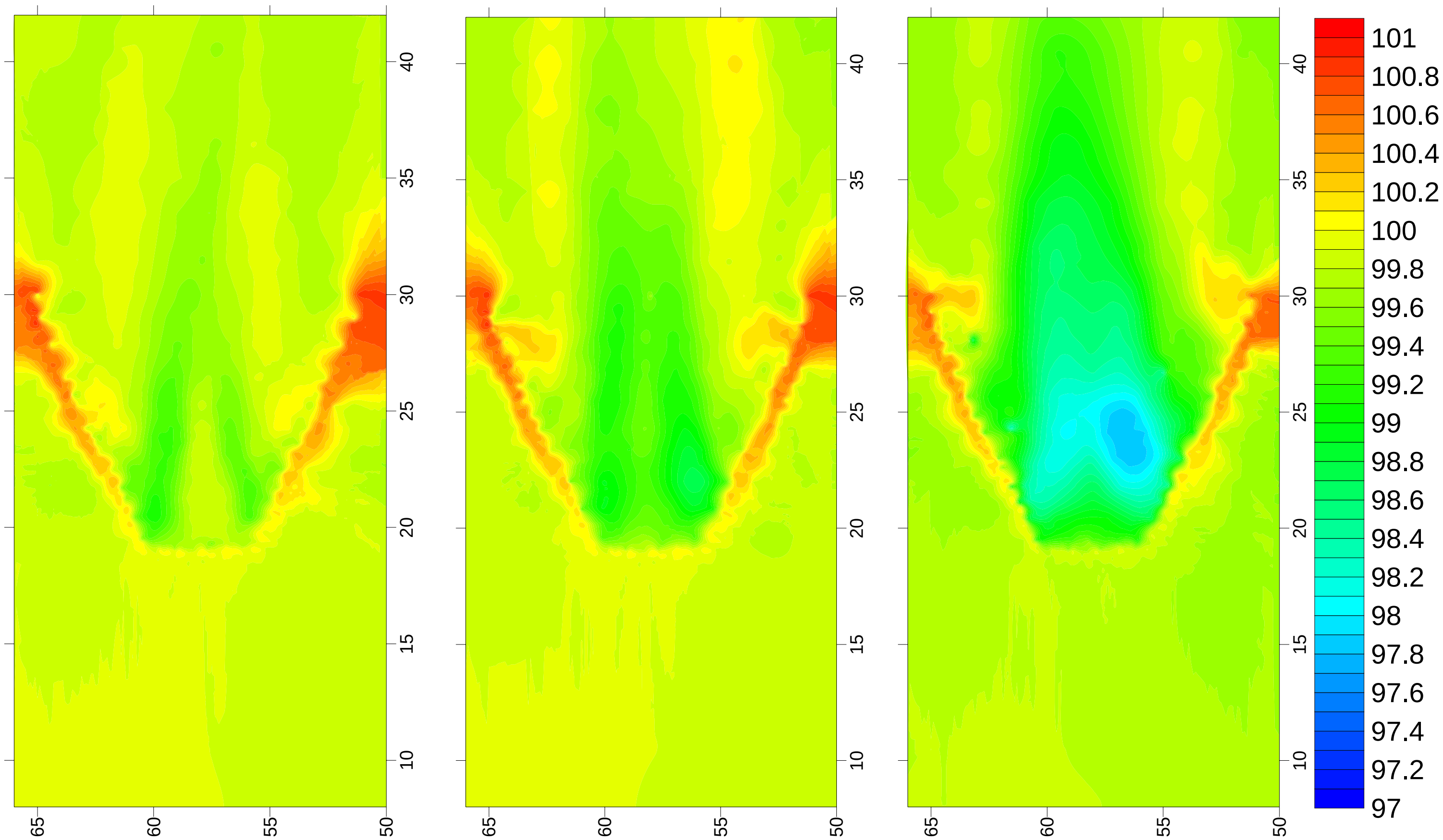
Figure 4.18. Photograph of Scour Observed After Test 10 (Bankfull Discharge)

Compared to previous tests, the rate of scour was not only greater, it was also concentrated further upstream (approximately one-fifth of the way down the weir). It was observed that while the flume was running that there was a greater flow concentration through the throat of the weir as well as more turbulence downstream of the weir compared to previous tests.

Table 4.3 summarizes the discharges and observed scour depths for each test. Bed contour plots generated with Surfer® illustrate the scour observed for each test and are presented in Figure 4.19.

Table 4.3. Approximate Scour Depths for the Tests in Configuration 3

Configuration	Test Number	Discharge (cfs)	Approx. Scour Depth (ft)
3	8	13.3	0.88
	9	26.6	1.27
	10	40.0	1.98



Test 8 (13.3 cfs) Test 9 (26.6 cfs) Test 10 (40.0 cfs)

Figure 4.19. Contour Plots for Configuration 3 (U-weir, 15-mm Bed Material, Anchored, Drop)

4.7.4 Configuration 4 – U-weir (15-mm bed material)

Testing for Configuration 4 began on April 10, 2006 and concluded on April 14, 2006. Configuration 4 corresponded to Tests 11 and 12 and consisted of a U-weir with 15-mm bed material, a bed slope of 0.0047 ft/ft, and a bankfull discharge of 40.0 cfs. For these tests, an anchor wall was constructed and the weir rocks were grouted together with no appreciable step along the weir arms. Header and footer rocks had an intermediate axis of 6.87 in. and the drop height was 0.14 ft. The section of the flume upstream of the weir was filled in with more bed material to reduce the slope by 1/2 (0.0023 ft/ft) to test the effects of upstream conditions on scour development and velocities downstream of the weir. Figure 4.15 and Figure 4.16 presented the plan and profile views of the Configuration 4 weir, respectively, which are the same as Configuration 3.

Tests were conducted at one-third and two-third bankfull discharges because of the previous testing showing the potential of scour reaching the floor at bankfull discharge. It was observed that scour depths were slightly reduced at one-third bankfull discharge but were approximately the same at two-third bankfull discharge. Like in previous tests, two discernable scour holes were seen at both discharges. A comprehensive bed survey was not collected on this test to reduce testing time, as this test was conducted to see if filling the upstream would have any significant effect on scour development. For these two tests, only the deepest points of scour were measured. Table 4.4 summarizes the discharges and observed scour depths for each test.

Table 4.4. Approximate Scour Depths for the Tests in Configuration 4

Configuration	Test Number	Discharge (cfs)	Approx. Scour Depth (ft)
4	11	13.3	0.80
	12	26.6	1.28

4.7.5 Configuration 5 – U-weir (15-mm bed material)

Testing for Configuration 5 began on April 27, 2006 and concluded on May 15, 2006. Configuration 5 corresponded to Tests 13 and 14 and consisted of a U-weir with 15-mm bed material, a bed slope of 0.0047 ft/ft, and a bankfull discharge of 40.0 cfs. For these tests, an anchor wall was constructed and the weir rocks were grouted together and a 2-by-8 board was anchored along the weir arms to mimic steps constructed in the field. Header and footer rocks had an intermediate axis of 6.87 in. and the drop height was 0.14 ft. The section of the flume upstream of the weir was filled in with more bed material to reduce the slope by one-half (0.0023 ft/ft). Figure 4.15 and Figure 4.16 presented the plan and profile views of the Configuration 5 weir, respectively, which are the same as Configuration 3.

