Physical Model Study, CSO Diversion through Bottom Outlet Slot, Site DS-4 Upper Rouge Tunnel System

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Executive Summary

The objective of this study was to determine the discharge characteristics of flow through a bottom discharge slot in a nearly horizontal circular pipe. The study consisted of an experimental model constructed in the University of Michigan Hydraulics Laboratory. The model study was a scaled representation of a proposed bottom outlet slot diversion structure for the Upper Rouge Tunnel combined sewer overflow project in Southeast Michigan. The purpose of the slot is to allow discharge from the flow conduit into a deeper storage facility until the storage facility was filled to capacity after which the flow would continue to overflow in the original conduit. The main goals of the bottom outlet slot design are to control the flow passively and to minimize head losses in the conduit to avoid excessive backwater effects from the diversion structure.

The design flow of the DS-4 site is 1197 cfs and the conduit diameter is 13 ft. The scaled experiments were performed with an 8 inch (I.D.) pipe making the physical scale ratio equal to 1:19.5. The discharge was regulated with a gate valve and metered with a master venturi meter. Initially, the model construction included the vertical side walls beneath the bottom outlet slot. However, it was determined that this geometry did not influence the discharge in any way that would affect the upstream flow profile or the length of slot filled by the outflow. The geometry of the slot was 1.23 inches wide by 42.63 inches long (prototype dimensions of 2 ft. wide by 69.2 ft. long). The width of the slot was later increased to 1.53 in. (2.5 ft. prototype) to observe the effect of the slot width on the flow behavior. For each slot width, the flow rate was adjusted to several different values and the length of flowing water in the slot was observed. The slot width, slot length occupied by the flowing water (subsequently referred to as simply "slot length"), pipe slope, and discharge were measured for each trial and are presented in Table A-1 of the appendix.

A number of observations were noticed during the model study analysis. One important observation in describing the flow was that the flow was supercritical above most of the slot length. The transition from subcritical to supercritical was observed near the upstream end of the bottom outlet slot. Further, the flow patterns above the slot were clearly not two-dimensional because considerable variations were noticed in the lateral direction. A layer of film flow developed along the edges of the slot at the downstream

end, which is most likely accentuated in the scaled model by the effect of surface tension. The experimental results showed that increasing the pipe slope causes only minor increases to slot length. A consistent relationship is observed between the discharge divided by slot width and the slot length for both slot widths. Based on these observations and the experimental analysis, a slot length of 70 feet is recommended for the slot width of 2 ft. and a slot length of 60 ft. is recommended for a slot width of 2.5 ft.

Introduction

An outlet slot constructed in the bottom of the existing DS-4 outfall conduit is to be used as a diversion structure conveying flow from the sanitary collection system to the Upper Rouge Tunnel during periods of high system discharge. Figures A-1 and A-2 of the appendix represent a preliminary version of the proposed design. The purpose of this slot is to allow flow to pass through the slot into the Upper Rouge Tunnel when the tunnel is not full and to allow flow to continue downstream with minimal head loss after the tunnel has filled.. The design flow for this site is 1197 cfs. and the goal for this project was to determine acceptable bottom outlet slot geometries such that 100% of the flow could be diverted through the slot whenever the storage tunnel is not full.

There are two main advantages for using a bottom outlet slot design as a diversion structure. First of all, once the structure is constructed the flow control is completely passive. There are no gates or control switches required to divert flow back to the conduit when the tunnel is full. Furthermore, this bottom outlet slot design minimizes the amount of hydraulic energy loss experienced in the system. With no obstructions protruding into the cross section of the flow, it will experience a minimal amount of resistance as flow passes over a full tunnel.

Experimental Setup

A scale model was constructed at the University of Michigan Hydraulics Laboratory in order to measure the flow properties through the Upper Rouge Tunnel DS-4 bottom outlet slot system. The diameter of the designed prototype system was 13 ft. and the experimental model used an 8 inch diameter (I.D.) pipe, thus making the physical scale ratio 1:19.5. Considering dynamic similarity based on the Froude number, the model discharge should be a factor of $(19.5)^{-2.5}$ of the prototype flow. The prototype design flow of the DS-4 site is 1197 cfs., which corresponds to 0.715 cfs. in the model. At the design discharge, the approach flow in the pipe will have a Reynolds Number in excess of 100,000, a level generally accepted as sufficiently large to avoid significant scale effects. The discharge was measured in the laboratory using a master venturi meter.

An illustration of the experimental setup is presented in Figure 1 below The source of flow came from a constant head reservoir tank and was controlled by an 8 inch gate valve. Approximately 15 ft. of 8 inch PVC pipe was placed upstream of the 5 ft.

