THESIS

EFFECT OF SPILLWAY-OGEE LOCATION ON FLOW UNIFORMITY AND TURBULENCE AT THE CREST OF AN OGEE WEIR

Submitted by

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ABSTRACT

EFFECT OF SPILLWAY-OGEE LOCATION ON FLOW UNIFORMITY

AND TURBULENCE AT THE CREST OF AN OGEE WIER

This study investigated the effect of spillway-crest location relative to spillway entrance, and spillway-abutment shape, on uniformity of flow distribution and turbulence intensity of flow, over the ogee crest of a spillway. These issues are especially of concern for spillways for which the approach flow to the ogee weir is relatively shallow. Circular and elliptical shapes of abutments were used. These abutment forms, and the bathymetry of the reservoir approach to the spillway, cause the approach flow to the ogee weir to be non-uniformly distributed and turbulent for part of the ogee weir. Turbulence can be generated by flow separation from an abutment or by the manner whereby the flow approaches the spillway. In the latter case, the reservoir bathymetry at the spillway entrance is important, as it affects flow distribution at the spillway entrance.

The base spillway used for the study was a hydraulic model used to assist in the design of the new spillway for Los Vaqueros Dam on Kellogg Creek near Brentwood, California. The flow approach to this spillway is typical of many, relatively shallow over-flow spillways that involve an ogee crest. As often is the case for spillways associated with embankment dams, the spillway is built on an abutment of the dam itself and must deal with non-uniform and turbulent approach flow from the reservoir retained by the dam to the spillway's location at the side of the dam. Consequently, the approach flow was non uniform and turbulent, and design questions arise as to where to place the ogee crest for the spillway and what shape to use for a spillway. Though the

investigation used the spillway just mentioned, the results have general application. The experiments were performed using a spillway flume with a rectangular cross-section, a circular abutment intake and a controllable spillway crest with changing the crest location to five locations (one downstream of the selected location and three upstream of that location). Measurements included water profiles, velocity across transects downstream of the spillway's entrance. These measurements were made for a circular spillway-abutment and for an elliptical spillway-abutment. The results show that changing the crest location significantly affects flow uniformity and possible shed-vortex formation from the intake abutment. Therefore, the results also indicate that spillway crest location has a direct impact on the hydraulic performance of the spillway. Suitable selection of crest location can be used to minimize non-uniformity and vortex-related problems in spillway design. The present study recommends that the ogee crest face be placed at least 1.5 crest widths from the entrance of the spillway. This position enables the flow to the crest to become suitably uniform and turbulence of flow within the entrance to extensively (though not entirely) decay.

The findings from this study are significant for engineers and researchers involved in spillway design and generally in many aspects of hydraulic engineering design. The findings also demonstrate the importance of careful consideration of crest location in spillway design to mitigate problems related to vortex formation. Overall, this study adds to the knowledge base regarding spillways and their design. Spillways have been used for hundreds of years but there are many aspects of these hydraulic structures requiring continued research.

ACKNOWLEDGMENTS

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CHAPTER 1: INTRODUCTION

1.1 Introduction

The efficient operation of spillways is crucial for the safe and accurately controlled release of water from reservoirs, ensuring the stability of dams, and protection of downstream channels. One key aspect of spillway performance is the uniform distribution of flow entering the spillway, and therefore passing down the spillway. Although uniformity of flow distribution is a well-known design concern, turbulence of an approach flow is a concern newly identified in this study. These aspects are affected by two components of a spillway: the spillway's ogee weir (flow of water over whose crest defines a rating curve for the spillway), and the form of the abutments placed at the spillway's entrance and used to guide flow into the spillway. The ogee's crest level usually coincides with the design level of the reservoir. Between the abutments and the ogee weir, a region of great turbulence can form owing to the flow field of flow passing around the abutments and entering the spillway. The region may be formed by several processes, including the following two processes:

- Flow separation forms a turbulence region as flow passes around a spillway's abutment and approaches the ogee weir.
- Flow passing over the bathymetry of the reservoir approaching the spillway, and around the spillway's abutment, may interact with flow entering the spillway and ogee presence to form a turbulence region immediately downstream of the abutment.

For either process, a key design question is the distance between the position of the ogee crest and the start of the abutments at the entrance to the spillway. In essence, this question concerns the presence of the ogee in the turbulence region potentially formed when flow passes around an abutment.

Achieving flow uniformity and low turbulence over the crest and is essential for accurate control of spillway hydraulic performance: to develop a reliable, precise crest-depth rating curve; to minimize erosion of the downstream channel at the base of the spillway; prevent scour of the channel; and to avoid potential structural damage to the spillway itself. Various factors influence flow uniformity and acceptable turbulence level for flow over an ogee crest, including the location of the spillway’s ogee crest and the shape of a spillway’s abutments. Crest location is a critical parameter affecting flow uniformity. The positioning of the spillway crest determines the flow patterns and distribution characteristics. If the crest is not appropriately located, it can result in localized high velocities and pressures, leading for example to erosion and scour of the stream bed downstream of the spillway, as noted above. Hence, understanding the influence of crest location on flow uniformity is critically important for the efficient design and operation of spillways.

Furthermore, spillway-abutment shape plays a significant role in flow distribution over a crest. The shape and configuration of the abutment affect the hydraulic performance of the spillway by influencing flow patterns and energy dissipation. Non-uniform abutment shapes can lead to flow concentration or diversion, causing flow non-uniformity over the spillway crest. Therefore, studying the impact of spillway-abutment shape on flow uniformity is crucial for optimizing spillway designs and mitigating potential issues.

1.2 Objectives and Scope

The primary objectives of this thesis were as follow:

1. Determine the effects of spillway-ogee weir location on flow uniformity and turbulence magnitude of over an ogee crest.
2. Ascertain the influence of spillway-abutment shape on flow distribution and turbulence at a spillway's ogee crest.
3. Recommend ogee weir location to ensure acceptable uniformity and turbulence level of flow over an ogee weir to precisely manage water release from a reservoir.

This thesis presents the findings of a study addressing the objectives mentioned above. For this purpose, the study made use of an existing physical hydraulic model of the spillway for the heightened form of Los Vaqueros Dam in California. Los Vaqueros Dam is in Contra Costa County, central California. The dam, whose layout and geometry set the scope of the present study, is a vital water-supply facility that provides water to the region for agricultural, industrial, and municipal use. The dam features a spillway designed to safely release excess water during periods of high inflow.

The crest of the ogee weir placed on the heightened spillway used for Los Vaqueros Dam was located and aligned, plus sized, to intersect the axis of the heightened dam. Questions arise, however, whether this location was optimal for the spillway and what comprised the flow field to ogee weir for the spillway's entrance abutments. The abutments were circular in form, having a radius (prototype) of 16.0 ft.

In many respects the spillway was representative of spillways at other dams, for which water in the dam's reservoir approaches the dam's spillway at an oblique horizontal angle to the spillway

(Figures 1-1 and 1-2), thereby raising the concern for uniformity of flow over the spillway's ogee crest. In this regard, to be considered also is the bathymetry of the approach to the spillway. However, there have been prior concerns regarding flow non-uniformity and turbulence of flow over the spillway crest, which could potentially lead to adverse effects, such as inadequate performance of energy-dissipation structure at the end of the spillway. In adequate performance could cause scour of the river or stream channel downstream of the spillway, with possible consequences of damage to the spillway structure and the dam itself. In accordance with the scope for the original hydraulic model study, the model of the dam's spillway was designed and constructed to accurately represent the spillway's geometric features of the actual spillway.

The experiments conducted for the preset study involved varying the crest location and modifying the spillway-abutment shape to assess their effects on flow uniformity and turbulence as encountered at the ogee crest. Figure 1-3 schematically illustrates that the crest of the ogee weir for Los Vaqueros Dam could encroach into the turbulence zone formed as flow passes downstream of a spillway abutment.

The approach taken measured flow uniformity in terms of distributions across the ogee crest of water depth, mean velocity of flow, and unit discharge (depth time mean velocity). Flow measurements were taken using Acoustic Doppler velocimetry (ADV) and point gauges. These measurements provided quantitative data on flow velocities, water depths, and distribution over the spillway crest under different crest locations and spillway-abutment shapes. Also, the measurements were supplemented with observations of flow and flow-visualization techniques, including the use of dye. Observations were recorded by means of photography and video.

In addition, the study sought to give a list of recommendations for aspects needing further research. Such aspects included, for example, the effect of a spillway's length on acceptable flow uniformity at the location of an ogee crest.

Figure 1-1. The present ogee-shaped weir set back from the circular abutments of the existing Los Vaqueros Dam (view shows unheightened dam).

Figure 1-2. Existing dam and proposed heightened dam indicated. (The dam is to be heightened c. 18 m; but the stilling basin is to be retained.)

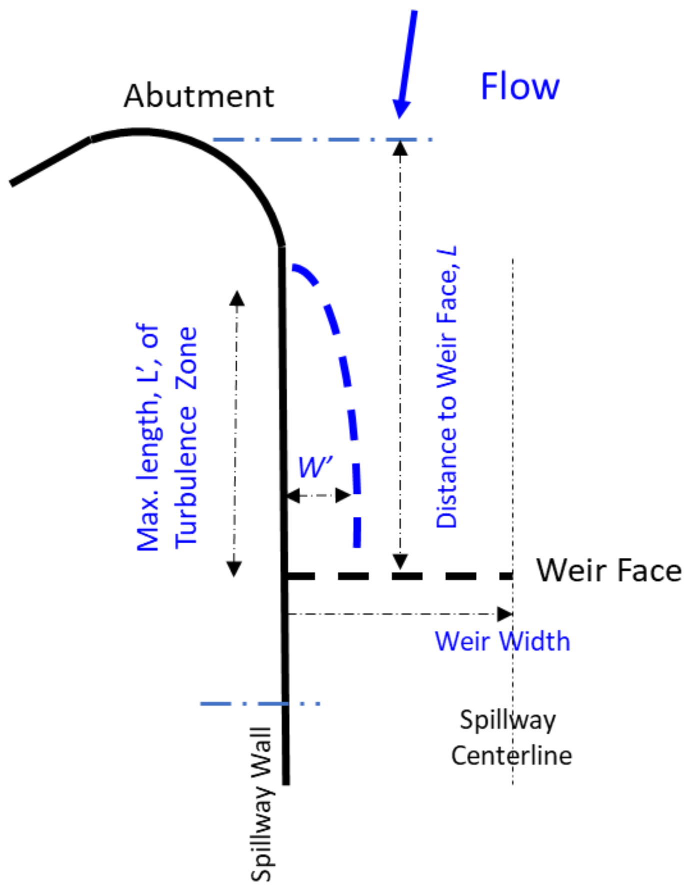


Figure 1-3. A schematic of the turbulence region downstream of a spillway abutment.

CHAPTER 2: DIMENSIONAL ANALYSIS AND LITERATURE REVIEW

2.1 Introduction

Spillways play a critical role in water-management systems by decanting water from a prescribed level of reservoirs. Commonly, the level of a spillway's ogee crest is at or close to the maximum water level in the reservoir retained by the dam. Acceptable spillway-ogee performance means achieving uniform flow distribution and acceptable turbulence intensity over the spillway's ogee crest. It may not be easy to achieve overall performance of a spillway, because non-uniform flow and high levels of turbulence can lead to adverse issues for the spillway, such as inadequate performance of ogee, as well as inadequate energy dissipation (in the terminal structure at the end of the spillway), flow-induced vibration of structural elements of the spillway, cavitation along the spillway' chute, and sedimentation concerns in the channel downstream of the spillway. This literature review explores the factors influencing flow non-uniformity, measurement techniques, consequences of non-uniform flow, and mitigation strategies. By considering these factors, this review provides useful insights into understanding and addressing flow non-uniformity in spillway intakes.

The literature on spillway performance is extensive. The present study does not attempt to review all the literature. Worth mentioning, however, is that none of the standard guides used for design provides guidance on the location of ogee weirs on spillways for relatively shallow approach flows (e.g., USBR 1987, USACE 1992, Novak et al. 2007). At best, USBR (1987) indicates how height of approach flow depth relative to height of ogee crest, Y/Y_C, affects ogee performance. This reference shows that, when Y/Y_C > approx. 4, Y_C no longer affects the performance of the ogee crest. However, depending on the bathymetry along which the approach flow must pass, the issues of flow uniformity and turbulence level may remain irrespective of whether the approach to a spillway is relatively shallow or deep.

The chapter begins with a straightforward dimensional analysis to identify the main variable (and resulting non-dimensional parameters) that may influence the uniformity and turbulence level of flow over a spillway's ogee crest. Of particular interest is the distance for a spillway's ogee downstream of the spillway's entrance, and the form of the spillway abutments at the entrance to the spillway.

2.2 Dimensional Analysis

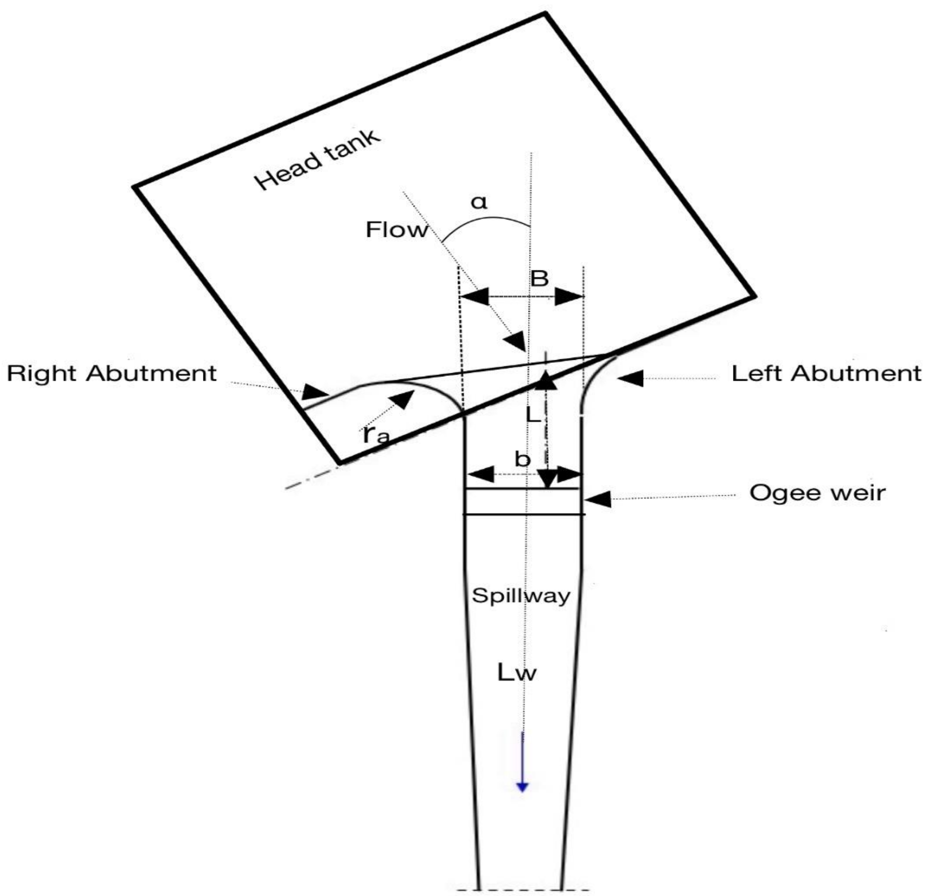
Dimensional analysis, together with similitude analysis, are useful for rationalizing and relating the hydraulic performance of a hydraulic structure to the variables defining its geometry and water flow. Dimensional analysis leads to non-dimensional parameters (e.g., Reynolds number, Re, and Froude Number, Fr), which then are used in similitude considerations to design and interpret the results of experiments (and to set the scales for length, velocity, time, force, etc.). Accordingly, dimensional analysis was used in the present study to identify the parameters to be considered in the experiments conducted for this study.