These tests were conducted to see the effects of an installed artificial step on scour development and velocities. It was found that the step did in fact effect scour. Two distinct scour holes were observed that had migrated further downstream and scour depth was slightly decreased compared to Configuration 4. At one-third bankfull discharge, it was observed that the water did fall onto the step and then onto the bed. At higher flows, the effect of the step was negated. Figure 4.20 presents a photograph of the flume after the step was installed. Table 4.5 summarizes the discharges and observed scour depths for each test. Bed contour plots generated with Surfer® illustrate the scour observed for each test and are presented in Figure 4.21.

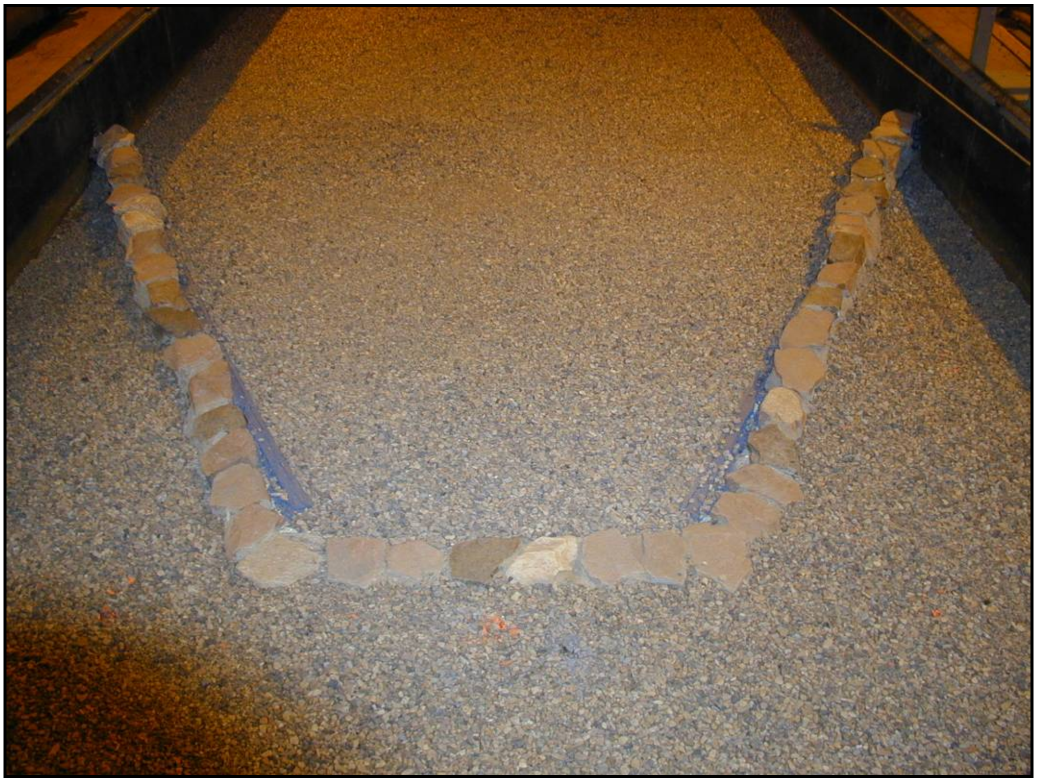
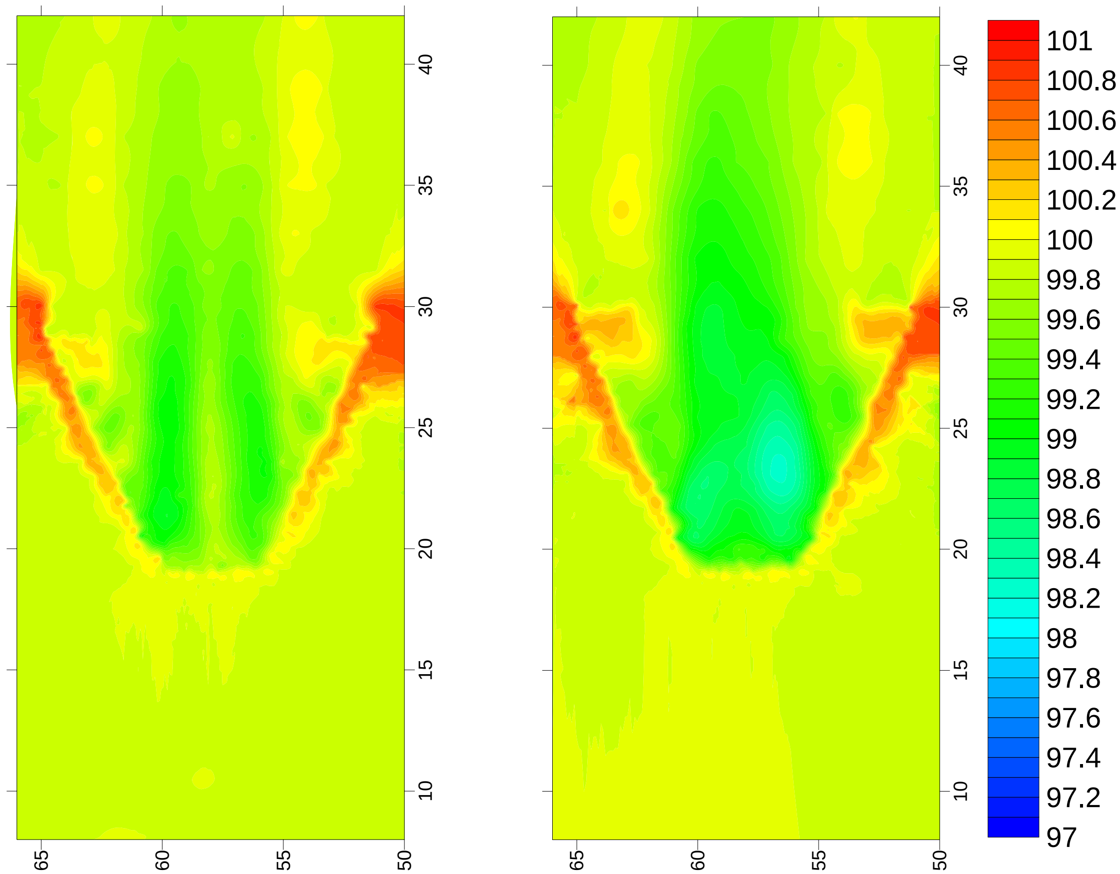


Figure 4.20. Photograph of Installed Step (Test 13)

Table 4.5. Approximate Scour Depths for the Tests in Configuration 5

Configuration	Test Number	Discharge (cfs)	Approx. Scour Depth (ft)
5	13	26.6	1.11
	14	34.0	1.72



Test 14 (34.0 cfs)

Figure 4.21. Contour Plots for Configuration 5 (U-weir, 15-mm Bed Material, Anchored, Drop)

Test 13 (26.6 cfs)

4.7.6 Configuration 6 – U-weir (5-mm bed material)

Testing for Configuration 6 began on July 12, 2006 and concluded on July 28, 2006. Configuration 6 corresponded to Tests 15 through 17 and consisted of a U-weir with 5-mm bed material, a bed slope of 0.0021 ft/ft, and a bankfull discharge of 20.0 cfs. Header and footer rocks had an intermediate axis of 10.0 in. and the drop height was 0.18 ft. For these tests, an anchor wall was constructed and the weir rocks were grouted together, and the header and footer rocks were offset by one-third of the d_{50} of the footer rocks to create a step. Figure 4.22 and Figure 4.23 present the plan and profile views of the Configuration 6 weir, respectively. Data-collection points for Configuration 6 are presented in a schematic shown in Figure 4.24.