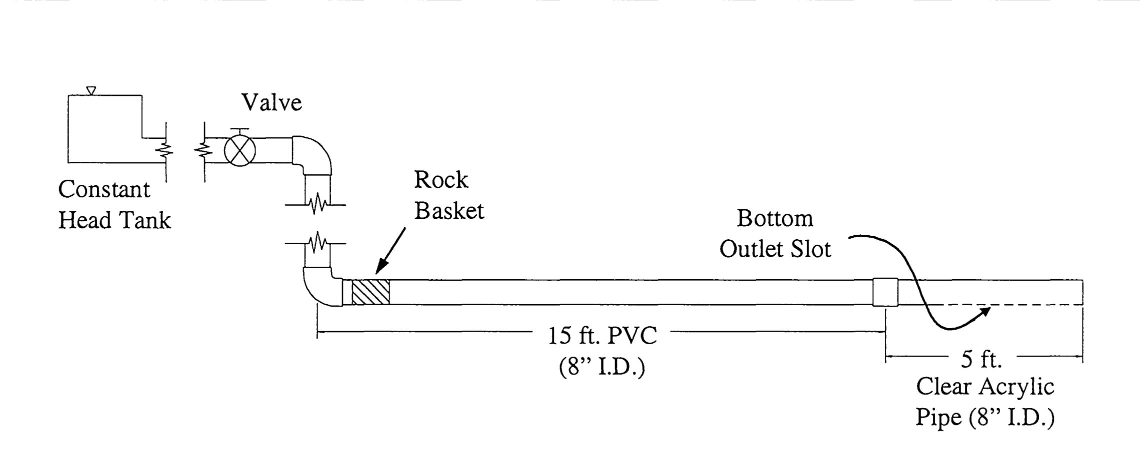

Figure 1: Experimental Setup

clear acrylic pipe section containing the bottom outlet slot. A wire basket filled with coarse crushed limestone was placed at the start of the straight length of PVC pipe to eliminate any secondary flows from the upstream bends. The downstream end of the acrylic pipe was open such that any continuing flow freely exited out the end.

The slot was constructed by mounting the acrylic pipe on a mill bed and machining the slot to the desired dimensions. The slot walls were thus vertical as opposed to aligned with the pipe radius.

Initially, the model construction included the vertical walls (as shown in Figure 2; here the camera was not completely horizontal) below the slot opening with the dimensions provided in preliminary design drawings that were provided by Wade Trim (Figures A-1 and A-2 of the appendix). Preliminary experiments were performed with these walls in place and with a free discharge (walls removed) to determine whether either the slot length or the upstream water depth was influenced by their presence. It was concluded that these walls do not influence the slot discharge in any way that modifies either the upstream depth in the conduit or the length of slot filled by a particular flow. Following this determination, the remaining measurements were conducted with the freely discharging slot since this configuration allowed for better observations of the nature of the flow.