The variables considered were as follow:

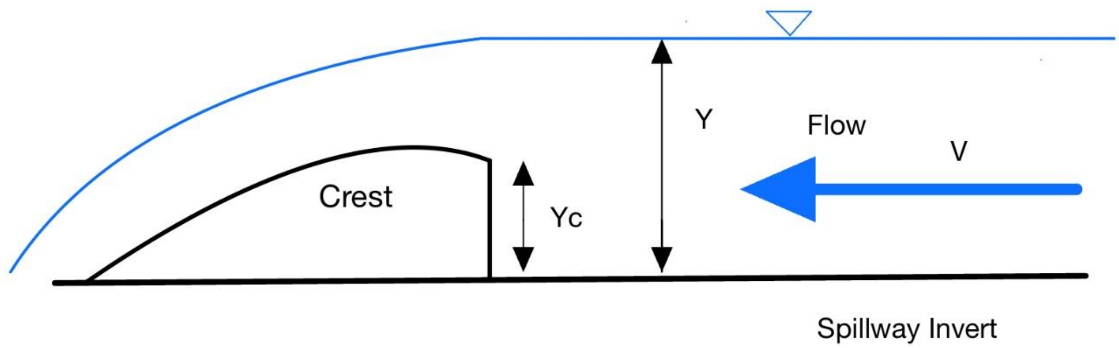
- Reservoir orientation – main direction of flow (and flow field generally) relative to spillway axis, a
- Geometry of spillway and ogee weir – abutment radius times a shape factor, br_a (for circular abutments, b = 1.0, and for elliptical abutments b < 1.0); width of spillway at

spillway entrance, *B*; width of spillway at ogee crest, *b*; distance from spillway entrance to ogee crest, *L*; ogee-crest elevation, Y_c; and length of spillway downstream of ogee crest, L_S.

- Flow to and over an ogee weir – depth of flow at the crest of the ogee weir, *Y*; average velocity of flow approaching the spillway and the depth of flow approaching the ogee crest of the ogee weir; *V* = velocity of flow at the ogee crest; a quantification of non-uniformity of flow velocity on ogee crest, s_V.
- Water properties – density, *r*; dynamic viscosity, *m*
- Planet – gravity acceleration, *g*



(a)



(b)

Figure 2-1: The variables considered in the dimensional analysis of the performance of a spillway: (a) plan view of the spillway, and (b) profile view of an ogee weir on a spillway. Note that flow depth *Y* is here assumed also to be the average depth of flow as the flow approaches the spillway entrance.

These variables can be cast as follow:

$$\varphi = f_1\begin{pmatrix} main\ flow\ direction\ to\ spillway, geometry\ of\ spillway\ entrance, \\ geometry\ of\ ogee\ weir; \\ flow\ to\ and\ over\ an\ ogee\ weir; \\ water\ properties; gravity\ acceleration \end{pmatrix}$$

Or

$$\varphi = f_1(a, \beta r_a, B, b, L, L_S, Y_C, Y, V, \sigma_V, S_S, \rho, \mu, g\ )$$

So, with the three units of length, mass, and time involved, the equation becomes for circular and elliptical abutments:

$$P = f_2\left(a, \frac{\beta r_a}{L}, \frac{B}{L}, \frac{b}{L}, \frac{Y}{L}, \frac{Y}{Y_C}, \frac{V}{\sqrt{gY}}, \frac{\sigma_V}{V}, \frac{L_S}{L}, \frac{\rho V Y}{\mu}, S_S\right)$$

The parameters (non-dimensional terms) considered in this study were as follow:

$$P = f_3\left(\frac{\beta r_a}{L}, \frac{B}{L}, \frac{b}{L}, \frac{Y}{L}, \frac{Y_C}{L}\right)$$

Or simply, as the present experiments set Y_C and Y at $Y = 0.96$ ft., and $Y/Y_C \approx 4$,

$$P = f_4\left(\frac{\beta r_a}{L}, \frac{B}{L}, \frac{b}{L}\right)$$

With L and β being the main variables altered for this study. The values of B and b were fixed.

The dependent parameters immediately above will affect the discharge coefficient, C, of the ogee weir. The weir equation is as follows:

$$Q = CLH_0^{3/2}$$

Where H_0 is here taken as the distance from the ogee crest to the design water level of the reservoir. The water discharge over the ogee weir, $Q = V(bY)$.

The other parameters were fixed in value for the thesis experiments presented here. The principal variable in this study was L, the distance between the spillway entrance and the face of the ogee weir. Also, investigated for the given spillway was the influence of β, with spillway abutment shape being circular then elliptical.

The parameters Π for this study were the uniformities of flow depth, Y_C, flow velocity, V, (average value at each vertical position), and unit discharge at each vertical position, q_c for flow very near the crest of the ogee weir. Also examined were values of flow velocity uniformity at each vertical position. This consideration was done in terms of quantifying the standard deviation, σ_v, of flow velocity at each velocity measurement vertical. Velocity was used as an indicator of q and y.

2.3 Factors Influencing Flow Non-Uniformity

The factors for outflow from a dam include intake design, approach-flow conditions, intake submergence, and inlet-flow control devices. These factors are elaborated briefly below.

2.3.1 Intake Design

The design variables of spillway intakes, including shape, dimensions, and location, significantly influence flow non-uniformity. Studies by Bollaert et al. (2014), Verwey et al. (2017), and de Vos et al. (2021) have examined the effects of intake geometry on flow distribution, emphasizing the importance of design considerations for achieving uniformity. The variables usually considered of dam intakes are:

- Approach flow
- Intake submergence
- Intake flow-control devices

2.3.2 Approach Flow Conditions:

The approach flow's characteristics, including velocity, turbulence, and submergence, significantly impact flow non-uniformity. Research by Zarrati et al. (2018), Takeuchi et al. (2020), and Li et al. (2022) have explored the influence of approach flow conditions on flow distribution through spillway intakes.

2.3.3 Intake Submergence

The submergence of spillway intakes due to upstream water levels affects flow distribution. Studies by Haun et al. (2015), El Naggar et al. (2019), and Zhang et al. (2022) have investigated the relationship between intake submergence and flow non-uniformity, providing insights into the impact of submergence ratios on flow patterns.

2.3.4 Inlet Flow Control Devices

The presence of flow control devices, such as weirs or screens, within spillway intakes can influence flow non-uniformity. Investigations by Garde et al. (2016), Zhao et al. (2019), and Hu et al. (2020) have examined the impact of these devices on flow distribution and identified strategies to enhance uniformity.

2.4. Measurement Techniques

Accurate assessment of flow non-uniformity in spillway intakes requires reliable measurement techniques. Various approaches have been employed, including physical modeling, computational fluid dynamics (CFD), and field measurements. Experimental studies by Mofidi et al. (2017), Thota et al. (2022), and Jeyapandiyan et al. (2023) have utilized physical models and advanced measurement techniques to analyze flow non-uniformity in spillway intakes.

2.5. Consequences of Non-Uniform Flow

2.5.1 Sedimentation and Deposition

Non-uniform flow through spillway intakes can lead to sedimentation and deposition, reducing their operational efficiency. Research by Kang et al. (2016), Tarek and Amin (2020), and Zhang et al. (2021) has investigated the relationship between flow non-uniformity and sediment transport, emphasizing the need for effective mitigation measures.

2.5.2 Cavitation and Flow-Induced Vibrations

Non-uniform flow patterns can induce cavitation and flow-induced vibrations, resulting in damage to

the intake structure. Studies by Hong et al. (2018), Zhao et al. (2021), and Miao et al. (2022) have examined the effects of flow non-uniformity on cavitation and vibrations, highlighting the importance of controlling flow distribution.

2.6 Mitigation Strategies

Several mitigation strategies have been proposed to enhance flow uniformity in spillway intakes. These include the use of flow control devices, modifications to intake geometry, and optimization of approach flow conditions. Research by Ma et al. (2019), Bai et al. (2022), and Wang et al. (2023) has explored these strategies and their effectiveness in achieving uniform flow distribution.

2.7 Conclusion from Brief Review of Literature

The references cited here provide a general overview of spillway design, hydraulics, and flow measurement. While specific references related to the ogee crest position and how does it affect the uniformity of water may not be available in many important textbooks and manuals, such as the USACE guide on spillway design and the US Bureau of Reclamation’s widely used book, *Design of Small Dams*, the cited sources encompass relevant knowledge and principles in the field of spillway engineering.

This brief literature review has provided insights into the factors influencing flow non-uniformity in spillway intakes, measurement techniques employed, consequences of non-uniform flow, and mitigation strategies. The references cited here provide a foundation for further exploration and research in this critical field of study.

CHAPTER 3: EXPERIMENTS

3.1 Introduction

The objectives stated in Section 1.2 were investigated using an existing hydraulic model of a new spillway formed with the heightening of Los Vaqueros Dam. The experiments entailed adjusting the location of the spillway's ogee crest (i.e., adjusting L as in Chapters 2 and the present chapter) for two plan-form shapes of entrance abutment for the spillway (i.e., circular and elliptical). These steps were done with the discharge set at the design discharge value (prototype) of 3,000 cfs. This discharge was the estimated value of the Probable Maximum Flow (PMF) that the spillway was required to convey.

The hydraulic model utilized standard similarity principles to ensure that the spillway accurately represented the main forces and processes involved in water flow down the spillway. The key factors, scales, and limitations in designing and operating the model are outlined in Section 3.3. For instance, the height of the laboratory determined the length scale of the model, as explained in Section 3.2. The chosen length scale (prototype/model) was 12, striking a balance between maintaining the fidelity of surface tension and viscous effects, particularly in energy dissipation and velocity distribution, as water flowed down the spillway's chute.

3.2 Layout and Dimensions of the Hydraulic Model

The layout of the hydraulic model included an area that replicated a 137.25 ft-wide, 113.75 ft-long, and 35.00 ft-deep section of the Los Vaqueros Reservoir surrounding the new spillway. Sufficient volume was created to ensure that the model accurately simulated the flow performance of the spillway's crest. Furthermore, the volume of approach flow allowed for adequate distance between the model's boundaries and the crest, ensuring that the boundaries did not affect the hydraulic performance of the crest.

To accurately simulate the hydraulic performance of the spillway, a length scale of 12 was chosen for the model. The model also incorporated sufficient freeboard around the headtank, replicating a section of the reservoir upstream of the spillway crest. Figure 3-1 and Figure 3-2 give plan and side views of the model, respectively, showcasing the layout schematics. The model extended from prototype station 102+60 (about 125 feet downstream of the end of the eyebrow deflector) shown in Figure 3-1, to station 98+15 (about 147 feet upstream of the spillway crest), as also indicated. The prototype dimensions of the spillway headtank were 113.75 ft in length, 137.75 ft in width, and 36.36 ft. in maximum depth.

The bottom of the spillway headtank was positioned 25.0 ft below the spillway crest in the prototype. The design head on the ogee crest was 9.9 ft. The headtank was structurally designed to support the weight of water contained in the headtank. An internal porous wall and diffuser pipe were installed to disperse the flow, allowing it to pass from a riser inlet-pipe and discharge uniformly over the spillway crest.

Care was taken to construct the spillway chute in a manner that facilitated modifications to key design components. The modular construction approach included an 80-20 aluminum frame extending from the headtank, floor sections made of High-Density-Overlay (HDO) plywood for structural support, and clear acrylic for visualizing the flow from different perspectives. A 40 hp pump was utilized to deliver the flow through an 18-inch-diameter pipe, connected to two 8-inch-diameter PVC pipes that led to the headtank of the model. During the calibration of the model, the discharge and head capacities of the pump used to supply flow to the model's headtank were evaluated. Preliminary experiments confirmed that these capacities posed no concerns for the operation of the model. Figure 3-3 and Figure 3-4 illustrate the model, indicating its size and complexity.

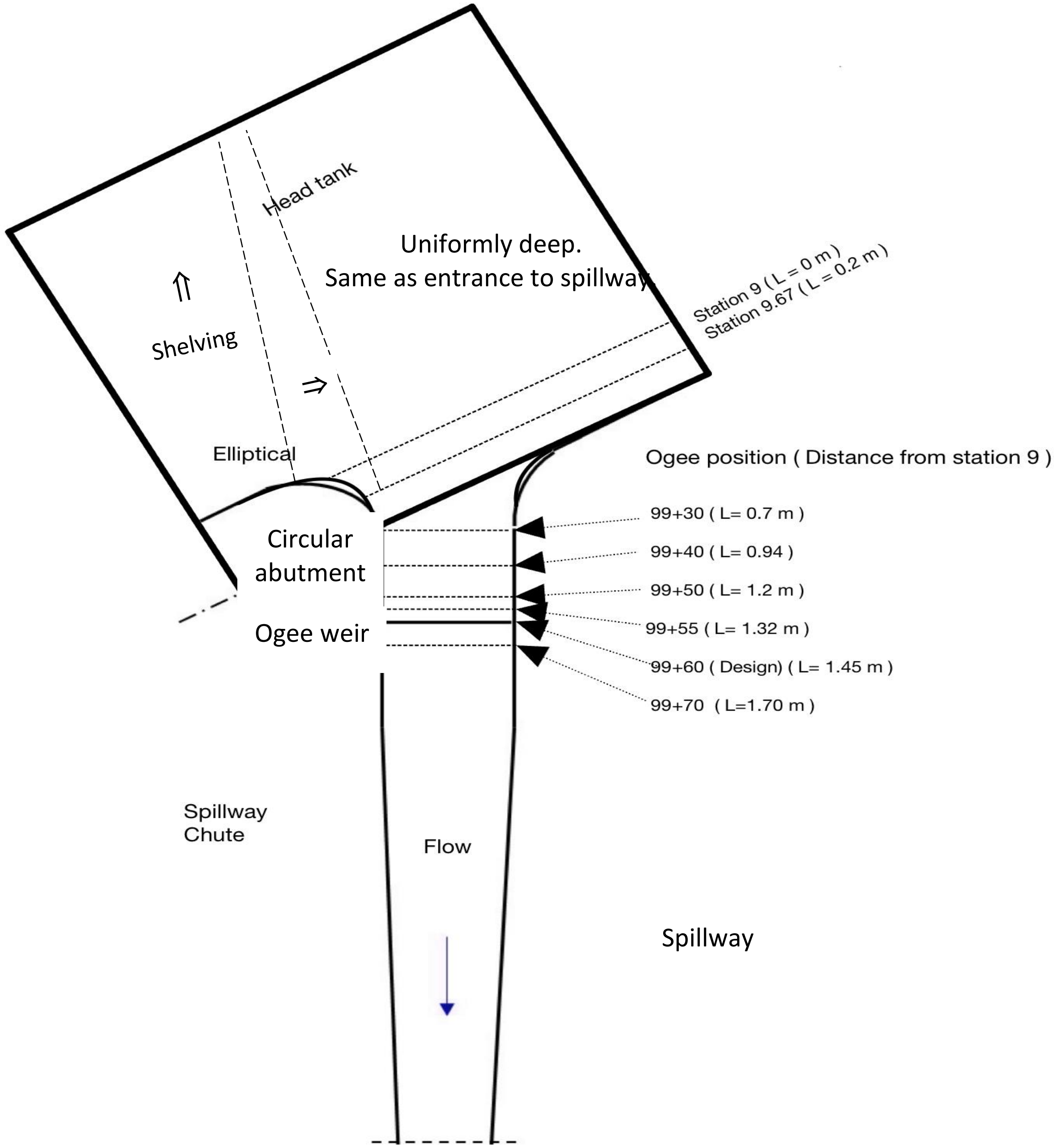


Figure 3-1. A plan view of the crest layout with circular and elliptical abutments used for the spillway proposed for Los Vaqueros Dam (heightened). This figure also shows the head tank bathymetry and the variation of the ogee-crest position this study investigated.

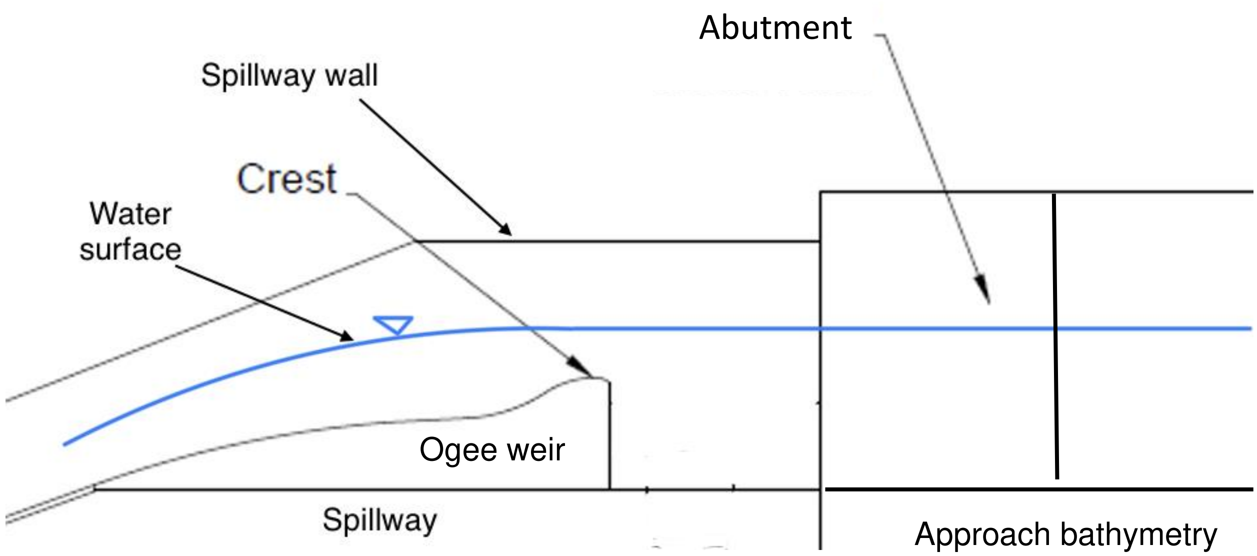


Figure 3-2 Profile view of model from the left abutment.