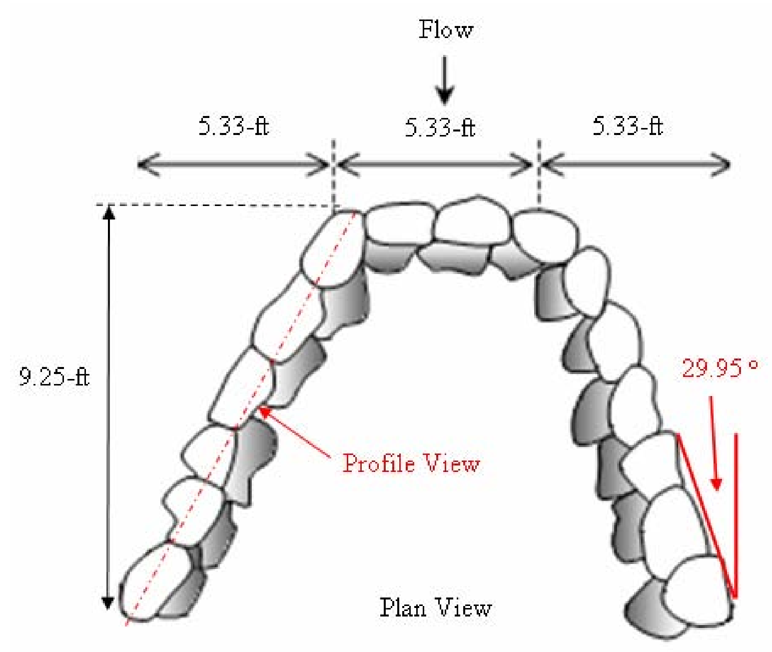


Figure 4.22. Plan View of U-weir for Configuration 6 (adapted from Rosgen (2001))

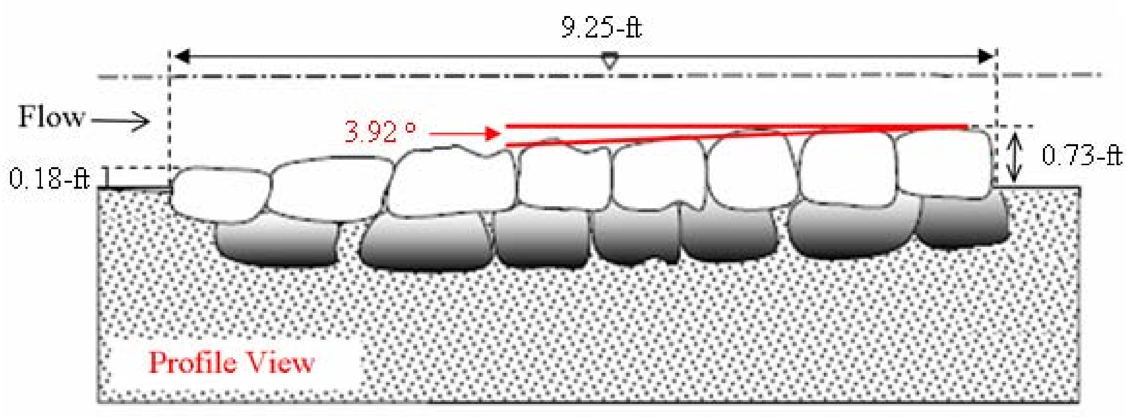


Figure 4.23. Profile View of U-weir for Configuration 6 (adapted from Rosgen (2001))