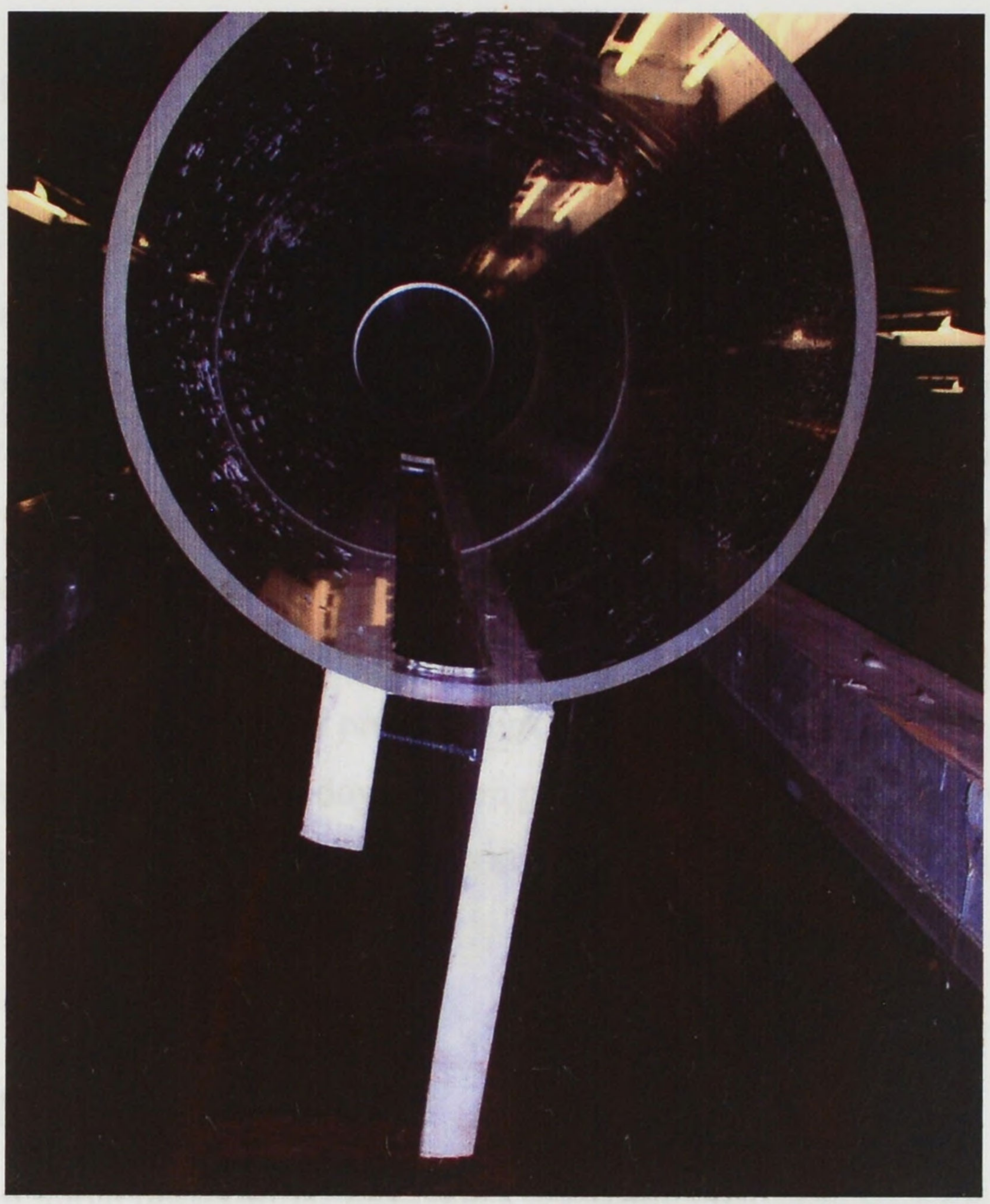

Figure 2: Side Walls Below Slot

The slot width in the preliminary design was 2 ft, corresponding to a 1.23 inch slot width for the model. The initial slot length of the model was 2.67 ft. (52 ft. prototype) based on some preliminary measurements that were made in a much smaller diameter pipe. When it became clear that the slot was unable to pass the design discharge, the slot length was increased to 3.55 ft (69.3 ft. prototype). Following experiments with this slot width, the width was increased to 1.53 in. (2.5 ft. prototype). \. The pipe was supported along the top of a laboratory flume with adjustable slope capability. The pipe slope could be altered using the flume slope adjustment mechanism. Measurements were taken at slopes of 0 and 0.008.

Experimental Procedure

Once the experimental model was prepared, the procedure was straightforward. The only variables which changed for each slot width were the slope of the model, slot width, and discharge. As the flow changed, the slot length required to accommodate such a flow also changed. Starting with an initially closed valve, it was opened incrementally until the flow could no longer fully pass through the slot. For each valve opening the venturi meter reading was recorded as well as the slot length distance. Defining this distance of flow at the downstream end required careful interpretation. The slot length for this study has been defined as the complete distance covered by the flow, including the distance after which the center profile drops below the invert of the pipe. In other words, there was a portion of the downstream profile which experienced flow only along the side edges of the slot and this distance was included in the definition of the slot length measurement.

Results & Discussion

Several initial observations were made concerning the characteristics of the flow. The trajectory of water leaving the bottom outlet slot was very similar at both ends of the opening. Although the flow is more complex than that, this observation is indicative that the horizontal velocity in the flow is fairly consistent in the pipe above the slot. Since the depth is continuously decreasing along the slot, this observation would also imply that the Froude number of the flow is increasing along the slot length. To verify this behavior a small obstacle was placed in the flow above the slot to determine whether a hydraulic jump would form locally upstream of the obstacle. The hydraulic jump would indicate a transition between a supercritical flow and the subcritical flow caused by the obstacle. By moving the obstacle further upstream, it was observed that the flow passes from a subcritical state upstream of the slot to a supercritical state over the slot with the transition through critical flow depth occurring approximately at the upstream end of the slot. A photograph of the flow profile can be seen in Figure 3.