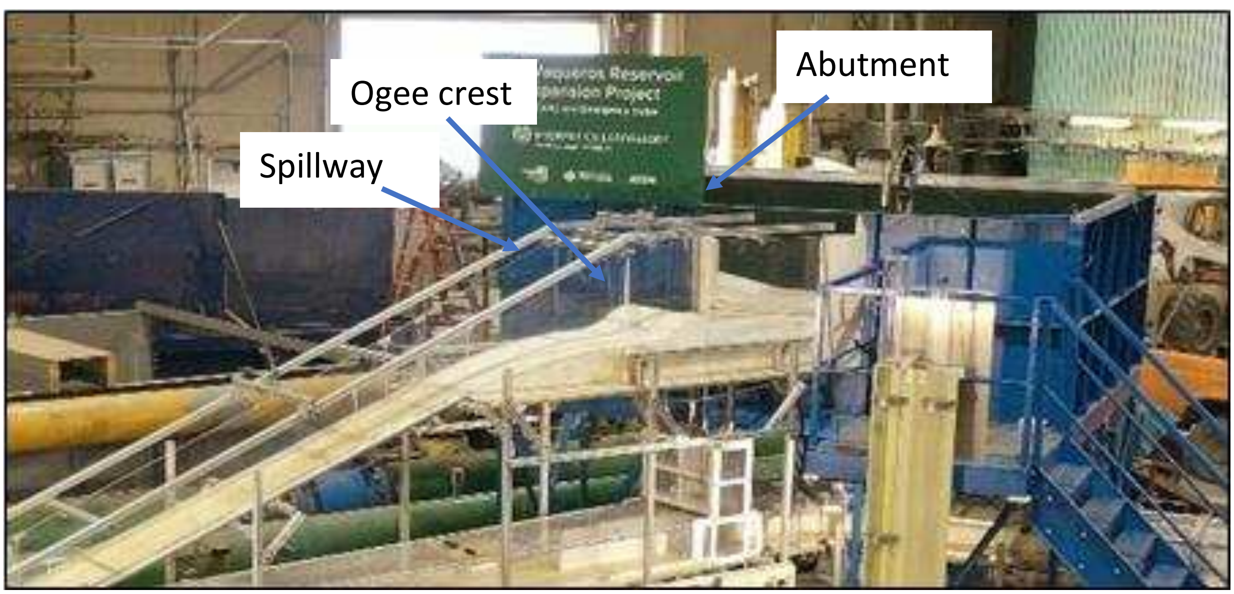


Figure 3-3. Photograph of the spillway model: no flow on the spillway.

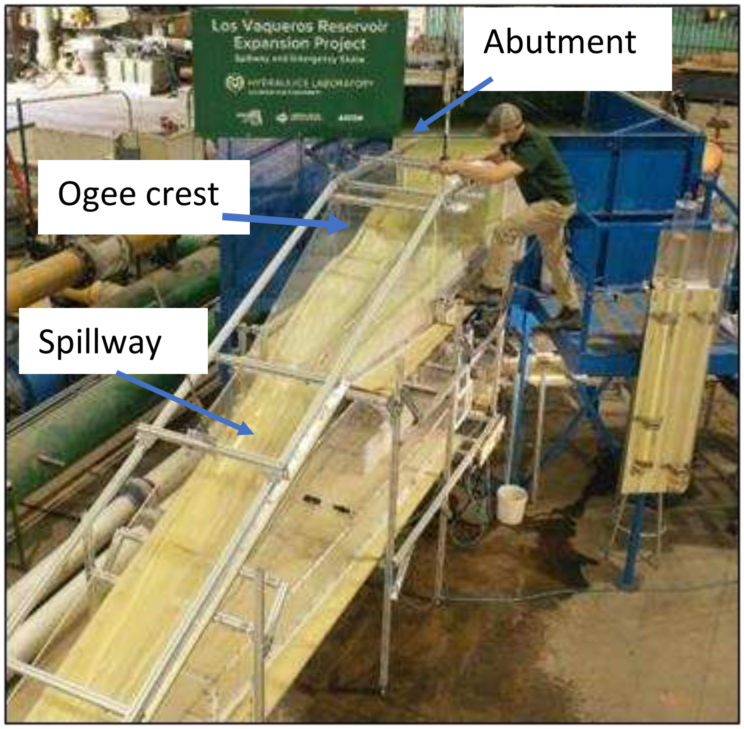


Figure 3-4. Photograph of the spillway model: flow passing down the spillway.

3.3 Similitude Considerations

The use of a hydraulic model to simulate prototype flow requires that certain dimensionless parameters describing the geometric, kinematic, and dynamic properties of the model assume scaled (or acceptable) values in the model and prototype. Table 3-1 lists the scales and quantity dimensions used for the model. The basic similitude conditions for modeling flow processes involve a free-surface flow (a flow with an air-water interface, such as an open-channel flow). When such flows also involve air entrainment, they become mixed flows of water and air.

For water flows, three forces usually are important:

- Inertia force (a contact force) associated with rate of change of flow momentum.
- Gravitational force (a body force) associated with the planet's gravitational field.
- Kinematic viscosity (a contact force), associated with the molecular structure of water.

Relative magnitudes of these forces are expressed as two dimensionless numbers: Froude number (inertia/gravity forces), and Reynolds number (inertia/viscous forces).

A key notion is that the present model's scales were based on Froude-number similitude, and that the values of Reynolds number in the model were sufficiently large (around 2×10^6) that the effect of water viscosity did not influence the overall capacity of the model to simulate flow processes with acceptable fidelity to meet the objectives set for the model (ASCE 2000). Table 3-1 summarizes the pertinent scales used for the present model, and the ensuing sub-sections of this chapter explain the similitude considerations associated with operating the model.

Table 3-1. Summary of scales used for the model.

Prototype/Model Parameter	**Scale**	**Prototype Value**	**Model Value** (metric value)
Froude number, F_r	1	1	1
Reynolds number, Re	12	$2.9x10^6$	$2.4x10^5$
Length scale, L_r	12	Weir length = 26.4 ft. (8.04m)	Weir length = 2.20 ft. (0.67 m)
Velocity scale. V_r	$L_r^{1/2} = 3.46$	(Varies with location)	(Varies with location)
Discharge scale, Q_r	$L_r^{5/2} = 498.83$	3,000 cfs (85 m^3/s)	6.0 cfs (0.21 m^3/s)

3.3.1 Geometric Similitude

The model spillway system should be geometrically like the prototype spillway-sluice system. Equation 1 describes the relationship between some characteristic length L between the prototype and model:

$$L_r = \frac{L_p}{L_m} \tag{1}$$

In which subscript *r* denotes the scale for the quantity (length); and subscripts *p* and *m* refer respectively to prototype and model.

3.3.2 Discharge Similitude

The basic requirement for dynamic similarity of free-surface flow over a fixed boundary is satisfied if the prototype and the model have the same value of Froude number, Fr, which expresses a balance of inertia forces relative to gravitational forces: i.e.,

$$\mathrm{F_{rm}} = \mathrm{F_{Rp}} \tag{2}$$

Equation (3) describes how velocity and flow depth were used to calculate Froude number:

$$\mathrm{F_r} = \frac{V}{\sqrt{g}Y} \tag{3}$$

Here, V = flow velocity, Y = flow depth; and g = acceleration due to gravity. Equations (2) and (3) lead to this study's scaling criteria for velocity and discharge:

$$V_r = L_r^{1/2} \tag{4}$$

and

$$Q_r = V_r L_r^2 = L_r^{\frac{5}{2}} \tag{5}$$

Here, Q_r = discharge scale, and L_r^2 = area scale.

3.4 Measurements and Instrumentation

The measurements made with the model were used to quantify and achieve the objectives stated in Section 1.2. Table 3-2 summarizes the measurements and the instruments used to obtain the measurements. The present section briefly describes the information sought from the measurements, and the ensuing section describes the specifications related to the instruments used to obtain the measurements.

Extensive observations were made and accessibly documented (data, photograph, and video) regarding flow to, down, and exiting the spillway. In this regard, Chapter 4 and the appendices of this thesis present extensive photographs of flow conveyed by the spillway crest. Additionally, video recordings of the flow are available from the Hydraulics Laboratory.

Table 3-2 lists the flow instruments used to make and record measurements throughout model experimenting. The precision of each of the instruments is described in the ensuing sub-sections.

3.4.1 Model Elevations

Elevations of all key components of the model were determined using the following instruments:

1. LiDAR scans were made using a Topcon-GLS-2000, whose measurement accuracy was 0.14 inch between distances of 3.0 ft to 450.0 ft (prototype); and,
2. A Leica Total Station (TCR703R) was used to place and check the elements of the model.

Both instruments were used to check elevations of the model during the current investigation, but the instruments were not the main instruments used during the investigations for measuring the water surface profiles.

Table 3-2. Summary of measurements and instrumentation.

Model Component		Discharge (Design value at model scale)	Measurement	Instrument
Headtank	Flow approach to the spillway	6.0 cfs	Flow velocity distribution, water depth, water surface distribution	ADV; Point gauge
Spillway	Flow approach in the vicinity of the ogee crest	6.0 cfs	Flow velocity distribution, water depth, water surface distribution	ADV; Point gauge
Spillway	Flow over the ogee crest	6.0 cfs	Flow velocity distribution, water depth, water surface distribution	ADV; Point gauge

3.4.2 Flow Rate

Water to the model was pumped from the laboratory's 1.0-acre-foot-volume underground tank and maintained a temperature of 49°F ± 2°F. Discharges through the model were measured using an Endress + Hauser Promag 53 W, electromagnetic MagMeter installed in the 18.0-inch-diameter pipe supplying water to the headtanks of the model. The maximum measurement error for discharge was ±0.5% of the reading (measured quantity); ±0.030 cfs for the PMF discharge of 6.0 cfs (model scale). The repeatability of the flowmeter was ±0.1% of the set reading. Influence on discharge of the ambient temperature of water was ±0.005%/°C. The meter was calibrated by its vendor.

3.4.3 Water-Surface Elevations

Water-surface elevations were collected along the spillway chute and headtank with a mobile point gage, whose accuracy was ±0.001 feet. Water-surface elevations also were measured using distance-tape measures mounted on the walls of the spillway chute at areas of interest.

3.4.4 Flow Velocity

Velocity measurements were collected using a Nortek Vectrino+, Acoustic Doppler Velocimeter (ADV). The ADV had three orthogonal, velocity components (in the *x*, *y*, and *z* directions). Additionally, a key advantage of this velocity probe was that velocities could be measured at suitably high frequencies to estimate a reliable average value of velocity at each measurement location, and the probe measured velocity fluctuations that could be used to estimate a standard deviation, σ_V, of velocity fluctuation at each measurement location. Velocity samples potentially can be collected at rates up to 200 Hz, but for the present investigation, the velocity sampling rates varied from between 1.0 and 50.0 Hz, with 3.0 Hz being the most used rate, as this rate greatly exceeded the rates of turbulence fluctuations observed in the turbulence region.

However, a slight disadvantage of the ADV probe could not produce velocity readings at the exact crest positions because the water on the crest was shallow. The measurement distance that the ADV could measure was at a depth of 2.8 in (70 mm) below the probe's stem. Therefore, ADV readings were taken in verticals 0.80 in (or about 20 mm) upstream of the crest location and 2.8 in (or 70 mm) from the bottom of the spillway as shown in Figure 3-9. These velocities were marginally below the crest elevation of the ogee weir, but the velocities were taken in this study to be equivalent to flow velocity over the crest, or at least they were closely indicative of flow velocity over the crest; ogee crest height = 2.9 in (or 73.6 mm).

3.4.5 Photographs and Video-recordings

Multiple photographs and video recordings were taken throughout every change in crest location. The photographs were taken using a mobile phone camera to capture the changes in water levels and the location of water separation. The video recordings documented the prevailing flow conditions associated with each position of ogee crest.

3.5 Program of Experiments

A systematic series of experiments were conducted on the spillway to achieve the objectives Section 3.2 mentions. Table 3-3 summarizes the experiment program pursued during the investigation.

Table 3-3. Summary of experiments program pursued during the investigation.

Model Scenario (Circular Abutment)	Sequence	Comment
Spillway Configuration 1: circular abutment, crest at station 99+60 (1.45 m from spillway entrance)	Approach velocity condition at headtank	ADV data used to determine approach flow velocity
	Approach velocity conditions at spillway	ADV data at the spillway in the spillways entrance used to determine approach-flow velocity
	Water-surface elevations (WSE)	WSE data for flow along modeled headtank and spillway chute at predetermined locations
Spillway Configuration 2: circular abutment, crest at station 99+50 (1.2 m from spillway entrance)	Approach velocity condition at headtank	ADV data in the headtank used to determine approach flow velocity
	Approach velocity conditions at spillway	ADV data in the spillway used to determine approach flow velocity
	Water-surface elevations (WSE)	WSE data indicate flow profiles along modeled headtank and spillway chute at predetermined locations
Spillway Configuration 3: circular abutment,	Approach velocity condition at headtank	ADV data in the headtank used to determine approach flow velocity

crest at station 99+40 (0.94 m from spillway entrance)	Approach velocity conditions at spillway	ADV data in the spillway used to determine approach flow velocity
	Water-surface elevations (WSE)	WSE data indicate flow profiles along modeled headtank and spillway chute at predetermined locations
Spillway Configuration 4: circular abutment, crest at station 99+70 (1.7 m from spillway entrance)	Approach velocity condition at headtank	ADV data in the headtank used to determine approach flow velocity
	Approach velocity conditions at spillway	ADV data in the spillway used to determine approach flow velocity
	Water-surface elevations (WSE)	WSE data indicate flow profiles along modeled headtank and spillway chute at predetermined locations
Spillway Configuration 5: circular abutment, crest at station 99+55 (1.32 m from spillway entrance)	Approach velocity condition at headtank	ADV data in the headtank used to determine approach flow velocity
	Approach velocity conditions at spillway	ADV data in the spillway used to determine approach flow velocity
	Water-surface elevations (WSE)	WSE data indicate flow profiles along modeled headtank and spillway chute at predetermined locations

Model Scenario (Elliptical Abutment)	**Sequence**	**Comment**
Spillway Configuration 6: elliptical abutment, crest at station 99+55 (1.32 m from spillway entrance)	Approach velocity condition at headtank	ADV data in the headtank used to determine approach flow velocity
	Approach velocity conditions at spillway	ADV data in the spillway used to determine approach flow velocity
	Water-surface elevations (WSE)	WSE data indicate flow profiles along modeled headtank and spillway chute at predetermined locations
Spillway Configuration 7: elliptical abutment, crest at station 99+70 (1.7 m from spillway entrance)	Approach velocity condition at headtank	ADV data in the headtank used to determine approach flow velocity
	Approach velocity conditions at spillway	ADV data in the spillway used to determine approach flow velocity

	Water-surface elevations (WSE)	WSE data indicate flow profiles along modeled headtank and spillway chute at predetermined locations
Spillway Configuration 8: elliptical abutment, crest at station 99+60 (1.45 m from spillway entrance)	Approach velocity condition at headtank	ADV data in the headtank used to determine approach flow velocity
	Approach velocity conditions at spillway	ADV data in the spillway used to determine approach flow velocity
	Water-surface elevations (WSE)	WSE data indicate flow profiles along modeled headtank and spillway chute at predetermined locations
Spillway Configuration 9: elliptical abutment, crest at station 99+50 (1.2 m from spillway entrance)	Approach velocity condition at headtank	ADV data in the headtank used to determine approach flow velocity
	Approach velocity conditions at spillway	ADV data in the spillway used to determine approach flow velocity
	Water-surface elevations (WSE)	WSE data indicate flow profiles along modeled headtank and spillway chute at predetermined locations
Spillway Configuration 10: elliptical abutment, crest at station 99+40 (0.94 m from spillway entrance)	Approach velocity condition at headtank	ADV data in the headtank used to determine approach flow velocity
	Approach velocity conditions at spillway	ADV data in the spillway used to determine approach flow velocity
	Water-surface elevations (WSE)	WSE data indicate flow profiles along modeled headtank and spillway chute at predetermined locations

3.6 Experiment Procedure

This sub-section describes the procedure used to investigate the effects of changing the ogee-crest location and abutment shape on water uniformity (depth, velocity, and unit discharge) at the face of the ogee crest. The procedure entailed measurements that were augmented using the photographs and video mentioned in Sub-section 3.4.6.