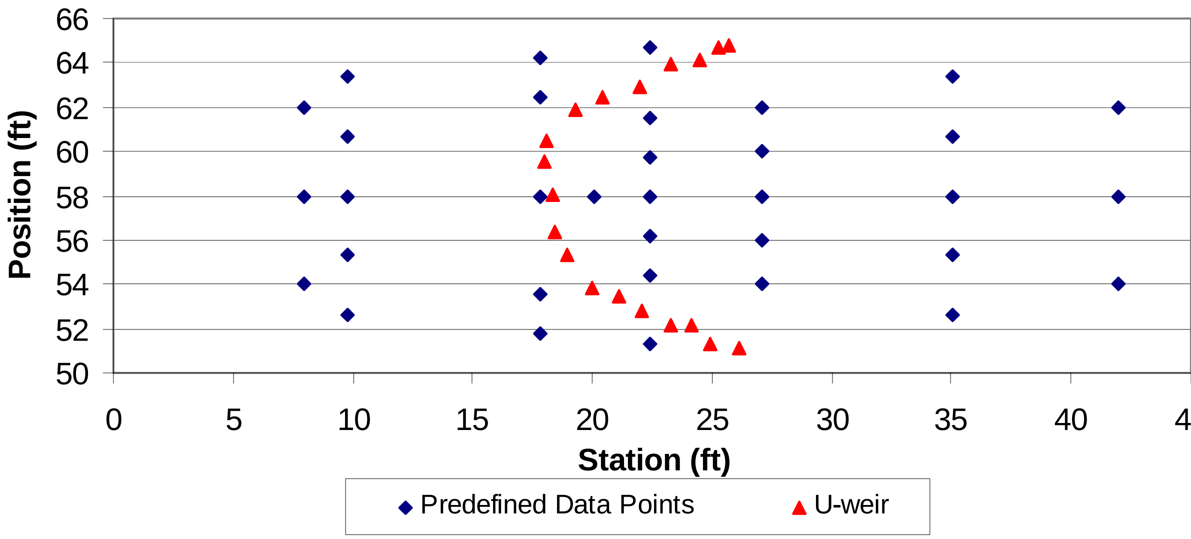


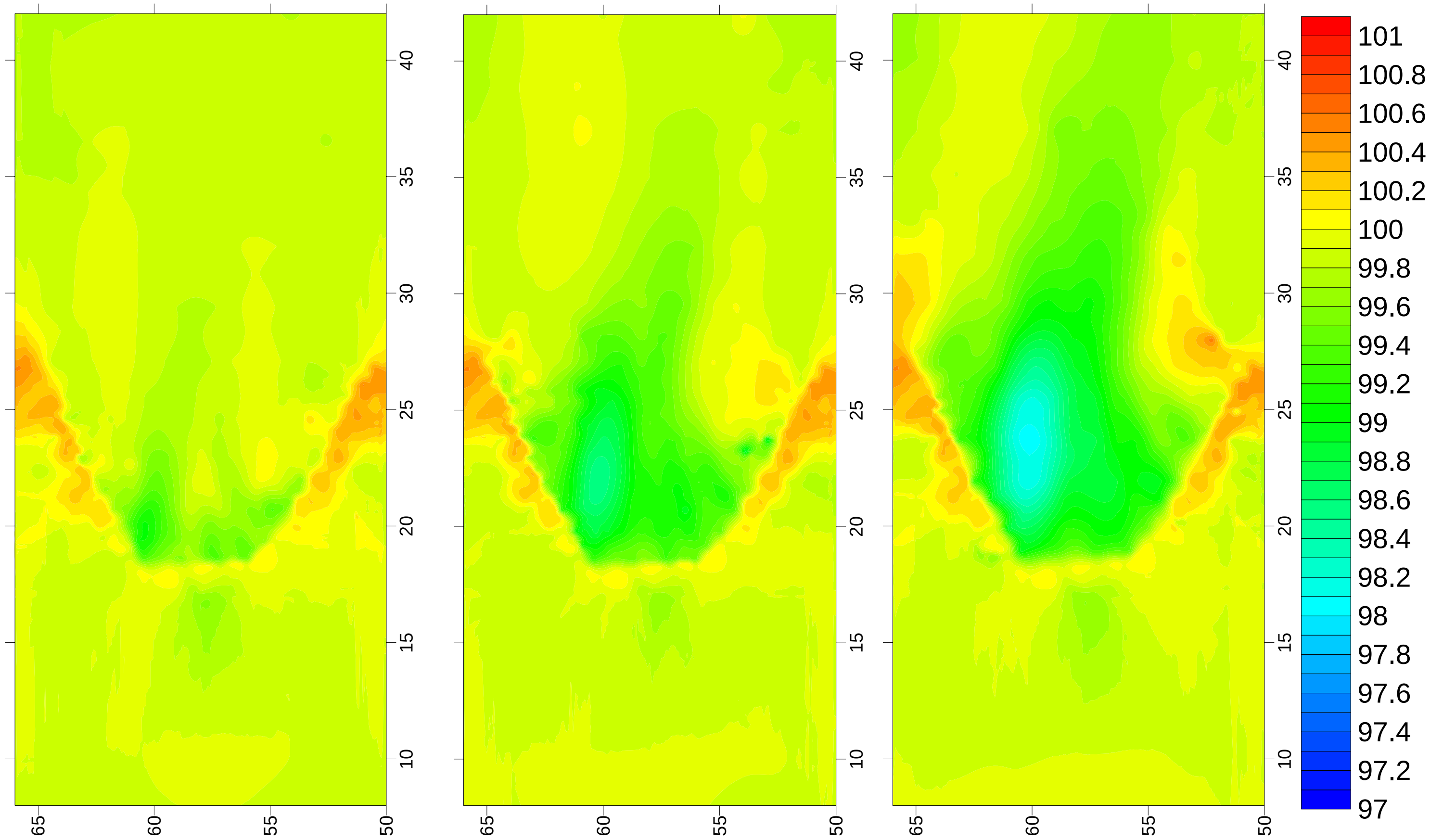
Figure 4.24. Data-collection Points for Configuration 6

It was observed that rock geometry was important at low flows. Irregular rock geometry was more prevalent with the larger rock size of the weir and because of this, the weir crest was less uniform with more undulations. As a result of the low spots and undulations, scour holes were concentrated in these areas, particularly at the lower discharges. This, along with the smaller bed material, aided in the creation of more numerous scour holes. Scour developed much more asymmetrically during this configuration. Figure 4.25 presents a photograph of the flume after running Test 17. Table 4.6 summarizes the discharges and observed scour depths for each test. Bed contour plots generated with Surfer® illustrate the scour observed for each test and are presented in Figure 4.26.

Figure 4.25. Photograph of Flume After Test 17

Table 4.6. Approximate Scour Depths for the Tests in Configuration 6

Configuration	Test Number	Discharge (cfs)	Approx. Scour Depth (ft)
6	15	6.5	0.93
	16	13.3	1.49
	17	20.0	1.97



Test 15 (6.5 cfs) Test 16 (13.3 cfs) Test 17 (20.0 cfs)

Figure 4.26. Contour Plots for Configuration 6 (U-weir, 5-mm Bed Material, Anchored, Drop)

4.7.7 Configuration 7 – U-weir (9.8-mm bed material)

Testing for Configuration 7 began on August 29, 2006 and concluded on October 21, 2006. Configuration 7 corresponded to Tests 18 through 20 and consisted of a U-weir with 9.8-mm bed material, a bed slope of 0.0033 ft/ft, and a bankfull discharge of 30.0 cfs. The size of the header and footer rocks was 8.8 in. and the drop height was 0.17 ft. For these tests, an anchor wall was constructed and the weir rocks were grouted together, and the header and footer rocks were offset by one-third of the intermediate axis of the footer rocks to create a step. Figure 4.27 and Figure 4.28 present the plan and profile views of the Configuration 7 and 8 weirs, respectively. Data-collection points for Configurations 7 and 8 are presented in a schematic shown in Figure 4.29.

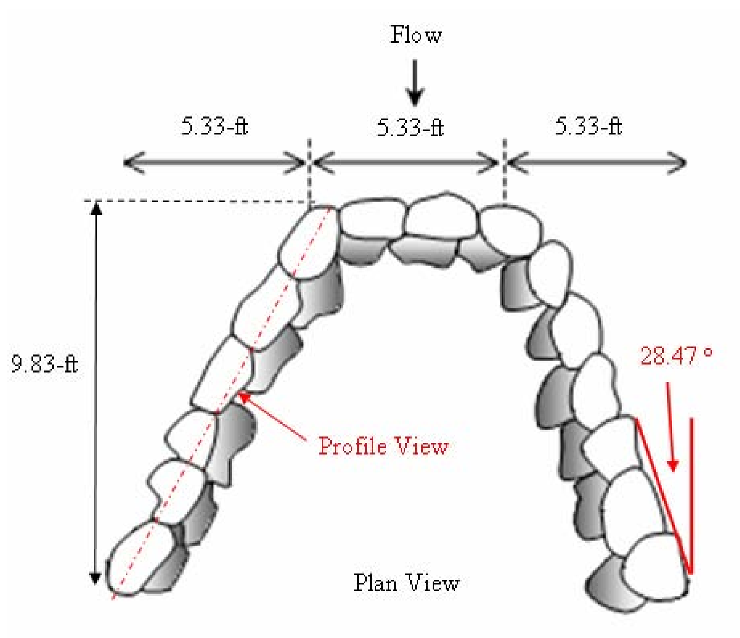


Figure 4.27. Plan View of U-weir for Configurations 7 and 8 (adapted from Rosgen (2001))