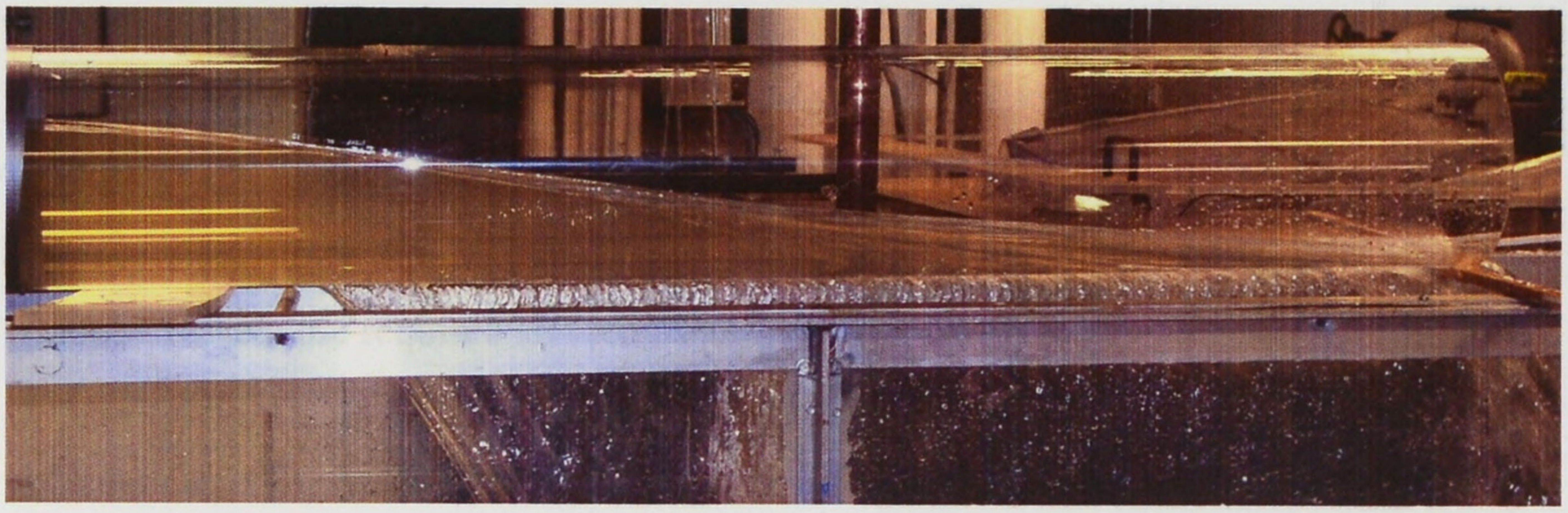

Figure 3: Photograph of Flow Profile

Observations clearly indicate that the flow in the conduit is definitely not two-dimensional above the slot and varies considerably in the lateral direction as the water depth approaches zero. At the upstream end of the slot the flow is fairly uniform laterally but this is not the case towards the downstream end of the slot flow. A very weak hydraulic jump developed immediately above the slot causing a small increase in depth above the slot compared to the flow on either side of the slot. Moving further downstream, eventually the leaving flow begins to influence the flow so that a depression in the water surface above the slot develops. This depression becomes so great that the water surface is below the pipe invert in the center of the slot, even where there is a fair amount of flow still remaining in the pipe. As the flow depth feathers out to approach zero, the center of the slot appears to be open to the atmosphere with flow still occurring near the edges of the slot. This flow persists for some distance downstream (typically a few inches at the laboratory scale) and it is believed that this effect would be accentuated by surface tension as a very thin film flow develops. Assuming the effect is due to surface tension, this effect is not reproduced properly in the smaller scale model and the film flow will be exaggerated compared to what would be expected in the prototype. In the results reported below, the slot is considered effective in capturing the flow when all but a small portion of the film flow leaves through the slot. Measurements of the rate of water passing downstream of the slot for a flow condition where the full length of the slot was deemed effective in passing the discharge indicate that this bypassing flow would be on the order of 3-4 cfs prototype, or less than one percent of the design flow. It is believed that this bypassing will not occur at the prototype scale.

Experimental results are presented in Figures A-3 through A-6 of the Appendix. For a given discharge, a higher pipe slope caused a minimally longer required slot length. Varying the slope from slightly adverse to a maximum of 0.008 results in only a very minor increase to the slot length. The more significant behavior was that as the slot width increased, the required slot length decreased, as seen by the presentation of the data in Figure A-5. Using dimensional analysis reasoning to combine variables, an equation was found that fits the data well:

$$L = 1.05 \cdot \left(\frac{Q}{W}\right)^{(2/3)}$$

The above equation is not dimensionally homogeneous and was developed to apply for prototype conditions with lengths given in feet and discharges in cubic feet per second Figure A-6 shows the discharge divided by the slot width versus the slot length. This plot shows that the data points form a consistent relationship according to the equation above within the range of flows that were considered. A complete set of the experimental measurements are presented in Table A-1.

Conclusions

Some general statements can be made concerning the behavior of flow through this bottom outlet slot design.

- The vertical side walls beneath the discharge slot do not influence the discharge in any way that modifies either the upstream depth in the conduit or the length of slot filled by a particular flow.
- The Froude number characterizing the flow increased in the downstream direction. The transition from subcritical to supercritical flow occurs near the start of the slot opening.

- The flow patterns varied considerably in all three dimensional directions, meaning that an accurate numerical model describing the flow behavior may require more than a 2-D approach.

- A layer of film flow developed along the edge of the slot at the downstream end, increasing the length of slot through which water flowed. It is reasonable to assume that surface tension influences this film flow by lengthening the flow along the slot edges.

- Small adjustments to the conduit slope have a relatively small influence on experimental measurements.

- The influence of changing the slot width can be described well by using the relationship: $L = 1.05 \cdot \left(\frac{Q}{W}\right)^{(2/3)}$ with L and W in feet and Q in cfs. This slot length includes the film flow along the sides of the slot and can be reduced by 10 percent and still capture all but a fraction of a percent of the total discharge. Under this assumption, the constant can be adjusted downward from 1.05 to 0.95.

Given the above analysis of the experiments, the slot length required to capture all of the design flow for two different slot widths, 2.0 ft and 2.5 ft, can be determined. It is recommended to provide a slot length of approximately 68 ft for the 2.0 ft wide slot and approximately 58 ft for the 2.5 ft slot. Because the definition of when the slot captures all the flow appears to be influenced by scale (surface tension) effects of unknown significance, it is further recommended to increase these two lengths to 70 and 60 ft, respectively to provide a small margin for error.