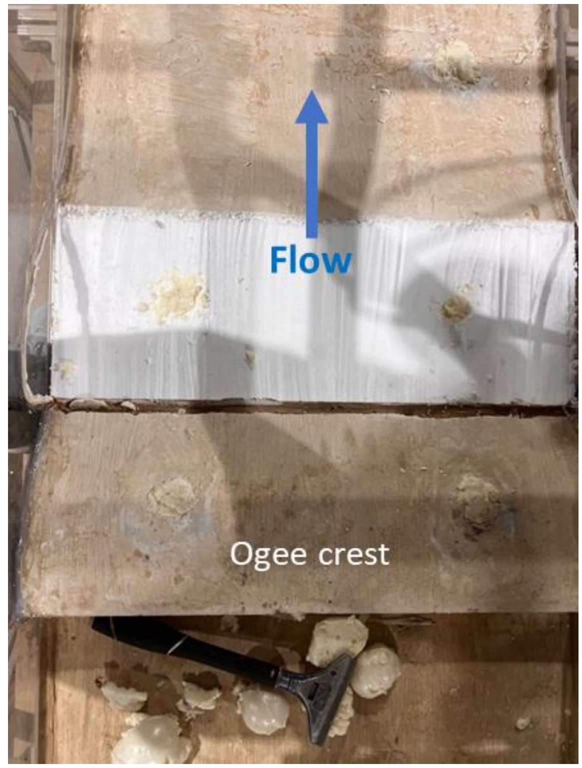
For each experiment, the procedure required starting and setting the pump to deliver the prescribed discharge to the spillway's headtank (simulated the reservoir). Then, measurements were taken of flow departing the headtank. The standard deviation of the headtank water-surface elevation was computed using a LabView data-acquisition program using data collected through a stilling well and the Masa sounding gage, as illustrated in Figure 3-5. Stilling well readings were concurrent with the piezometer (Masa probes) locations within each headtank. The measurements were typically completed within a two-hour period. Data taken electronically (discharge and video related data) were recorded for future analysis.

The investigation focused on five locations of ogee crest – stations 99+40, 99+50, 99+55, 99+60, and 99+70) – and two types of abutment shapes: circular and elliptical. The crest location was altered using a hot wire, blade and marine glue as shown in Figure 3-6, and the flow at each location of ogee crest was examined for at least two hours, about 24 hours before proceeding to the next setup location of ogee crest. Also, a wood frame was used to observe flow conditions associated with each crest location. The wood frame could readily be moved to simulate the crest position. The height of the frame's wood face was the same as the ogee-crest face. Figure 3-12 illustrates the use of the frame.

The experiments were conducted in several stages. Initially, five experiments were carried out with a circular abutment, with the spillway crest locations adjusted sequentially as per the specified stations. Afterwards, an elliptical abutment replaced the circular abutment, and the experiments were repeated for same crest locations to evaluate the effect of abutment shape on water uniformity at the location of the ogee crest.

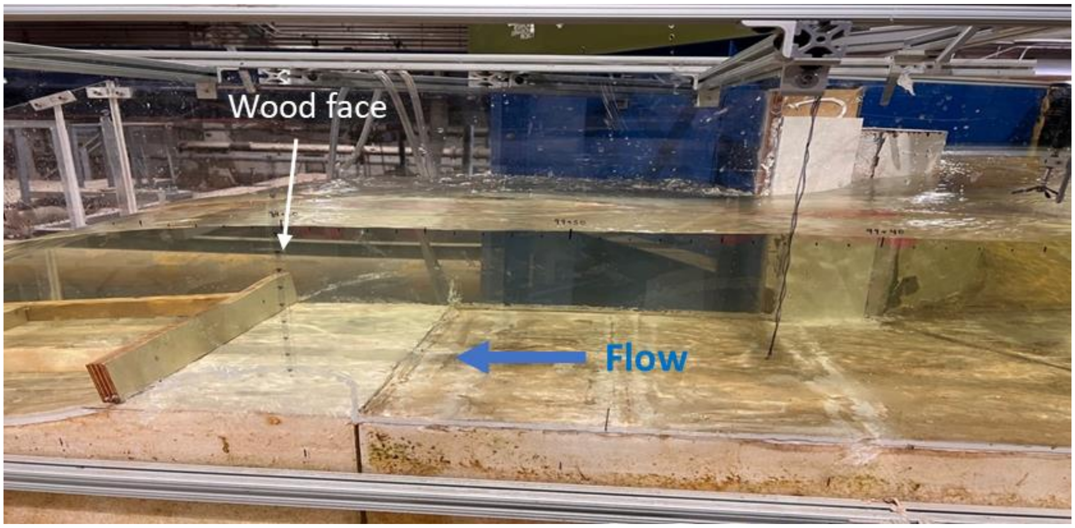
Figure 3-5. The Masa probe placed on the water-standpipes to monitor water-surface elevation in the headtank for the reservoir adjoining the spillway.

(a)



(b)

Figure 3-6. Views of the ogee crest being positioned: (a) use of a hot wire to cut the base of ogee crest (design location) from the spillway invert; and (b) use of a marine glue (placed at the sides and bottom of the ogee crest) to fix the ogee crest at a new location.



(a)

(b) (c)

Figure 3-7. Views of the spillway abutments: (a) the wood face used to simulate the location of the face of the ogee crest at each visualization location; (b) the circular abutment in position; and (c) the elliptical abutment being placed in position.

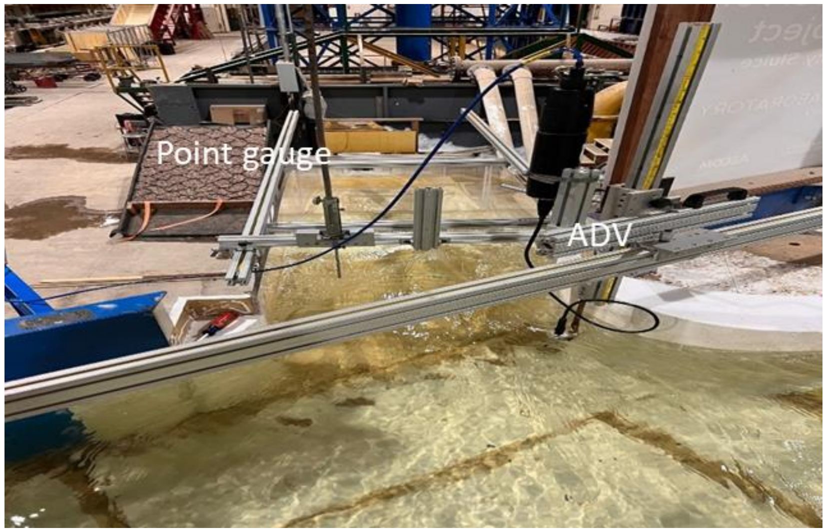


Figure 3-8. The ADV probe that was used to measure flow velocity (placed at the entrance to the spillway fitted with the circular abutment). Also shown is the point gauge used.

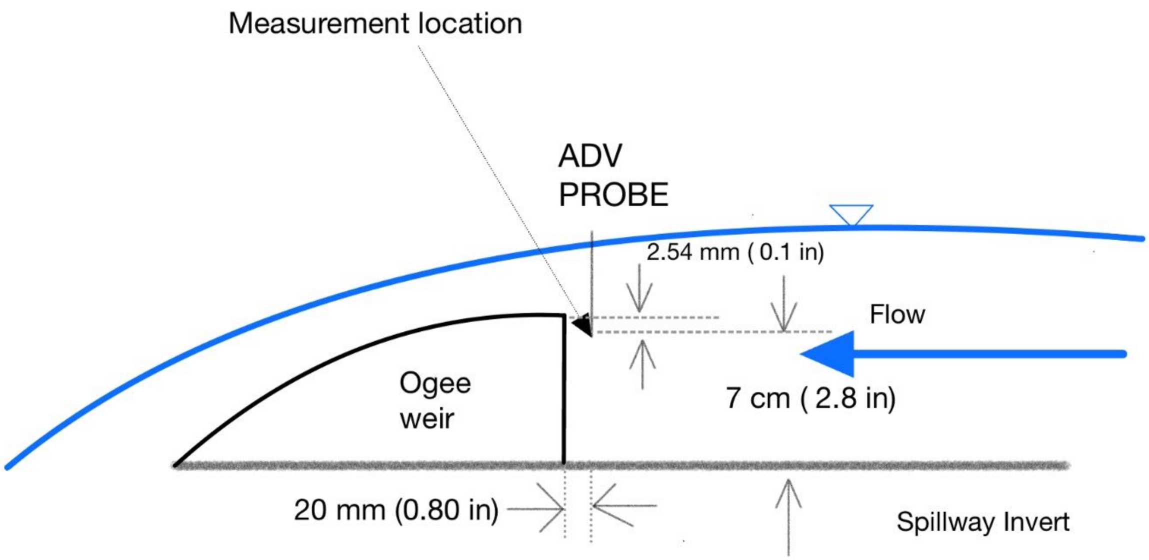


Figure 3-9. A sketch showing the location of the ADV measurements taken at vertical positions near the face of the ogee crest placed at the various locations along the spillway. This study used the locations as indicative of flow over the ogee weir.

3.7 Approach-Flow Conditions

The ADV data were collected at more than 30 spots within the headtank and spillway, in accordance with each location of the ogee. The resultant vectors were plotted as shown in Figure 3-10 for Experiment 2, used here as an example. The values of the approach velocity at the head tank did not vary much with respect to the circular abutment but they did increase at the head tank with the elliptical abutment. The velocities and depth for the head tank and spillway for all experiments can be found at the appendix.

Table 3-4 Headtank and spillway stations where the ADV results were taken for Experiment 2 (The right abutment is on the reader's left).

Station	**Right abutment**	**Stations at Headtank** (m)								**Left abutment**
9.00		27.081	26.853	26.548	26.304	26.030	25.756	25.490	25.295	
9.67			26.853	26.548	26.304	26.030	25.756	25.490		

Station	**Right abutment**	**Positions at Spillway (Lateral to Spillway Axis)** (m)								**Left abutment**
99+30		29.182	29.124	29.063	28.986	28.895	28.834	28.770	28.697	
99+40		29.182	29.124	29.063	28.986	28.895	28.834	28.770	28.697	
99+50		29.182	29.124	29.063	28.986	28.895	28.834	28.770	28.697	

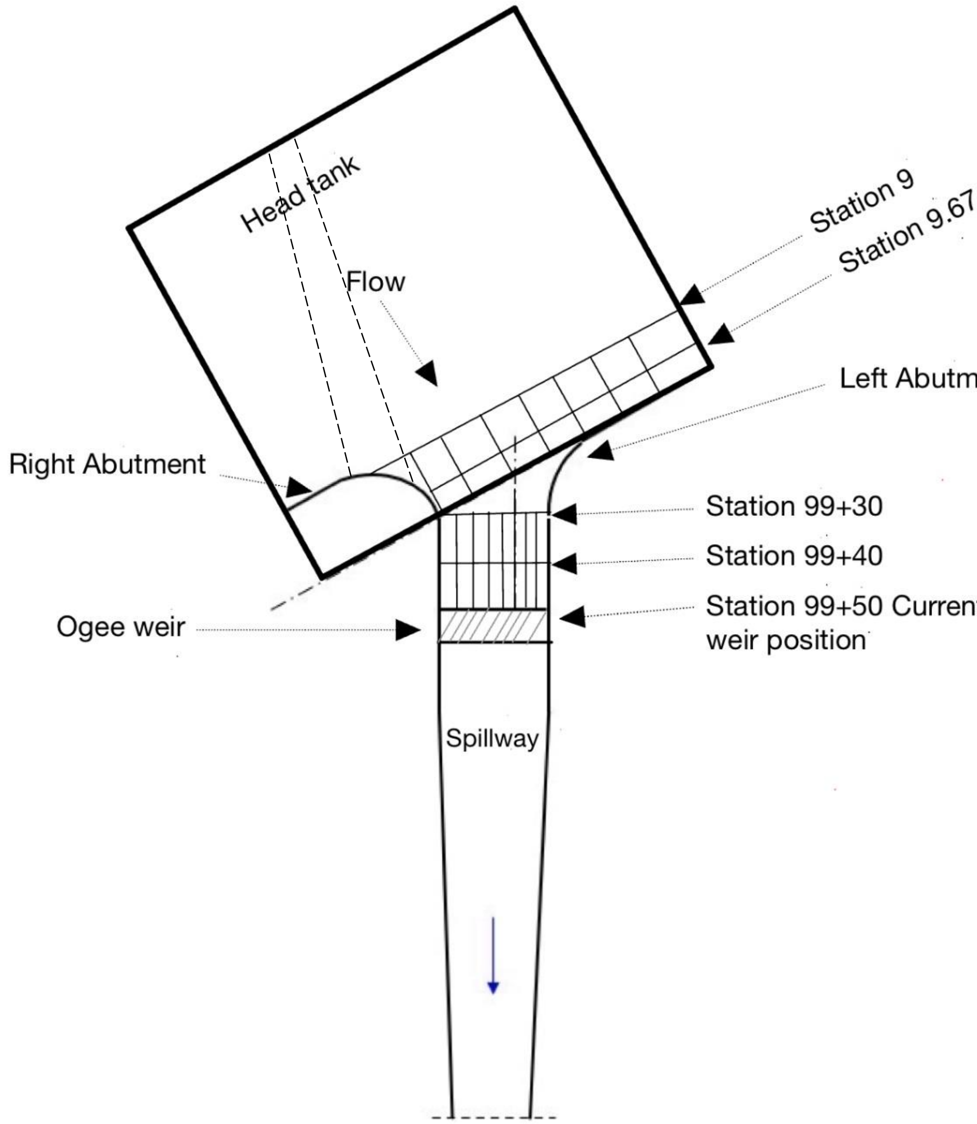
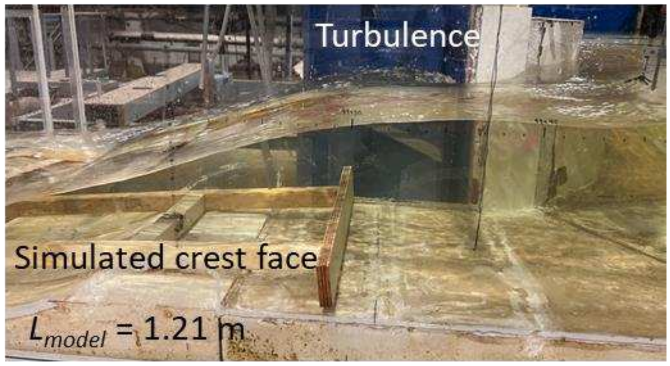
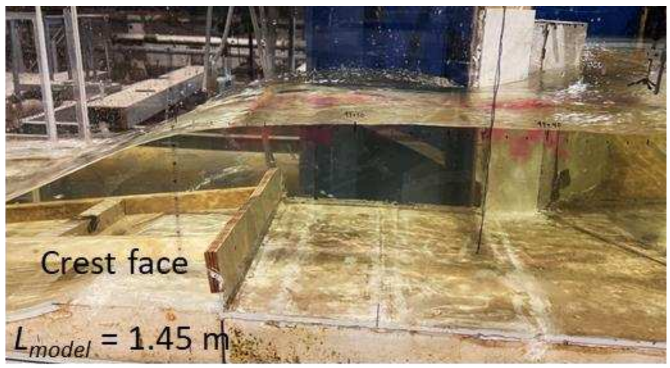


Figure 3-10. The squares show where the ADV probe was placed to get measurement cross-sections of approach flow velocity from the head tank to the ogee crest (Experiment 2).