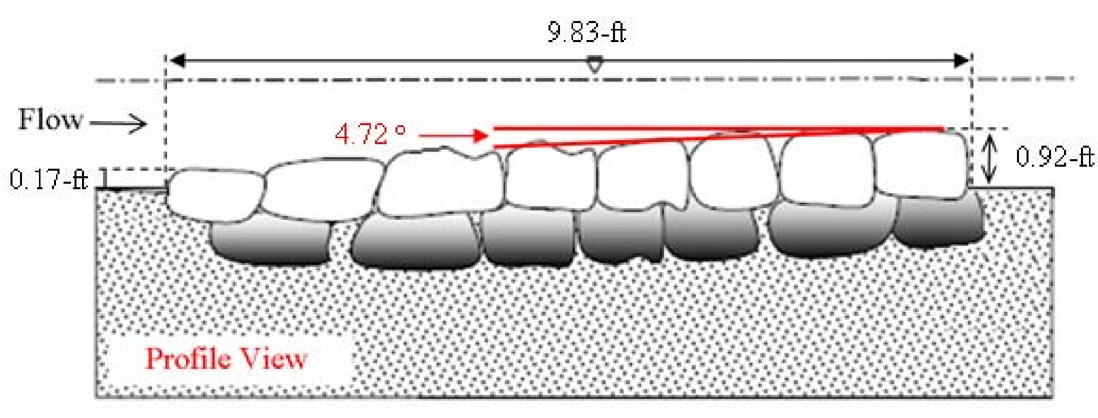


Figure 4.28. Profile View of U-weir for Configurations 7 and 8 (adapted from Rosgen (2001))

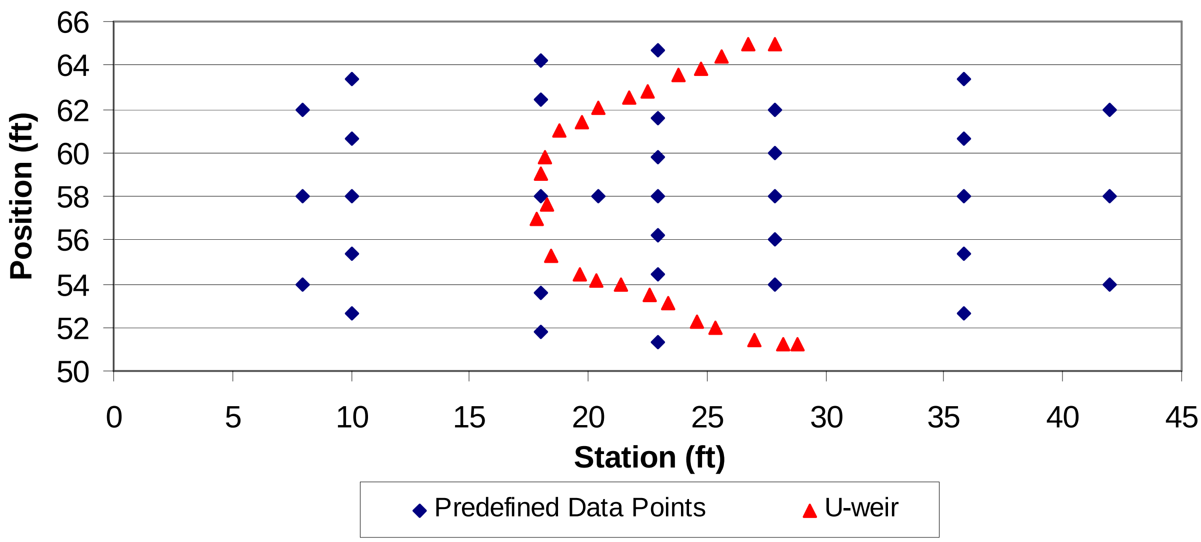


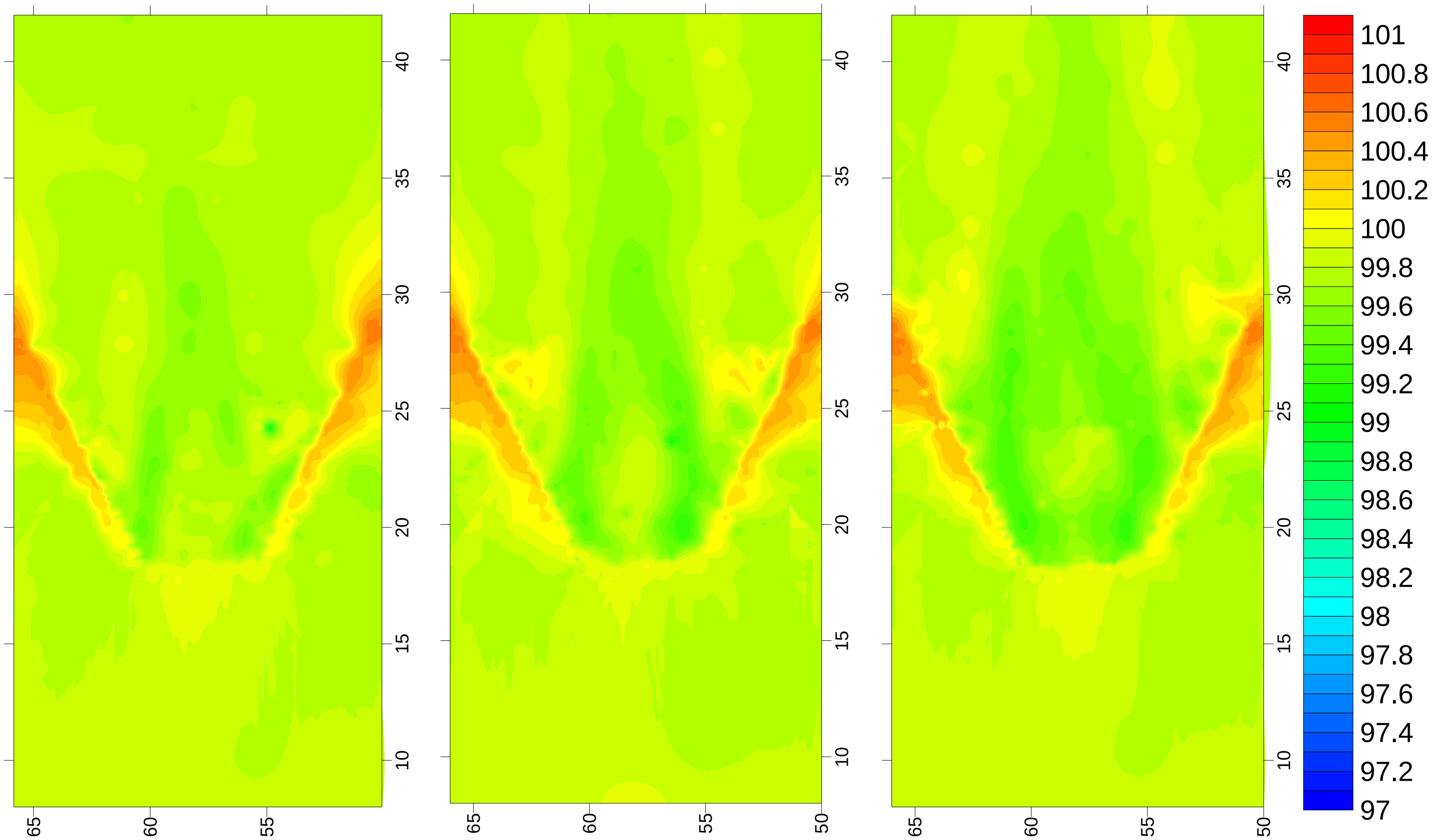
Figure 4.29. Data-collection Points for Configurations 7 and 8

These tests were peculiar since the deepest scour was observed at the one-third bankfull discharge, 1.07 ft, and decreased with increasing discharge. This could be attributed to armoring of the bed or the weir may have been submerged at the higher flows. Testing procedures for this configuration remained the same as previous configurations. More data analysis on the velocities and water-surface profiles is needed. Figure 4.30 presents a photograph of the flume after Test 20. Table 4.7 summarizes the discharges and observed scour depths for each test. Bed contour plots generated with Surfer® illustrate the scour observed for each test and are presented in Figure 4.31.