Appendix

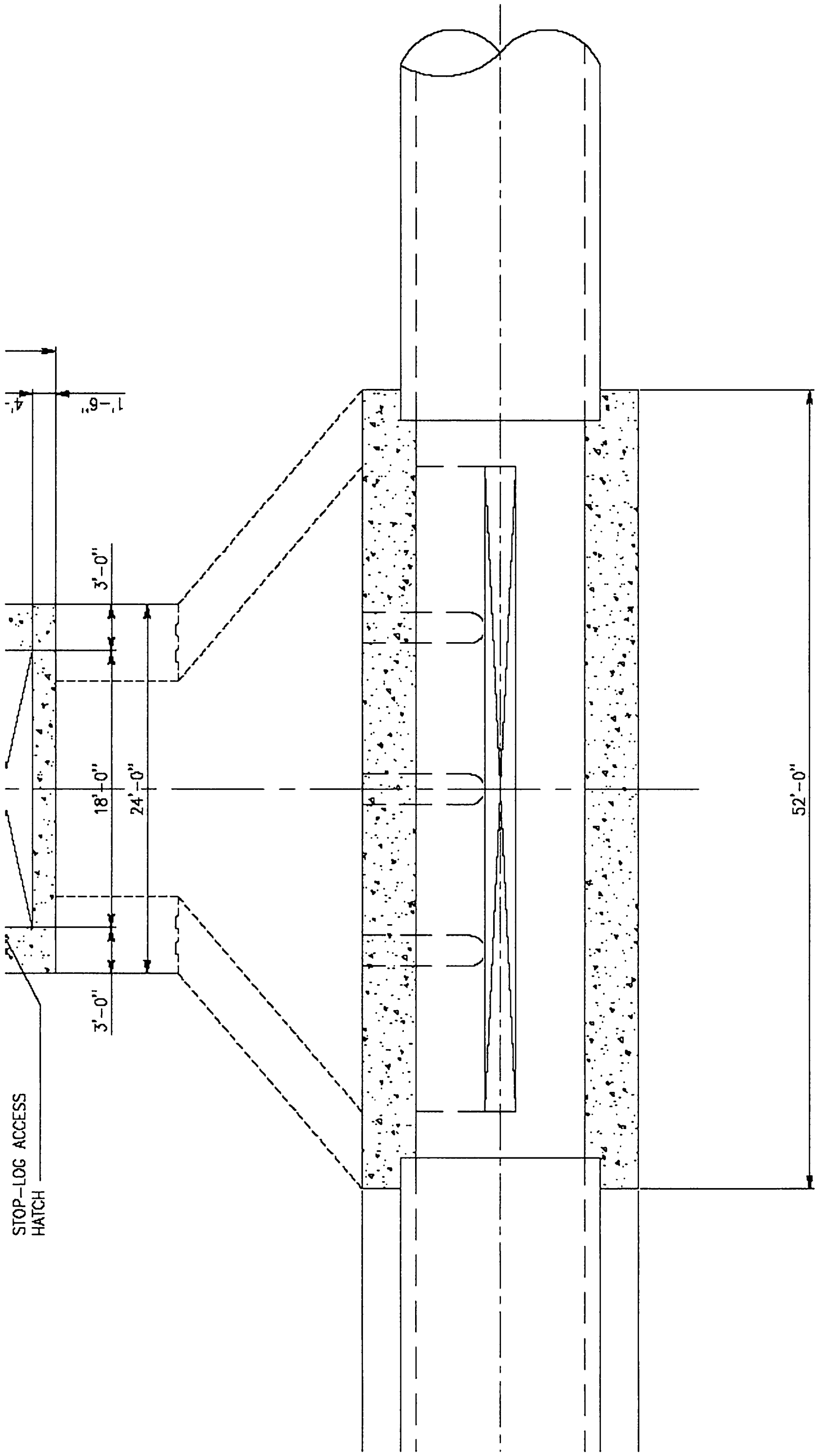

Figure A-1: Plan View of Proposed Bottom Outlet Slot Design at Site DS-4 (provided by Wade Trim)