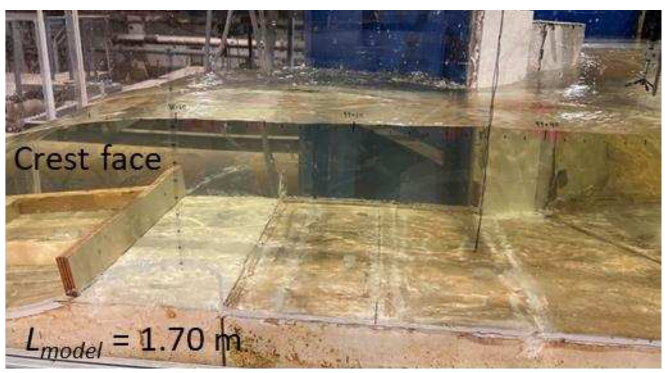
Figure 3-11. An illustration of flow entering the spillway for the spillway entrance fitted with circular abutments.



(a)



(b)



(c)

Figure 3-12. Illustrations of the wooden frame used to observe flow conditions when the ogee weir's crest face was at various positions: (a) *L* = 4.0 ft (1.21 m); (b) *L* = 4.75 ft (1.45 m); and (c) L = 5.57 ft (1.70 m)

CHAPTER 4: RESULTS

4.1 Introduction

This chapter presents the main results from the experiments described in Chapter 3. The experiments address the considerations mentioned in Chapter 2. The results from the experiments concern how the flow over the ogee crest was influenced by (a) the position of the ogee weir and its crest relative to the entrance (Station 9) of the spillway, and (b) the shape (circular of elliptical) of the spillway abutment. In particular, the present study focused on how these geometric factors affected uniformity of average velocity of flow over the ogee crest and turbulence level of flow over the ogee crest.

The findings are presented in the following order:

- Ogee weir position for the circular abutment at the spillway entrance.
- Ogee weir position for the elliptical abutment at the spillway entrance.
- Discussion of findings.

For abutment form (circular or elliptical) at the spillway entrance, the results begin with an illustrated description of the flow at the entrance. Presented next are lateral distributions of average velocity and a measure of turbulence near and upstream of ogee weir. Here, the measure of turbulence is taken as the standard deviation of velocity, as given by the ADV probe. A plan view of the layout of the spillway is given by Figure 3-1, which indicates the ogee locations examined during this study. Note that, in the figures presented, “right” refers to the viewer’s right when the viewer is looking downstream. The distances, *L*, of the ogee-crest positions from the spillway entrance are given in Figure 3-1.

4.2 Spillway with Circular Abutments

Flow accelerated from the spillway’s entrance toward the spillway’s ogee weir. Figure 4-1 shows the accelerating flow for the condition of design flow passed the circular abutments. Subsequently, Section 4.3 discusses the flow field for this condition when the spillway had elliptical abutments.

Prior to measurement of velocities associated with each of the abutment forms (circular and elliptical), dye was dispended from the dye wand to reveal the main features of the flow field. Flow entered the spillway slightly from the left (viewer’s left) and impacted the right abutment. The set of photographs given as Figure 4-2 show the design flow developed when the spillway had circular abutments.

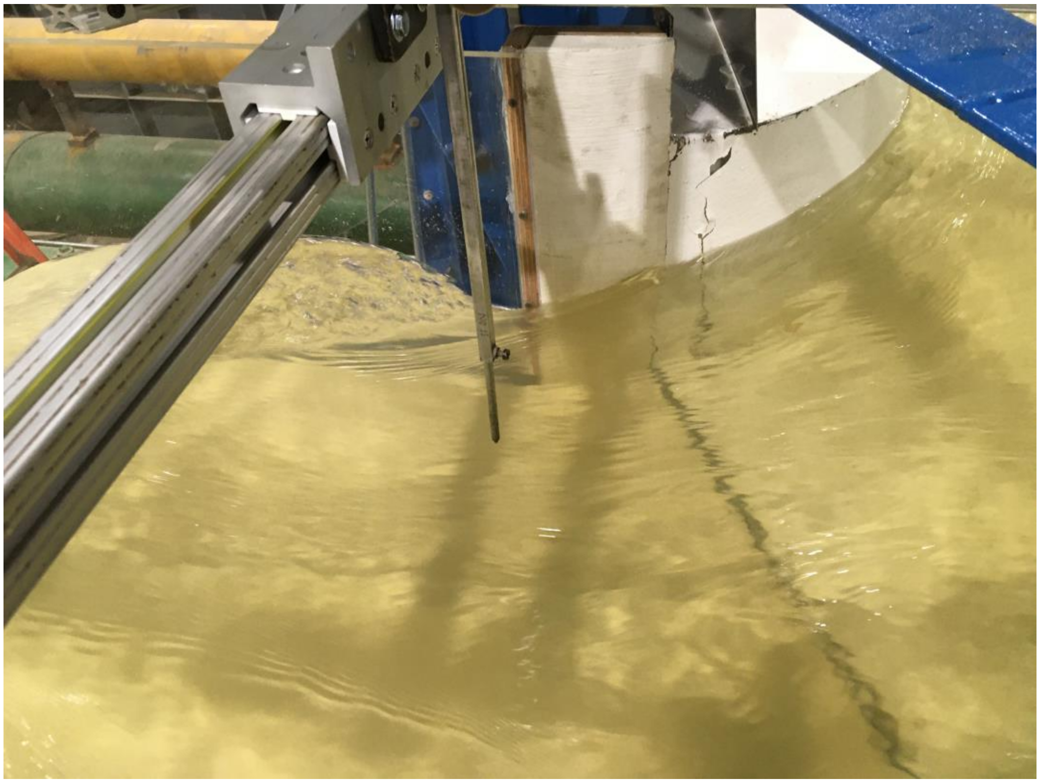


Figure 4-1. Flow accelerating from the spillway entrance into the spillway: circular abutments. The flow field at the abutment formed a zone of turbulence immediately downstream of the abutment.

A notable feature of the spillway with circular abutments was the sub-critical flow of water around the abutment face. No evident flow separation occurred. The flow close to the abutment accelerated around the side of the circular abutment and reduced in depth. As Figure 4-1 and Figure 4-2a show, here this flow met with the main portion of flow entering the spillway, flow formed a short smooth segment which then led to the zone of substantial turbulence. The zone of turbulence extended to the face or crest of the ogee weir then quickly dissipated as the flow accelerated over the weir and became upper-critical. The flow subsequently was super-critical down the spillway chute.

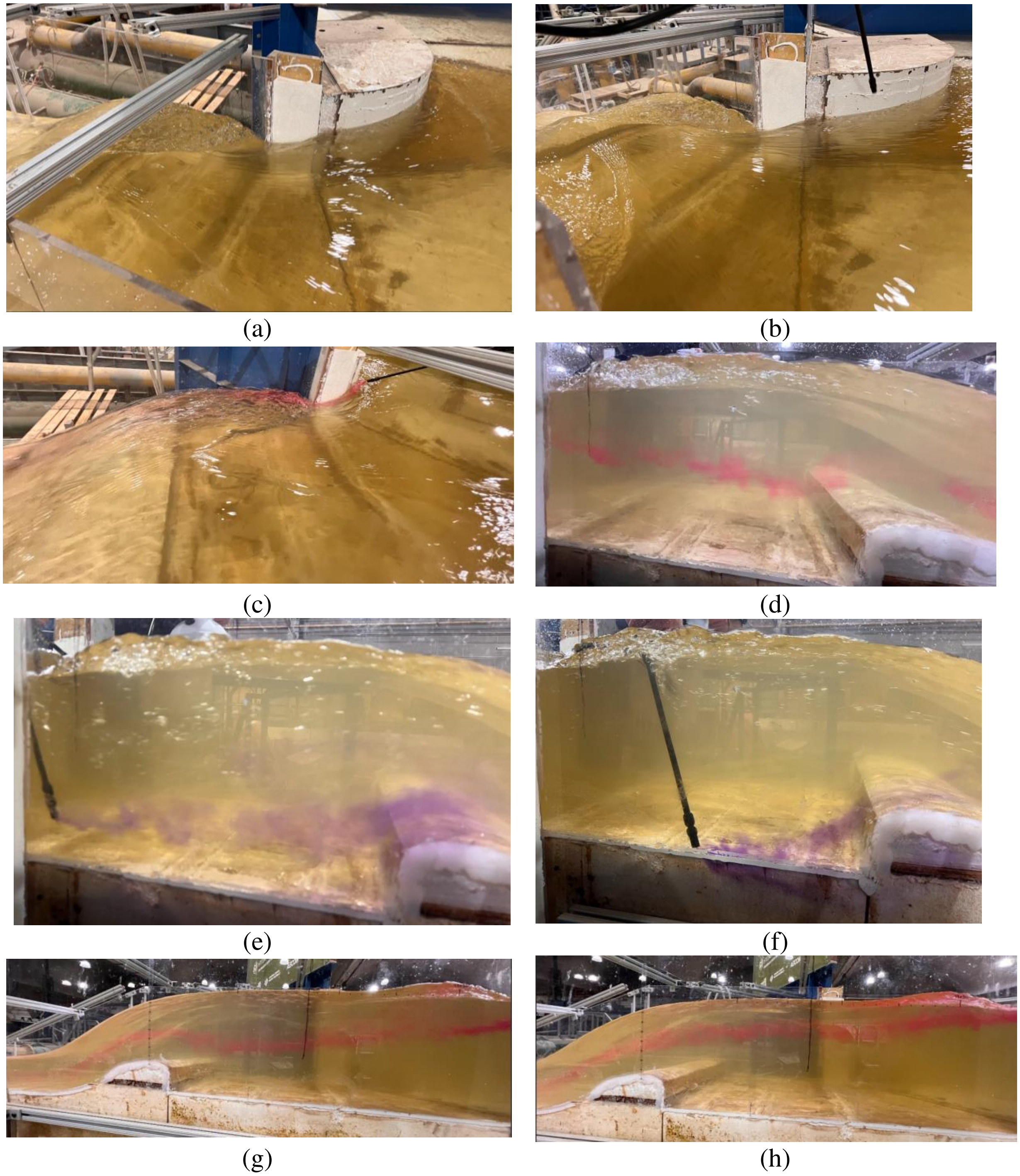


Figure 4-2. Views of the flow entering the spillway fitted with the circular abutments at the spillway's entrance.

Figure 4.3 shows the distribution of unit discharge entering the spillway with the circular abutments (Station 9.0). The flow was distinctly non-uniform in its approach at this section. The velocity data, obtained using ADV, were collected at more than 30 spots within the headtank approach to the spillway, and within the spillway, in accordance with each location of the ogee. The resultant vectors were plotted as shown in Figure 4-3 for Experiment 2, used here as an example. The values of the approach velocity at the head tank did not vary much with respect to the circular abutment, but they did increase at the head tank with the elliptical abutment, because it created a new separation at the left spillway abutment. The velocities, depth, and unit discharge for the head tank and spillway are shown in Table 4-1.

The distribution of velocities approaching the spillway reflects the non-uniformity of flow to the spillway. Such non-uniformity is typical of spillways placed on the shoulder of an earthfill dam, such that the flow must approach the spillway predominantly from one side of the dam.

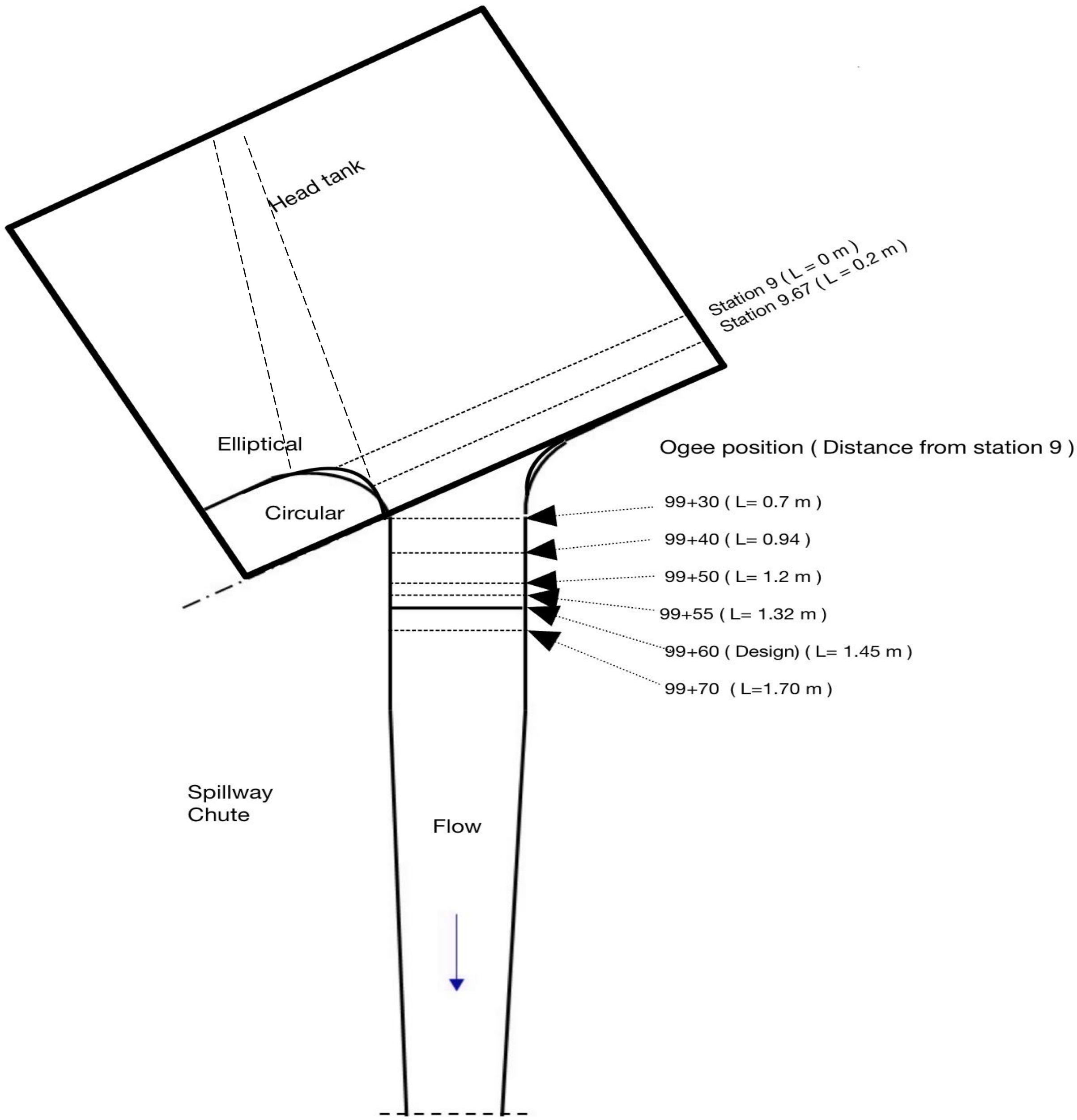


Figure 4-3. The measurement cross-sections of approach flow velocity and unit discharge from the head tank to the ogee crest for Experiment 2, for which the results were only taken at station 99+50 and the upstream stations. (Note that 1.00 m = 3.28 ft.)

Table. 4-1. The distribution of velocity and unit discharge entering the headtank and spillway; the flow was distinctly non-uniform where *L* is the distance from the spillway entrance (Station 9) to the experiment stations.

Station 9, *L*= 0.0 m	Positions accros the headtank (m)	27.081	26.853	26.548	26.304	26.030	25.756	25.490	25.295
	Velocity (m/s)	0.481	0.443	0.367	0.262	0.112	0.126	0.043	0.118
	Depth (m)	0.329	0.311	0.338	0.330	0.334	0.339	0.338	0.333
	Unit Discharge (m²/s)	0.158	0.138	0.124	0.086	0.037	0.043	0.015	0.039
Station 9.67, *L*= 0.20 m	Stations accros the headtank (m)		26.853	26.548	26.304	26.030	25.756	25.490	
	Velocity (m/s)		0.639	0.475	0.388	0.111	0.106	0.082	
	Depth (m)		0.317	0.320	0.325	0.331	0.335	0.334	
	Unit Discharge (m²/s)		0.203	0.152	0.126	0.037	0.036	0.027	
Station 99+30, *L*= 0.70 m	Stations accros the spillway (m)	29.182	29.124	29.063	28.986	28.895	28.834	28.770	28.697
	Velocity (m/s)	0.811	0.805	0.811	0.765	0.745	0.739	0.744	0.732
	Depth (m)	0.295	0.296	0.298	0.298	0.297	0.297	0.299	0.310
	Unit Discharge (m²/s)	0.239	0.238	0.241	0.228	0.221	0.219	0.222	0.227
station 99+40, *L*= 0.94 m	Stations accros the spillway (m)	29.182	29.124	29.063	28.986	28.895	28.834	28.770	28.697
	Velocity (m/s)	1.090	1.023	0.994	0.936	0.880	0.866	0.865	0.863
	Depth (m)	0.264	0.275	0.280	0.283	0.289	0.288	0.287	0.288
	Unit Discharge (m²/s)	0.288	0.281	0.279	0.265	0.254	0.250	0.248	0.249
station 99+50, *L*= 1.2 m	Stations accros the spillway (m)	29.182	29.124	29.063	28.986	28.895	28.834	28.770	28.697
	Velocity (m/s)	1.379	1.373	1.415	1.429	1.374	1.385	1.367	1.309
	Depth (m)	0.185	0.193	0.197	0.204	0.203	0.208	0.211	0.212
	Unit Discharge (m²/s)	0.256	0.265	0.279	0.292	0.279	0.288	0.288	0.278

Table 4-2. Summary of distances (*L*) for the experiment stations; *L* is the distance from the spillway entrance (Station 9) to the experiment stations.