Figure 4.30. Photograph of Flume After Test 20

Table 4.7. Approximate Scour Depths for the Tests in Configuration 7

Configuration	Test Number	Discharge (cfs)	Approx. Scour Depth (ft)
7	18	10.0	1.07
	19	20.0	0.90
	20	30.0	0.79



Test 19 (20.0 cfs)

Test 20 (30.0 cfs)

Figure 4.31. Contour Plots for Configuration 7 (U-weir, 9.8-mm Bed Material, Anchored, Drop)

Test 18 (10.0 cfts)

4.7.8 Configuration 8 – U-weir (9.8-mm bed material)

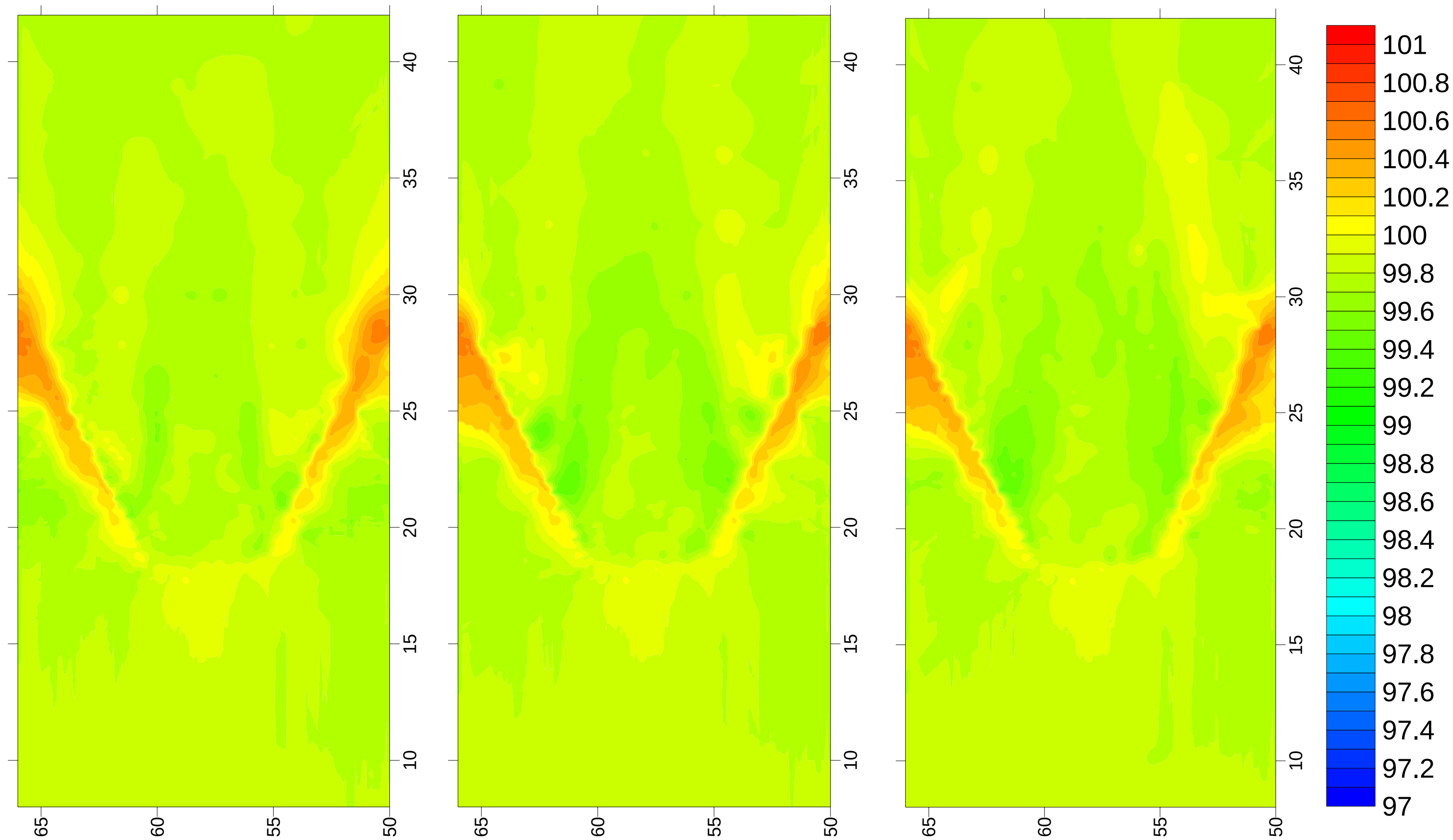
Testing for Configuration 8 began on November 1, 2006 and concluded on November 13, 2006. Configuration 8 corresponded to Tests 21 through 23 and consisted of a U-weir with 9.8-mm bed material, a bed slope of 0.0033 ft/ft, and a bankfull discharge of 30.0 cfs. Header and footer rocks had an intermediate axis of 8.8 in. and the drop height was 0.17 ft. For these tests, an anchor wall was constructed and the weir rocks were grouted together. Figure 4.27 and Figure 4.28 presented the plan and profile views of the Configuration 8 weir, respectively, which are the same as Configuration 7.

Despite efforts to set the normal depth of Test 21 equal to that of Test 18, the weir looked to be more submerged which might contribute to the fact that the observed scour depth for Test 21 was less than one-half of that observed for Test 18. However, the same trend of decreasing scour depth between two-third and bankfull discharges was observed. It is suspected that this trend might be due to the bed armoring. The weir may have also been submerged, which might account for the decreased scour depth. Differences between scour depth between two-third bankfull discharge and bankfull discharge were very small, 0.02 ft compared to 0.11 ft for Configuration 7. Figure 4.32 presents a photograph of the flume after Test 23. Table 4.8 summarizes the discharges and observed scour depths for each test. Bed contour plots generated with Surfer® illustrate the scour observed for each test and are presented in Figure 4.33.

Figure 4.32. Photograph of Flume After Test 23

Table 4.8. Approximate Scour Depths for the Tests in Configuration 8

Configuration	Test Number	Discharge (cfs)	Approx. Scour Depth (ft)
8	21	10.0	0.51
	22	20.0	0.61
	23	30.0	0.59



Test 21 (10.0 cfs) Test 22 (20.0 cfs) Test 23 (30.0 cfs)

Figure 4.33. Contour Plots for Configuration 8 (U-weir, 9.8-mm Bed Material, Anchored, Drop)

4.7.9 Configuration 9 – U-weir (5-mm bed material)

Testing for Configuration 9 began on December 19, 2006 and concluded on January 10, 2007. Configuration 9 corresponded to Tests 24 through 26 and consisted of a U-weir with 5-mm bed material, a bed slope of 0.0021 ft/ft, and a bankfull discharge of 20.0 cfs. Header and footer rocks had an intermediate axis of 10.0 in. and the drop height was 0.18 ft. For these tests, an anchor wall was constructed and the weir rocks were grouted together. Figure 4.34 and Figure 4.35 present the plan and profile views of the Configuration 9 weir, respectively. Data-collection points for Configuration 9 are presented in a schematic shown in Figure 4.36.