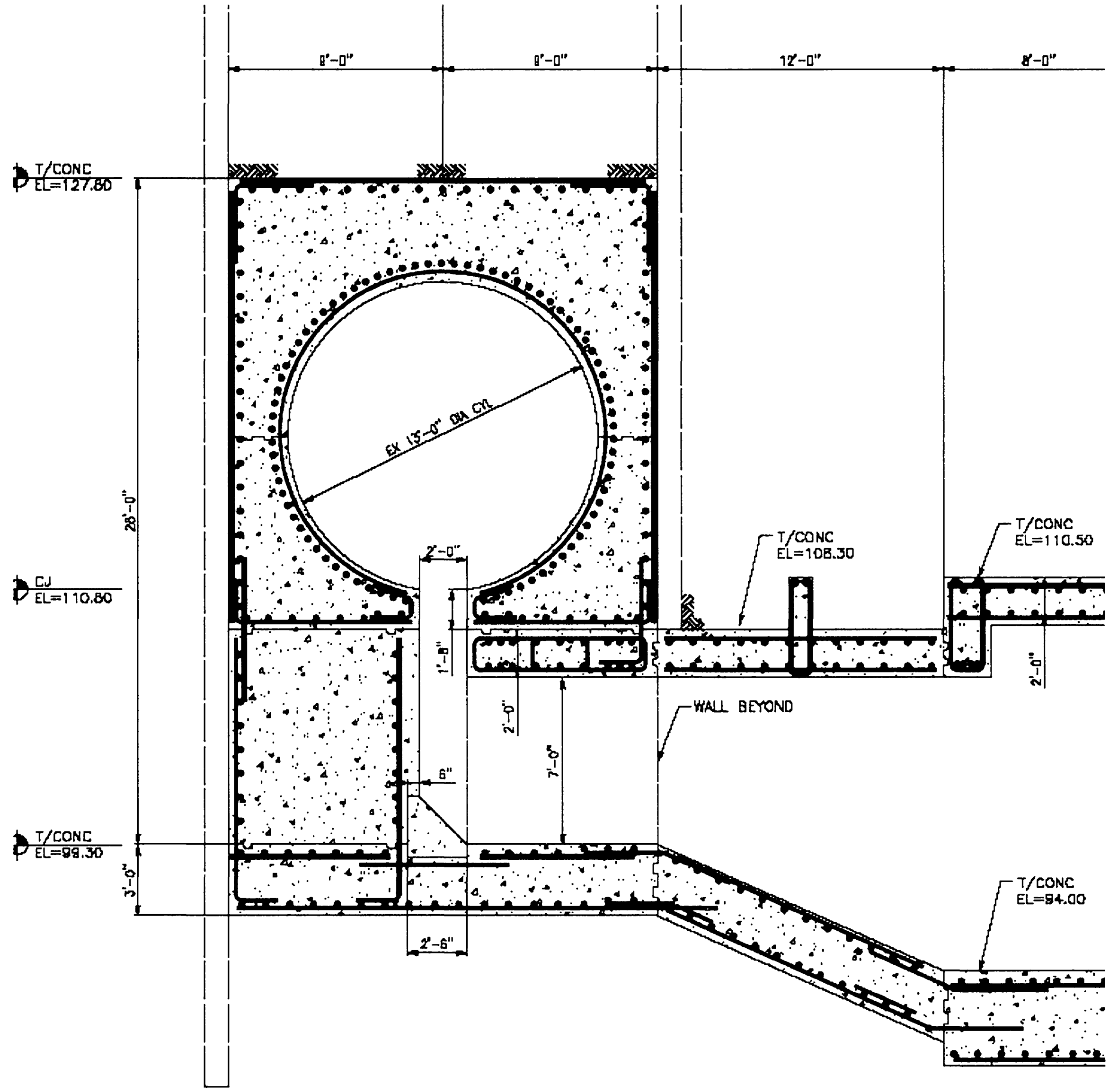

Figure A-2: Section View of Proposed Bottom Outlet Slot Design at Site DS-4 (provided by Wade Trim)

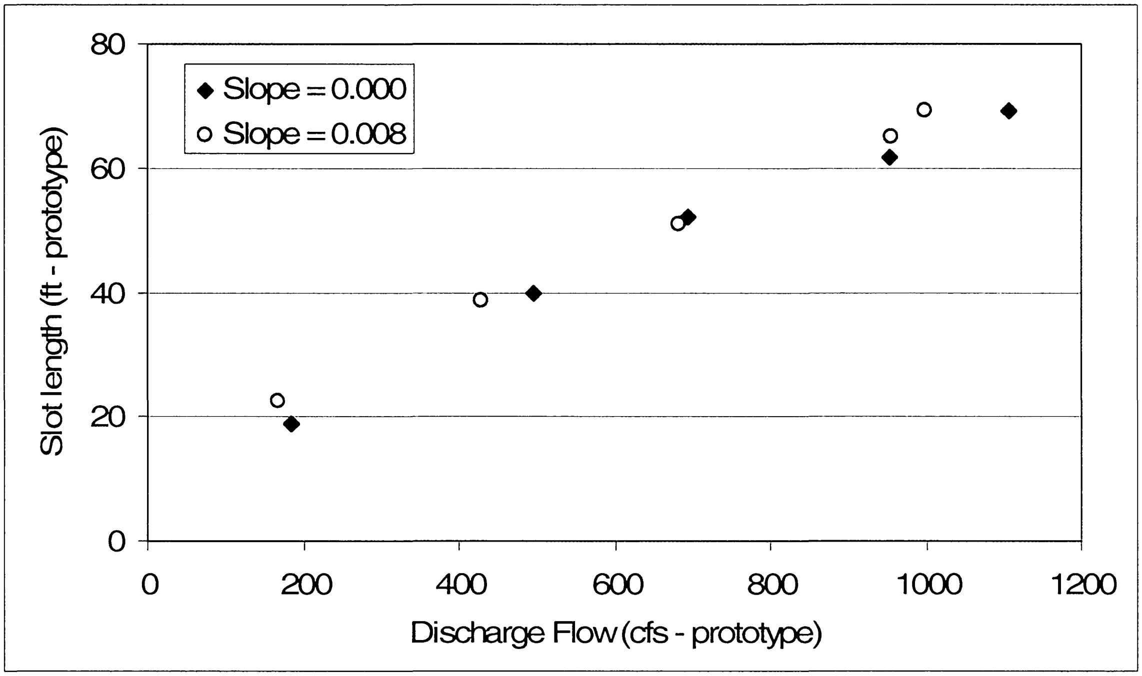

Figure A-3: Slot Width = 24” (prototype)