Station	**Distance, *L*** (ft) Meters also noted
9.00	0.00 ft. (0.00 m)
9.67	0. 66ft (0.20 m))
99+30	2.30 ft (0.70 m)
99+40	3.08 ft (0.94 m)
99+50	3.93 ft (1.20 m)
99+55	4.33 ft (1.32 m)
99+60 (Design Location)	4.75 ft (1.45 m)
99+70	5.57 ft (1.70 m)

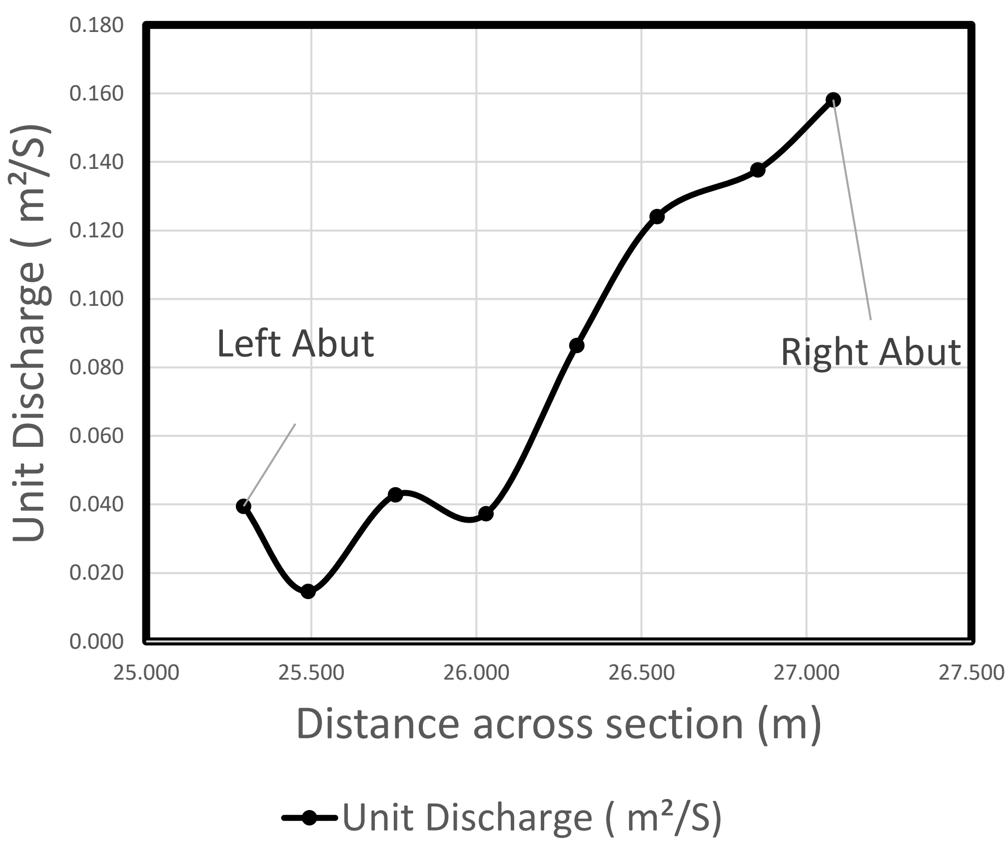


Figure 4-4. Non-uniform distribution of unit discharge entering the spillway entrance at Station 9 (Figure 4-3): circular abutments. (1.00 m = 3.28 ft.)

Values of the unit discharge, *q*, and mean velocity, *V*, are plotted in Figures 4-5 and 4-6 for the five positions at which the ogee weir was placed. For the design location, *L* = 4.75 ft (or 1.45 m). For each figure, the upper curve is mean velocity, *V*, and the lower curve is *q*. The right abutment is on the reader's right.

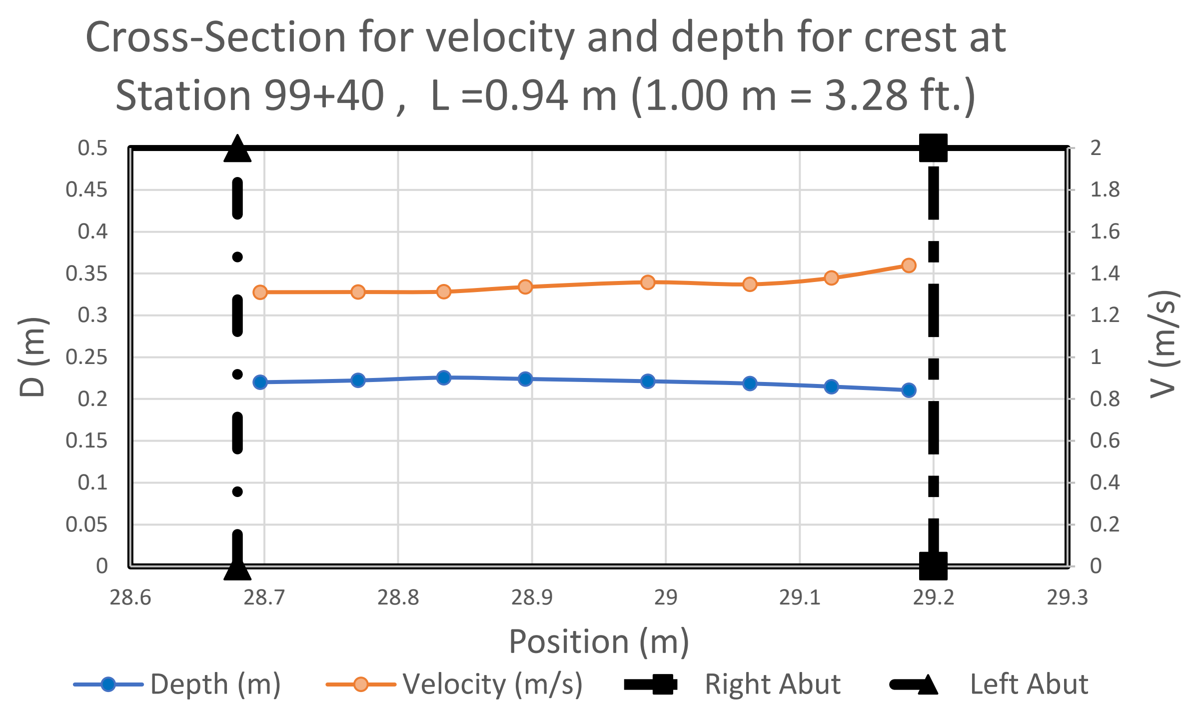
Figure 4-5 and 4-6 shows the following points:

- For the range of positions tested, the position of the ogee weir altered the extent and flow-field of flow turbulence formed downstream from the circular abutment (shown in Figure 4-1 and Figure 4-2).
- As the ogee position moved upstream and approached the 0 location, flow around the abutment developed less of a discernable turbulence zone. Instead, the water level of the approach flow remained laterally non-uniform and rough.
- When the ogee crest was downstream of the maximum width, *W'*, of the turbulence zone, flow uniformity over the ogee was best: flow widened, flow depth decreased slightly, flow velocity decreased slightly, thereby causing unit discharge also to decrease. Flow uniformity here is viewed in terms of lateral distribution of unit discharge and velocity.
- When the ogee crest was within the maximum width, *W'*, of the turbulence zone, flow uniformity over the ogee decreased as the values of the distance ratio *L/L'* decreased further because widened but reflected the original non-uniformity of flow approach to the spillway.
- As the width of the ogee weir increases (for a given flow depth at the weir face), the significance of flow turbulence at an abutment decreased.
- The circular-abutment form produced a greater uniformity of flow across the ogee crest than did the elliptical-abutment form, as the zone of flow turbulence was much smaller.

- Vortex formation in the separation zone occurred when the ogee position exceeded the length of the turbulence zone. Otherwise, ogee presence within the turbulence zone inhibited turbulence formation but did prevent non-uniformity of approach flow.

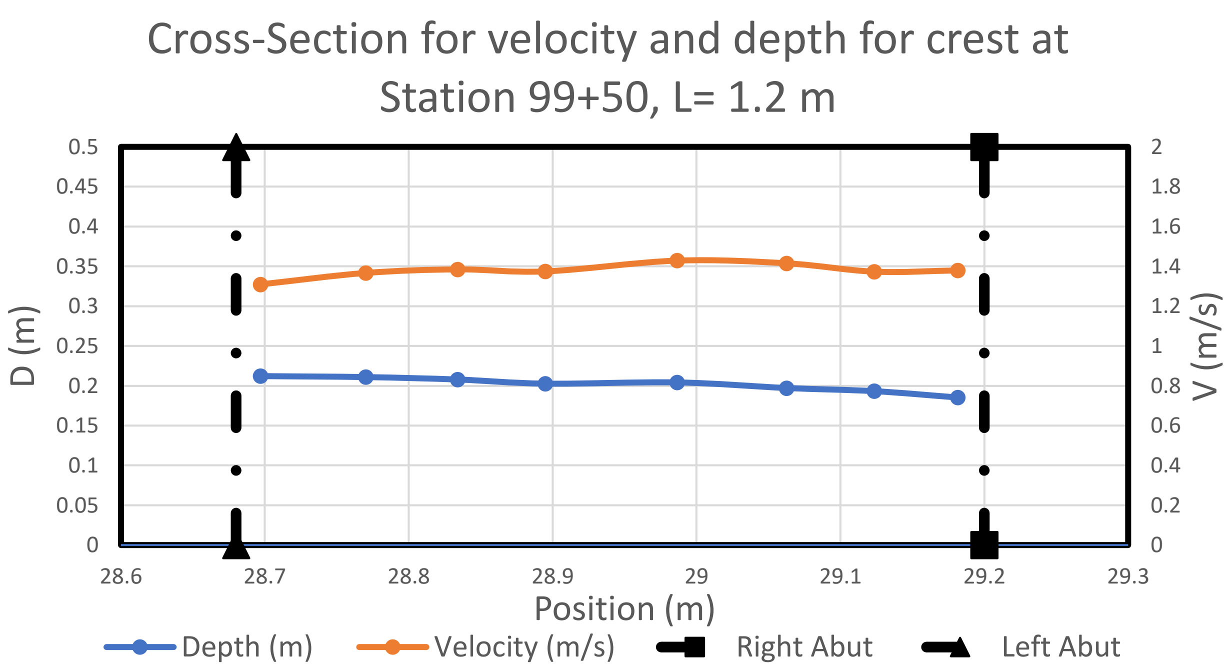
The turbulence levels are shown in Figures 4-12 for the circular abutments and the ogee crest at the range of locations investigated. The values are the maximum standard deviation for the velocity as obtained from the ADV measurements. The results show the following points:

- The standard deviation of turbulence was within acceptable range and did vary when the ogee crest was closest to spillway entrance (Figures 4-12a, b)
- When moving the ogee crest to the location positions, Stations 99+55 and 99+60 (design location), the standard deviation of turbulence would increase upstream of the ogee crest and then begin to decrease when it approaches the face of the ogee crest (Figures 4-12c, d).
- The standard deviation of turbulence reached its maximum value upstream of the ogee crest (0.69 m/s) when the ogee crest is placed furthest from the spillway entrance, but then began to decrease when it approached the ogee crest (Figure 4-12e).



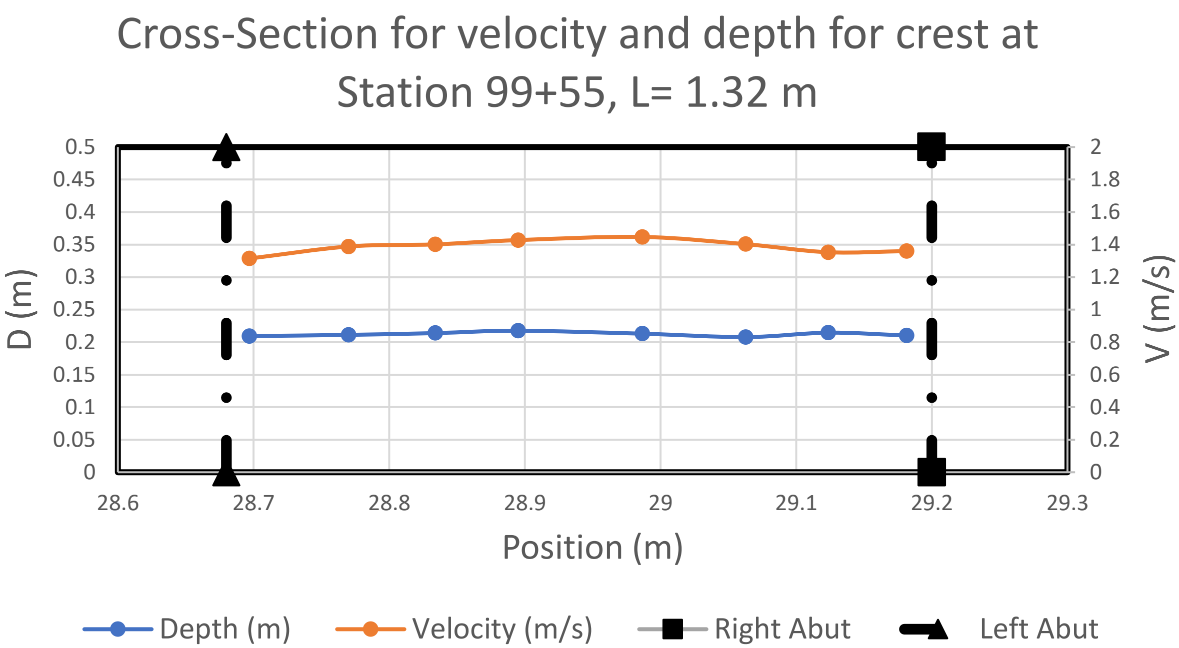
Cross-Section for velocity and depth for crest at Station 99+40 , L =0.94 m (1.00 m = 3.28 ft.)
D (m)
V (m/s)
Position (m)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
28.6
28.7
28.8
28.9
29
29.1
29.2
29.3
Depth (m)
Velocity (m/s)
Right Abut
Left Abut

(a)

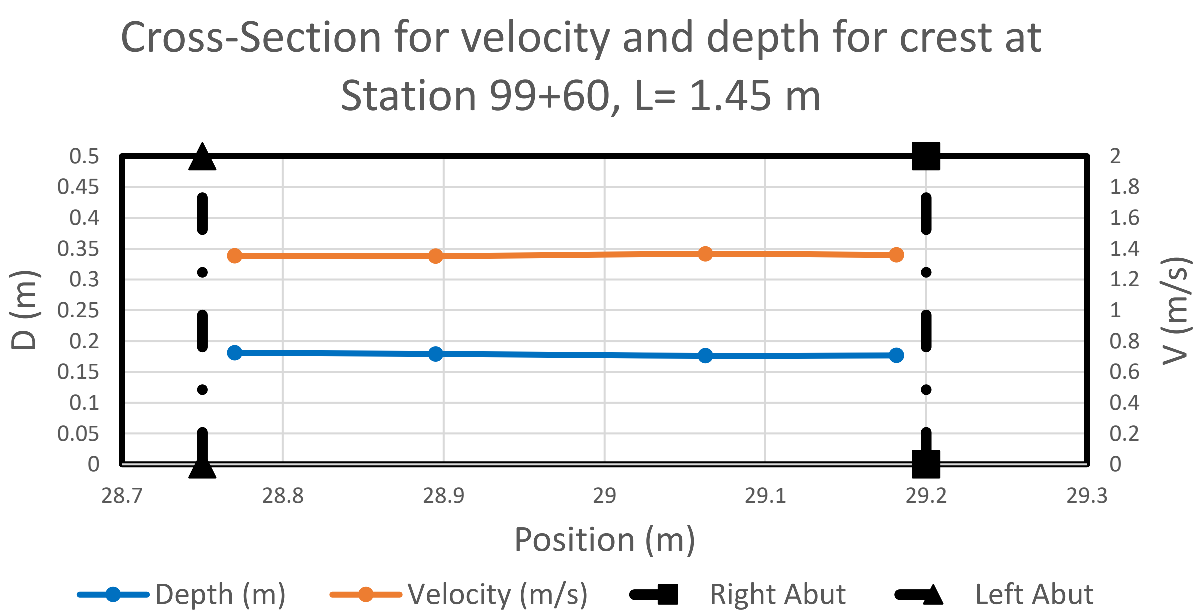


Cross-Section for velocity and depth for crest at Station 99+50, L= 1.2 m
D (m)
V (m/s)
Position (m)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
28.6
28.7
28.8
28.9
29
29.1
29.2
29.3
Depth (m)
Velocity (m/s)
Right Abut
Left Abut