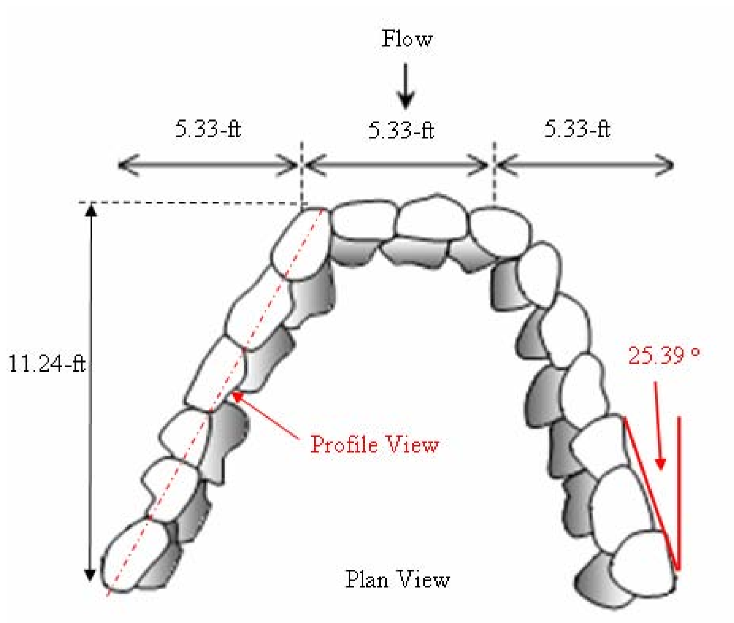


Figure 4.34. Plan View of U-weir for Configuration 9 (adapted from Rosgen (2001))

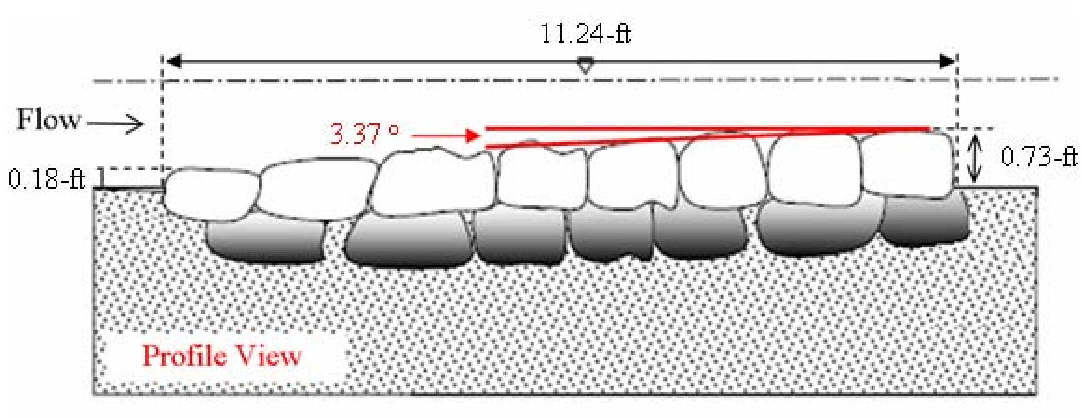


Figure 4.35. Profile View of U-weir for Configuration 9 (adapted from Rosgen (2001))

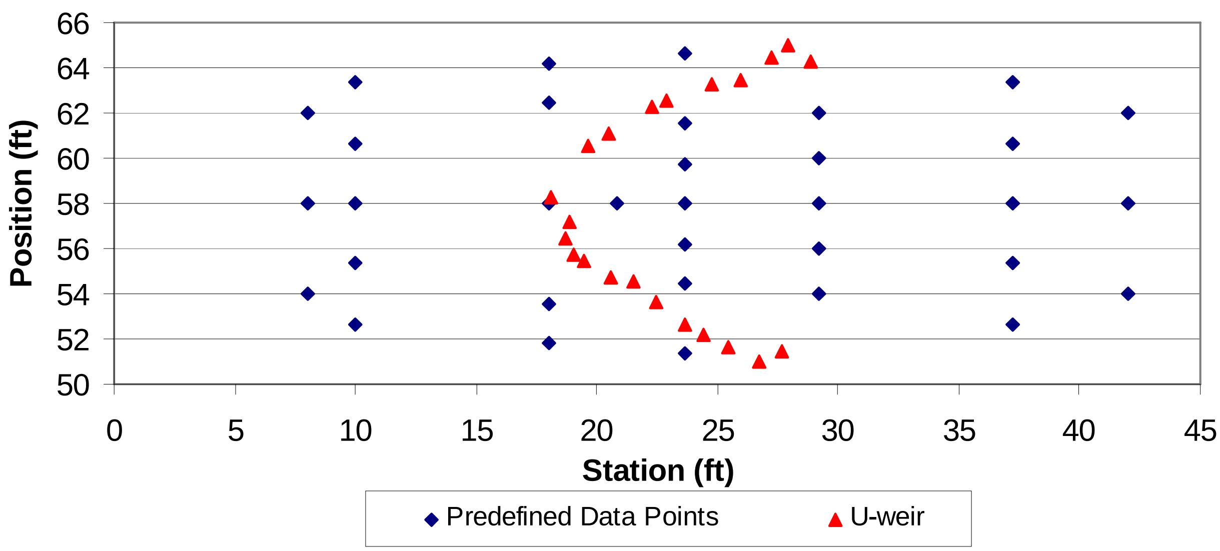


Figure 4.36. Data-collection Points for Configuration 9

During these tests, it was observed that rock geometry was important at low flows. Irregular rock geometry was more prevalent with the larger weir rock size and because of this the weir crest was less uniform with more undulations and low spots. As a result of the low spots and undulations, scour holes were concentrated in these areas, particularly at the lower discharges. This, along with the smaller bed material, aided in the creation of more numerous scour holes. Scour developed much more asymmetrically during this configuration. However, scour for this configuration was more symmetric than for Configuration 6. This can be attributed to the grout between the weir rocks being more uniform and level with the rock-surface elevation. Figure 4.37 presents a photograph of the flume after running Test 26. Table 4.9 summarizes the discharges and observed scour depths for each test. Bed contour plots generated with Surfer® illustrate the scour observed for each test and are presented in Figure 4.38.