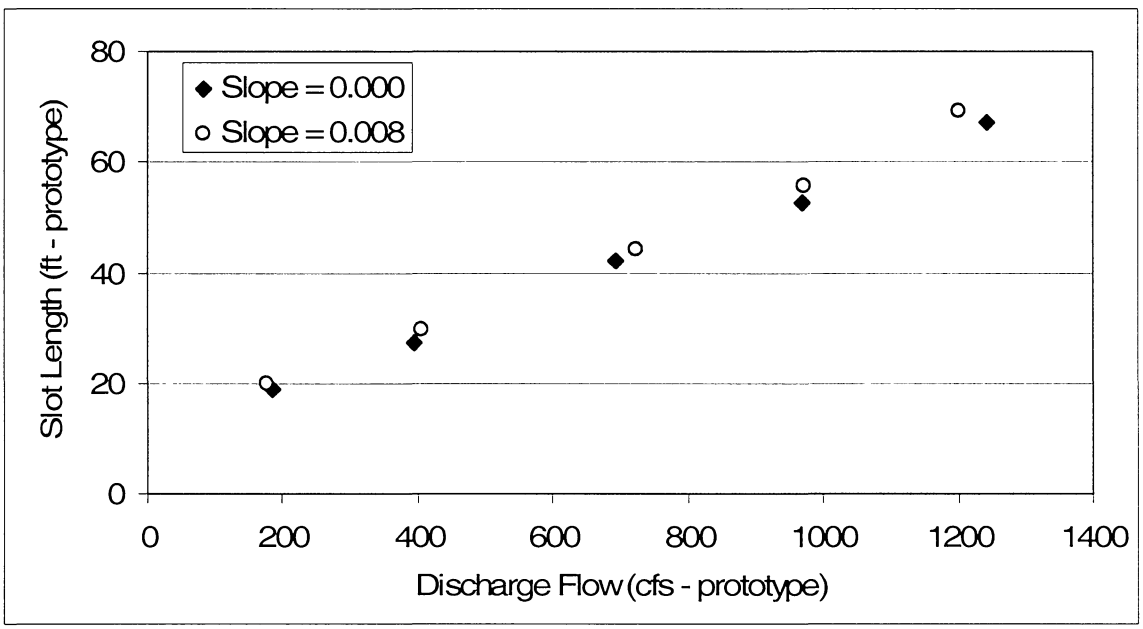

Figure A-4: Slot Width = 30” (prototype)

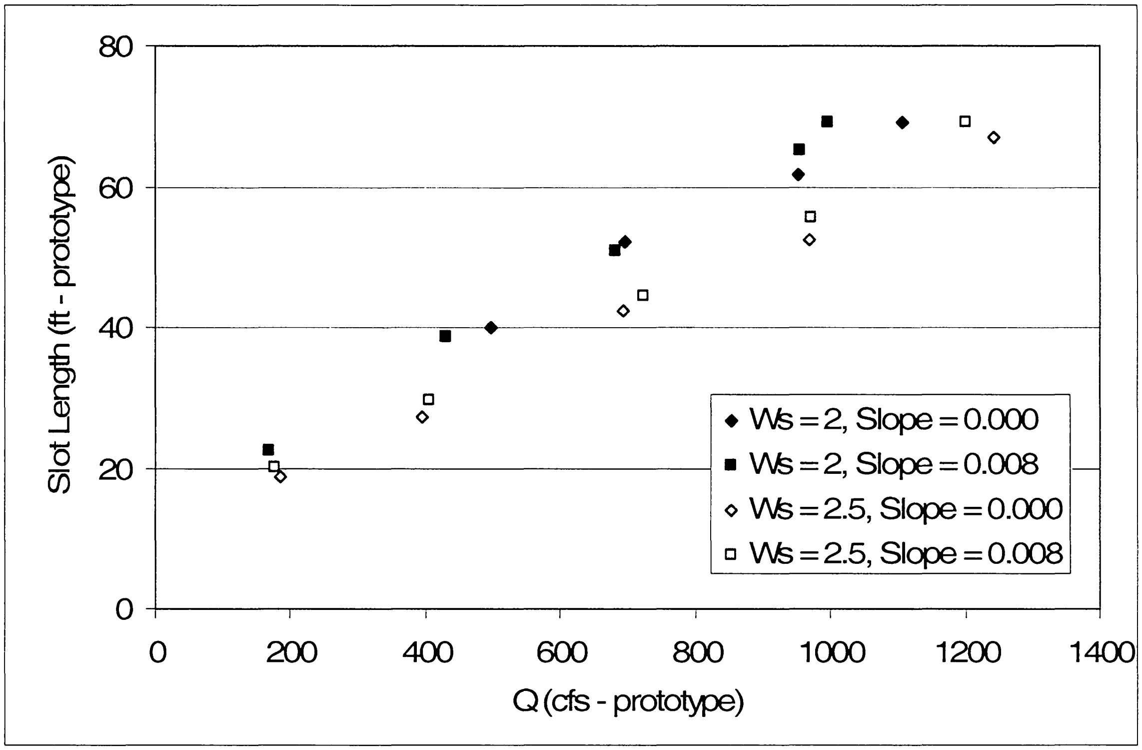

Figure A-5: Experimental Data
(Ws is the slot width, ft. prototype)