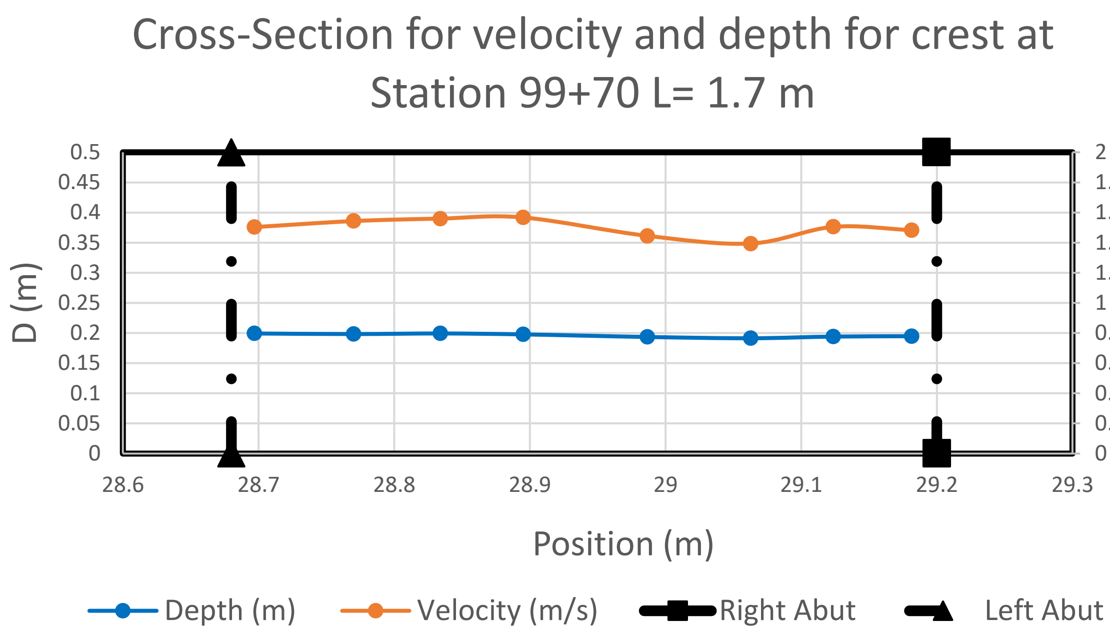
(b)


Cross-Section for velocity and depth for crest at Station 99+55, L= 1.32 m
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
D (m)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
V (m/s)
28.6
28.7
28.8
28.9
29
29.1
29.2
29.3
Position (m)
Depth (m)
Velocity (m/s)
Right Abut
Left Abut

(c)

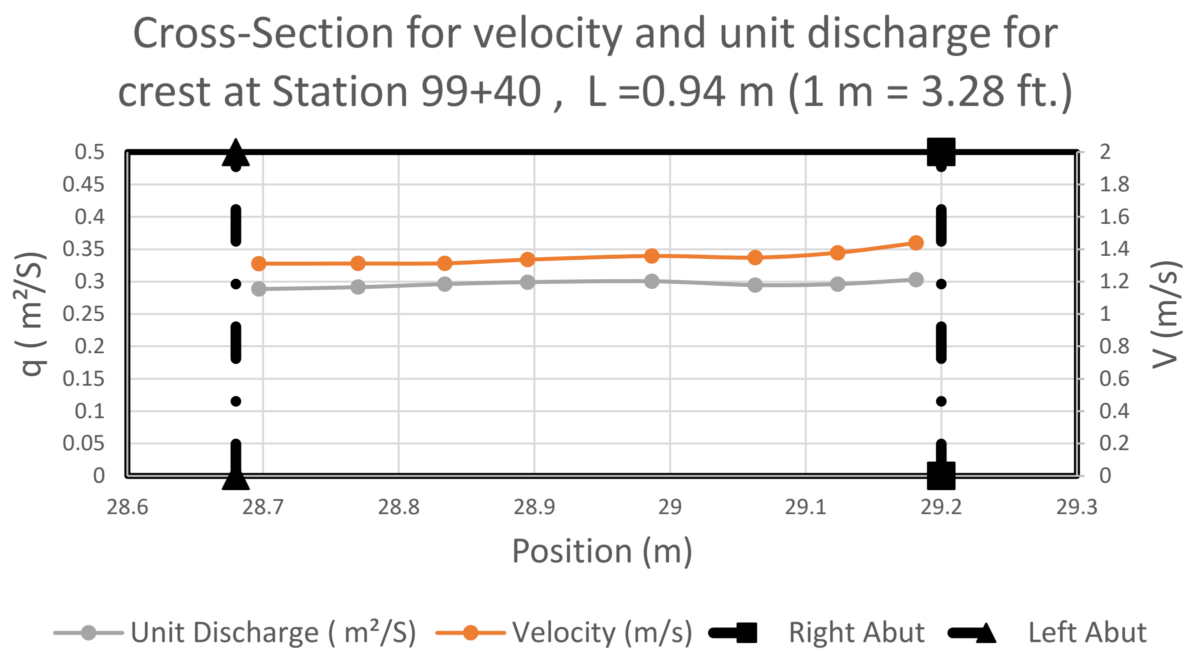

Cross-Section for velocity and depth for crest at Station 99+60, L= 1.45 m
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
D (m)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
V (m/s)
28.7
28.8
28.9
29
29.1
29.2
29.3
Position (m)
Depth (m)
Velocity (m/s)
Right Abut
Left Abut

(d)

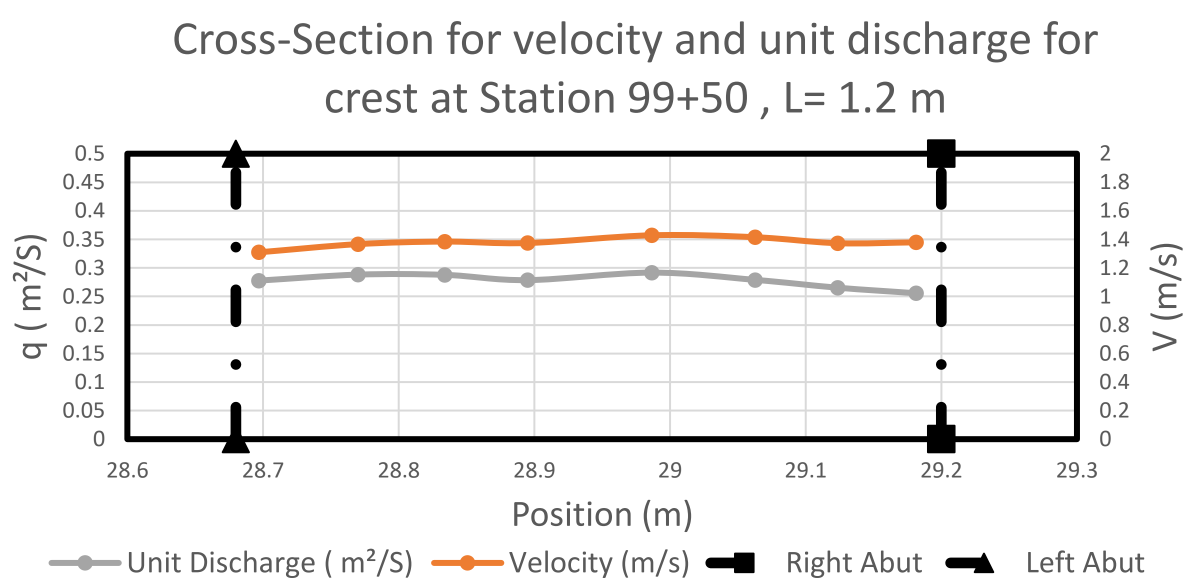


(e)

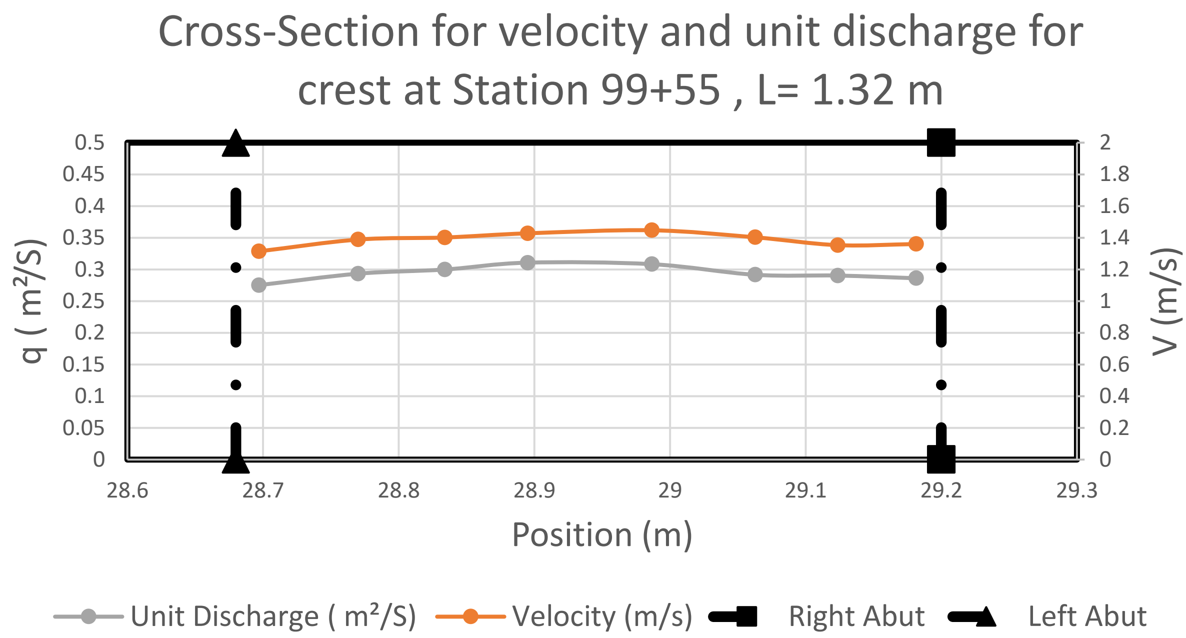
Figure 4-5. Distributions of depth (*d*) and depth-average velocity (*V*) for the circular abutment at the face of the ogee weir (model scale). The values of weir-face distance from spillway entrance (Station 9) were: (a) 0.94 m; (b) 1.2 m; (c) 1.32 m; (d) 1.45 m; and (e) 1.70 m. The values in (e) were affected by standing waves formed by flow in the approach to the ogee crest. (1.00 m = 3.28 ft.).


Cross-Section for velocity and unit discharge for crest at Station 99+40 , L =0.94 m (1 m = 3.28 ft.)
q (m²/S)
V (m/s)
Position (m)
Unit Discharge (m²/S)
Velocity (m/s)
Right Abut
Left Abut

(a)

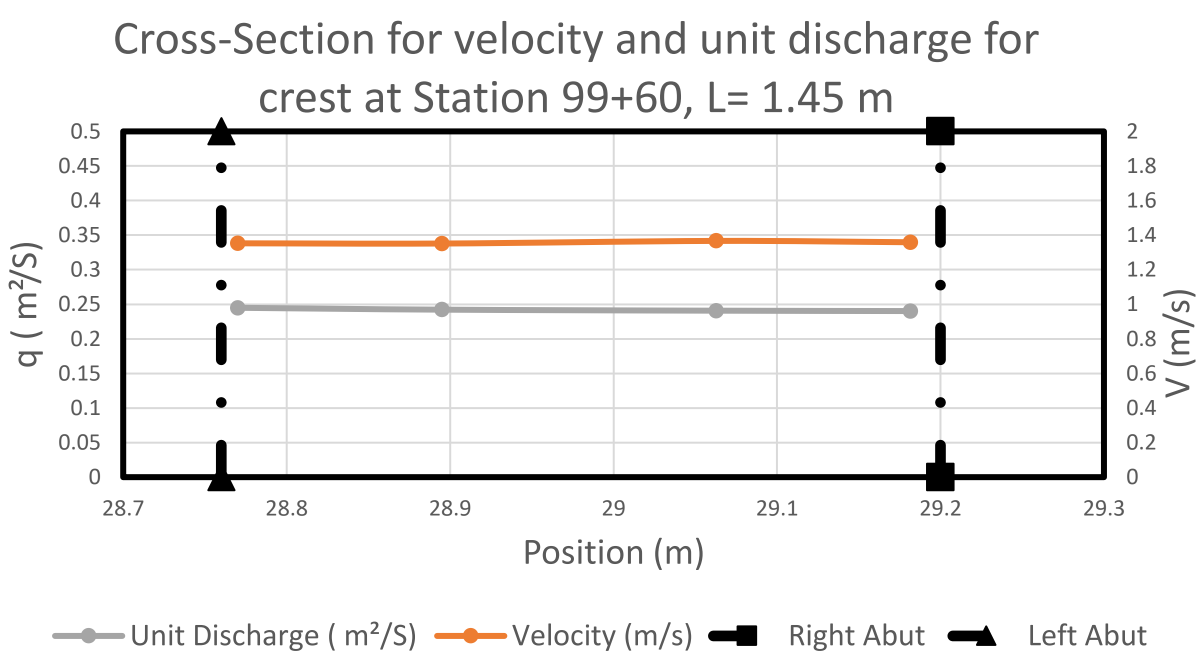

Cross-Section for velocity and unit discharge for crest at Station 99+50 , L= 1.2 m
q (m²/S)
V (m/s)
Position (m)
Unit Discharge (m²/S)
Velocity (m/s)
Right Abut
Left Abut

(b)



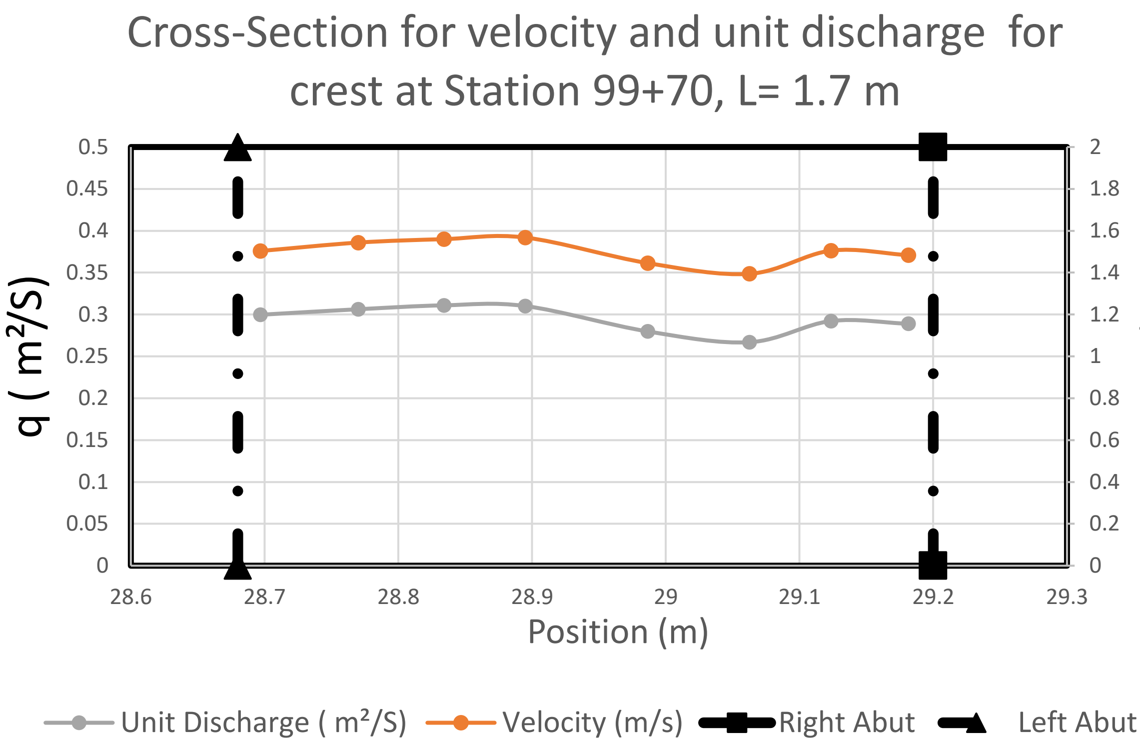
Cross-Section for velocity and unit discharge for crest at Station 99+55 , L= 1.32 m
q (m²/S)
V (m/s)
Position (m)
Unit Discharge (m²/S)
Velocity (m/s)
Right Abut
Left Abut

(c)



Cross-Section for velocity and unit discharge for crest at Station 99+60, L= 1.45 m
q (m²/S)
V (m/s)
Position (m)
Unit Discharge (m²/S)
Velocity (m/s)
Right Abut
Left Abut

(d)



(e)

Figure 4-6. Distributions of unit discharge (q) and depth-average velocity (*V*) for the circular abutment at the face of the ogee weir (model scale). The values of weir-face distance from spillway entrance (Station 9) were: (a) 0.94 m; (b) 1.2 m; (c) 1.32 m; (d) 1.45 m; and (e) 1.70 m. The values in (e) were affected by standing waves formed by flow in the approach to the crest. (1.00 m = 3.28 ft.).