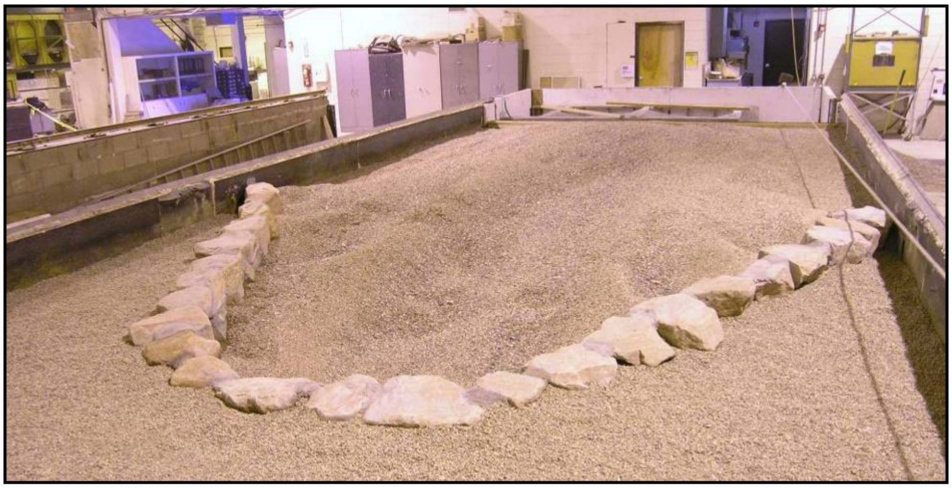
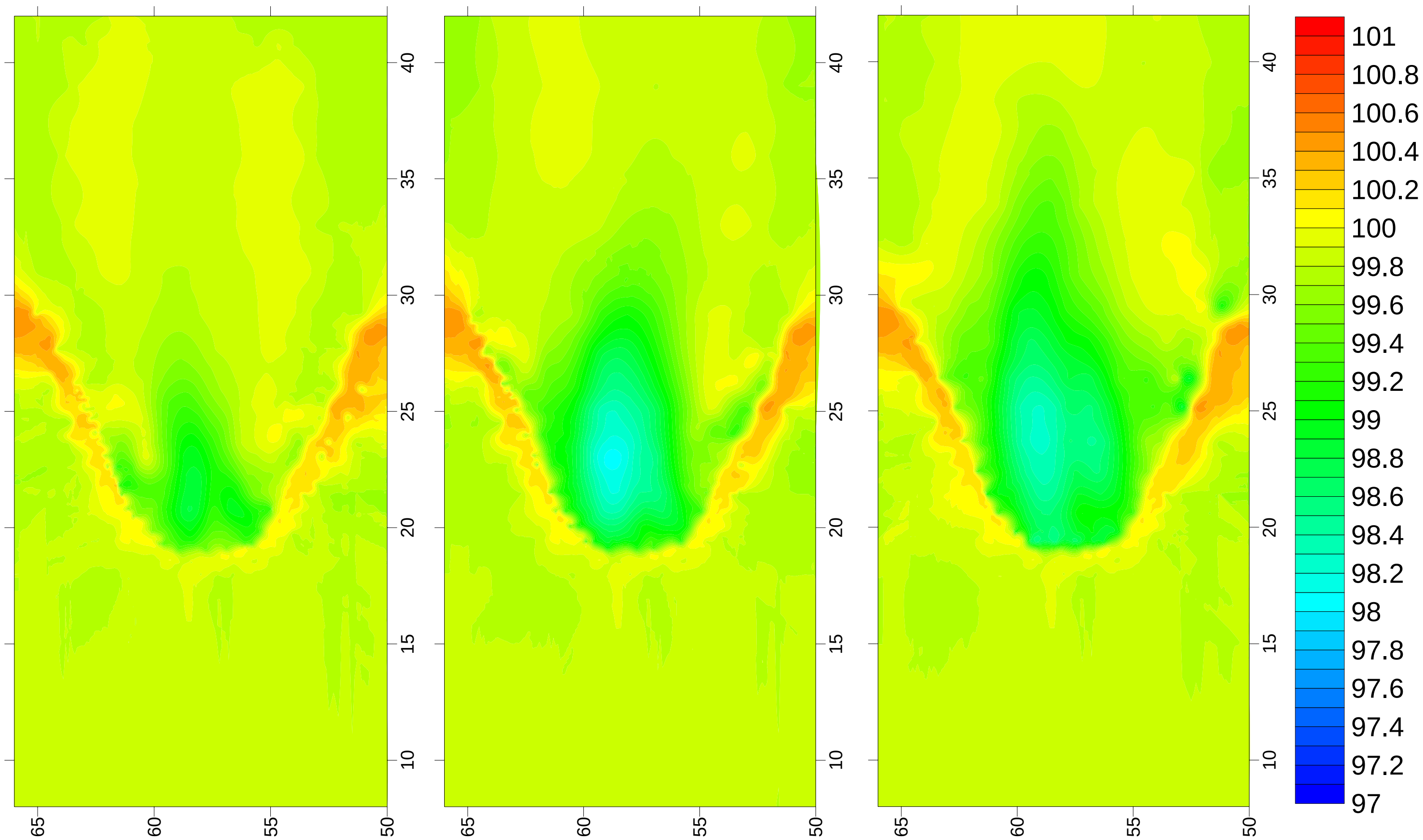


Figure 4.37. Photograph of Flume After Test 26

Table 4.9. Approximate Scour Depths for the Tests in Configuration 9

Configuration	Test Number	Discharge (cfs)	Approx. Scour Depth (ft)
9	24	6.7	1.22
	25	13.3	1.95
	26	20.0	1.77



Test 25 (13.3 cfs)

Test 26 (20.0 cfs)

Figure 4.38. Contour Plots for Configuration 9 (U-weir, 5-mm Bed Material, Anchored, Drop)

Test 24 (6.7 cfs)

CHAPTER 5

RECOMMENDATIONS

For future research, investigating different drop heights and their effect on scour would be important in creating a drop height versus scour depth relationship. Testing over greater bed slopes would aid in the applicability of the research to the most widespread field work. Looking into the effects of pre-dug scour holes on scour development would allow for tests more representative of weirs installed in the field. Additionally, investigating the effects of a fixed stop-log height would be valuable, since it is more representative of field conditions.

It is recommended that the research results be used for applications consistent with that of the laboratory (discharge, slope, weirs, etc.). The weirs should be constructed with blocky, tight-fitting rock, which minimizes interstitial flow. In addition, the header rocks should be offset upstream about one-third of the intermediate axis length. This research provided the required data to create a 3-D computer model with the intent to accurately predict velocities and scour development downstream of alphabet weirs.

CHAPTER 6

SUMMARY

From July 2005 to October 2006, Engineering Research Center personnel at Colorado State University have conducted physical model testing of alphabet weirs. Structure tested include U- and W-weirs, with bed materials of 5 mm, 9.8 mm, and 15 mm and bed slopes of 0.0021 ft/ft, 0.0033 ft/ft, and 0.0047 ft/ft, respectively. Correspondingly, the discharges for the 5-mm, 9.8-mm, and 15-mm bed materials were 20 cfs, 30 cfs, and 40 cfs, respectively. The purpose of this testing was to measure 3-D velocities, bed and water-surface readings, as well as bed contours. These data were collected with the intent to calibrate a 3-D numerical computer model created by the Bureau of Reclamation. A description of construction methods, testing procedures, test matrix, and results are presented in this report.

CHAPTER 7

REFERENCES

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