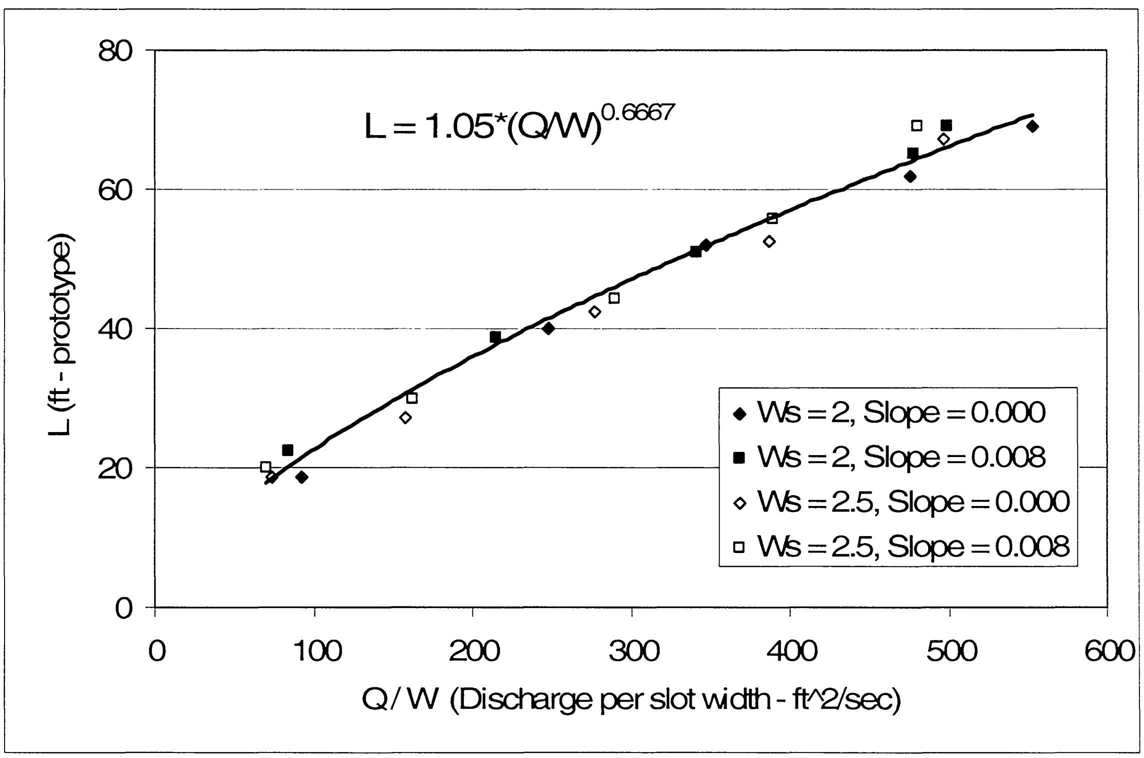

Figure A-6: Dimensional Analysis Q/W vs. L
(Ws is the slot width, ft. prototype)

Table A-1: Experimental Data

Slot Width (ft)	Slope	L (ft)	Q (cfs)
2	0.000	18.79	183.87
2	0.000	39.91	496.46
2	0.000	52.10	695.81
2	0.000	61.85	952.88
2	0.000	69.16	1106.00
2	0.008	22.445	168.504
2	0.008	38.695	429.729
2	0.008	50.883	682.551
2	0.008	65.102	956.157
2	0.008	69.164	997.913
2.5	0.000	18.789	183.873
2.5	0.000	27.320	394.376
2.5	0.000	42.352	693.614
2.5	0.000	52.508	969.180
2.5	0.000	67.133	1243.090
2.5	0.008	20.008	176.342
2.5	0.008	29.758	405.278
2.5	0.008	44.383	723.766
2.5	0.008	55.758	972.411
2.5	0.008	69.164	1201.205

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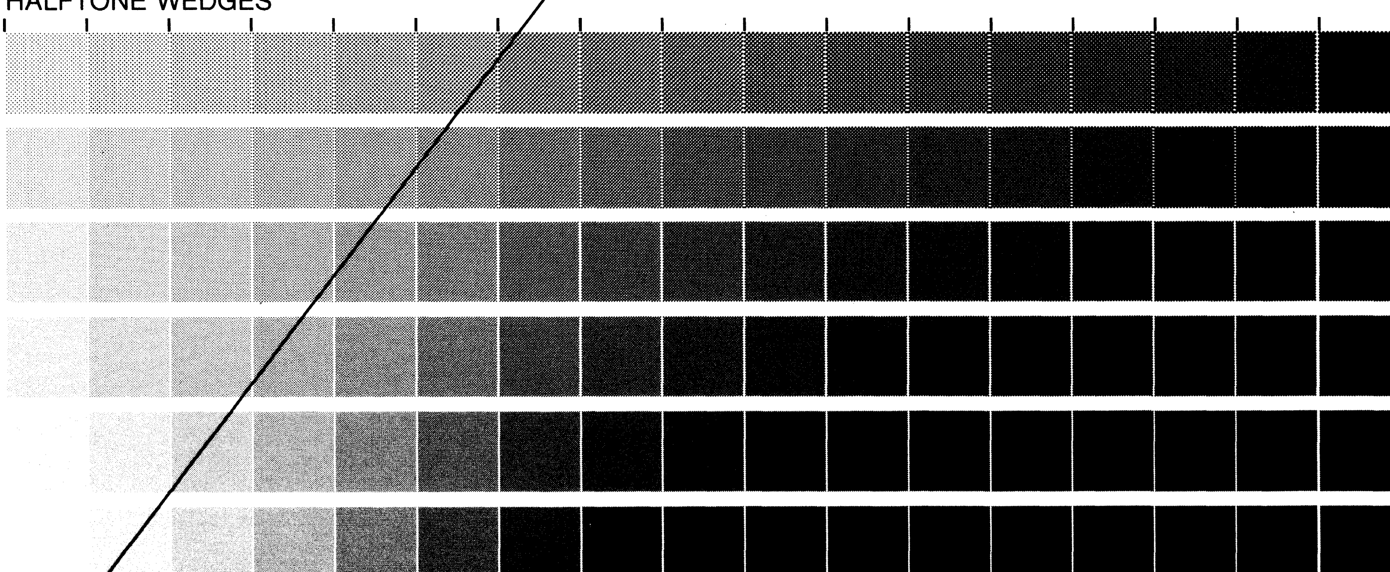

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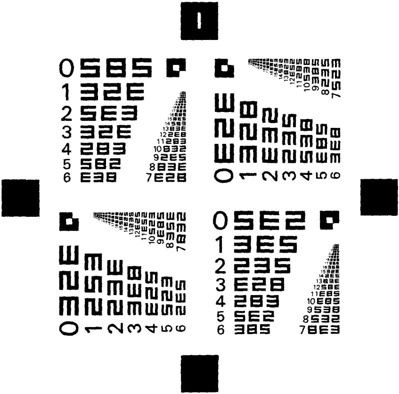

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