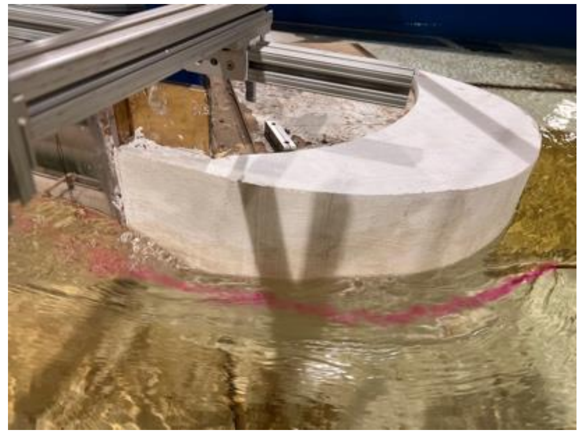
4.3 Spillway with Elliptical Abutments

As for the entrance formed with the circular abutments, the entrance with the elliptical abutments caused the flow to accelerate toward the spillway's ogee weir. Figure 4-7 shows the accelerating flow for the condition of design flow passed the circular abutments. Flow still entered the spillway slightly from the left (viewer's left) and impacted the right abutment. The set of photographs given as Figure 4-7 show the design flow developed when the spillway had elliptical abutments.

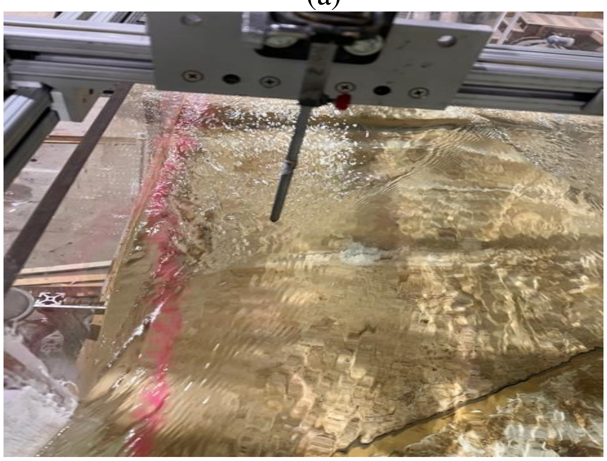
Values of the unit discharge, *q*, and mean velocity, *V*, are plotted in Figures 4-9 and 4-10 for the five positions at which the ogee weir was placed. For each figure, the upper curve is mean velocity, *V*, and the lower curve is *q*. As mentioned above, the right abutment is on the reader's right.

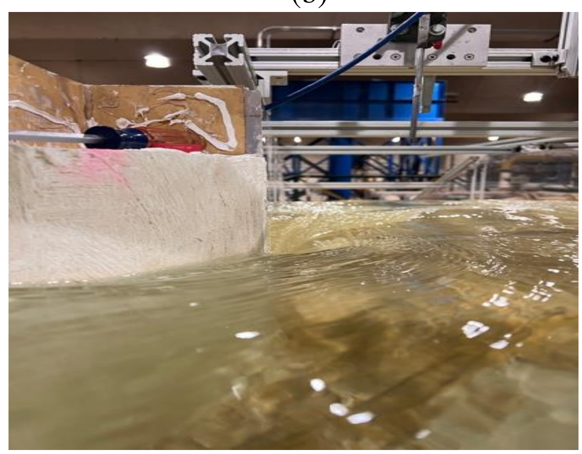
Figures 4-9 and 4-10 show the following points:

- For the range of positions tested, the position of the ogee weir altered the extent and flow-field of turbulence zone extending from the elliptical abutment (shown in Figure 4-8). The zone was reduced in surface area by about 40 percent compared to the area of the turbulence zone created by the circular abutment.
- The elliptical abutment placed at the spillway's left abutment which disturbed water uniformity slightly more than did the circular form of the abutment.
- As the ogee position moved upstream and approached the 0 location, flow around the abutment developed less of a discernable separation zone. Instead, the water level of the approach flow remained laterally non-uniform and rough.

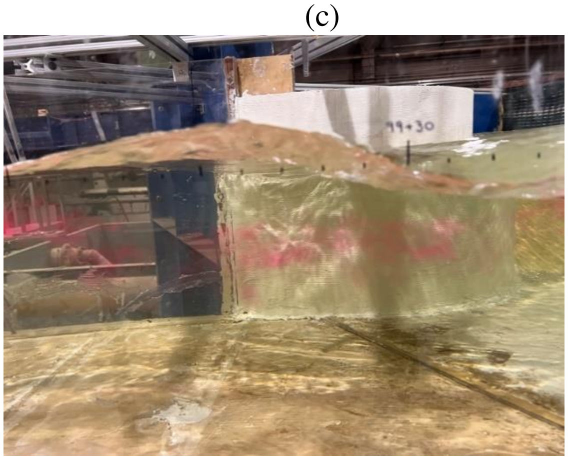


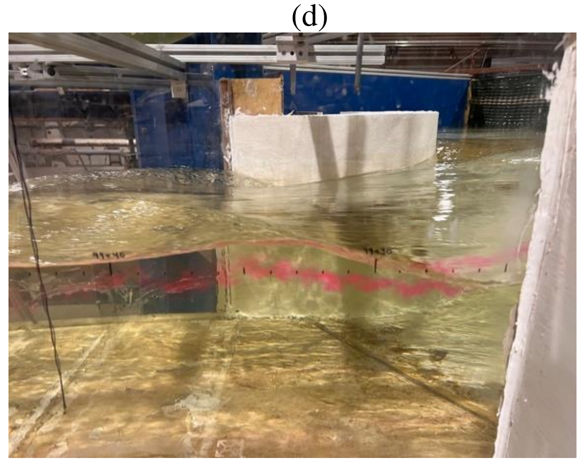
(a) (b)





(c) (d)





(e) (f)

(g) (h)

Figure 4-7. Views of the flow entering the spillway fitted with the elliptical abutment at the spillway entrance.

- When the ogee crest was downstream of the maximum width, *W'*, of the separation zone, flow uniformity over the ogee was best: flow widened, flow depth decreased slightly, flow velocity decreased slightly, thereby causing unit discharge also to decrease. Flow uniformity here is viewed in terms of lateral distribution of unit discharge and velocity.
- When the ogee crest was within the maximum width, *W'*, of the separation zone, flow uniformity over the ogee decreased as the values of the distance ratio *L/L'* decreased further because widened but reflected the original non-uniformity of flow approach to the spillway.
- As the width of the ogee weir increases (for a given flow depth at the weir face), the significance of flow separation at an abutment decreased.

The turbulence levels are shown in Figure 4-13 for the elliptical abutments and the ogee crest at the range of locations investigated. The values are the maximum standard deviation for the velocity as obtained from the ADV measurements.

The results show the following points:

- The standard deviation of turbulence would reach high result upstream of the ogee crest when the ogee crest is placed at station 99+40 but turbulence begins to drop when reaching the ogee crest (Figure 4-13a).
- The standard deviation of turbulence was within acceptable range and did vary much when the ogee crest was placed at stations 99+50 and 99+55 (Figure 4-13b, c)
- When moving the ogee crest to the station 99+60 (the design location for Los Vaqueros spillway) the standard deviation of turbulence would increase upstream of the ogee crest and then begin to become less turbulent when it approaches the face of the ogee crest (Figure 4-13d).
- The standard deviation of turbulence would fluctuate along the spillway and reach its highest value at the ogee crest when the crest is placed at station 99+70 (Figure4-13 e).

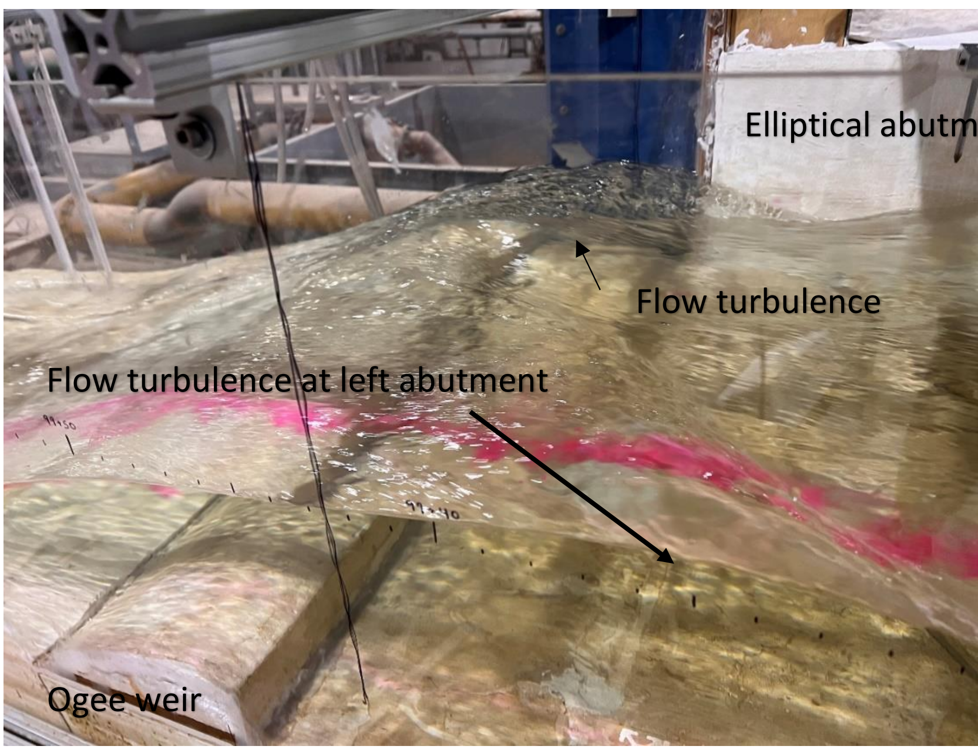
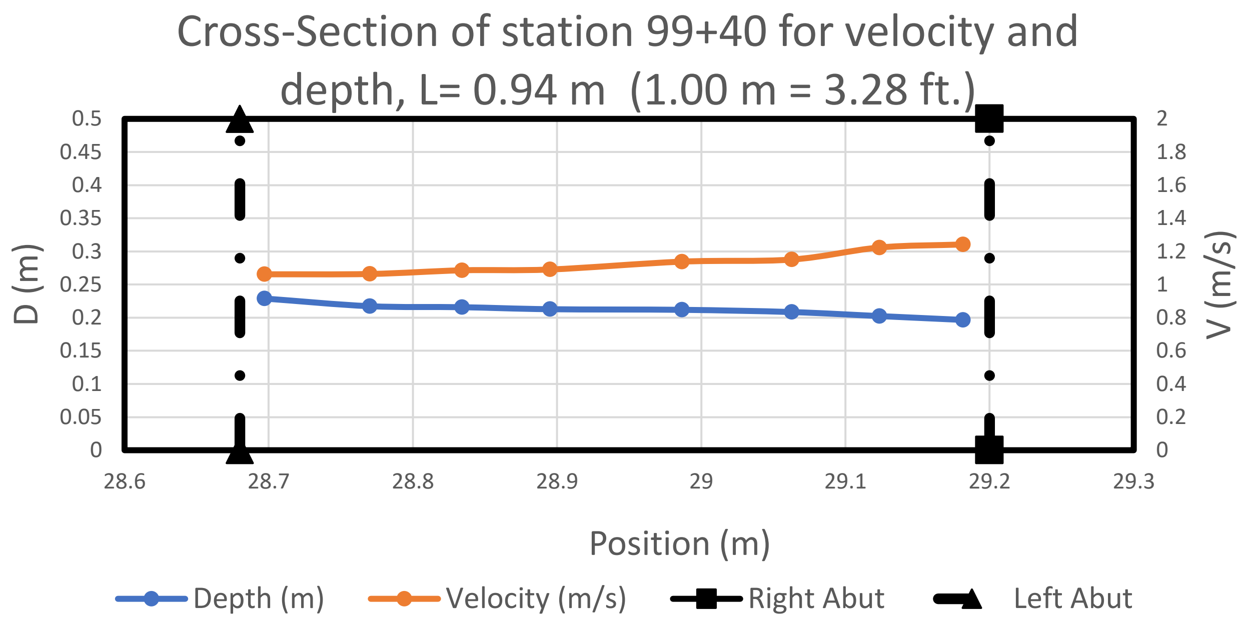
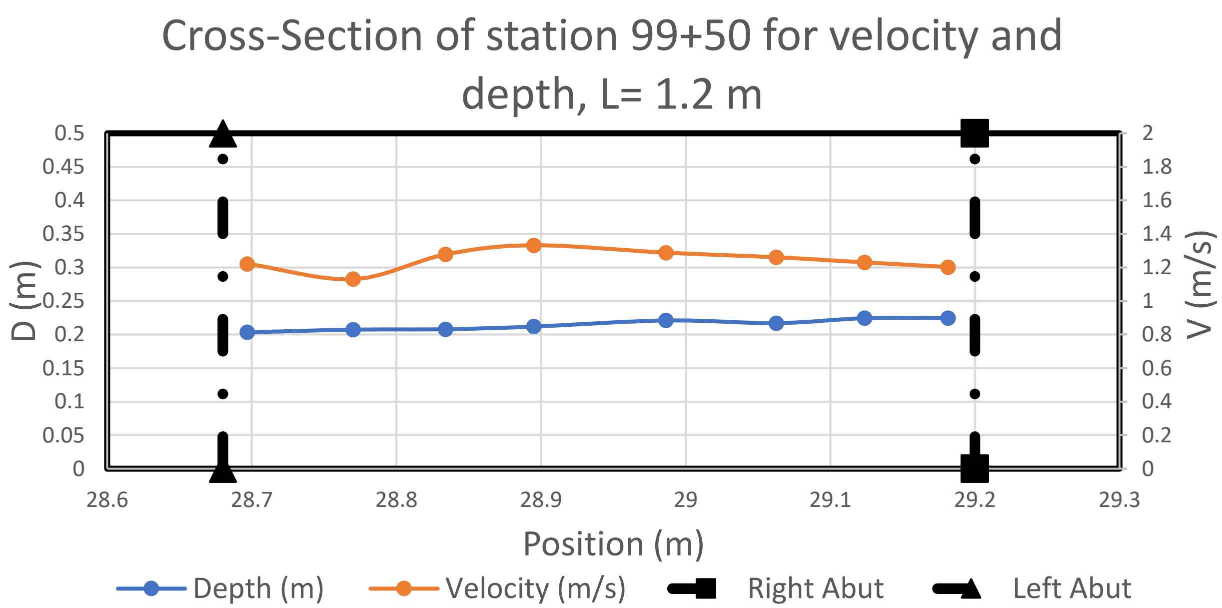


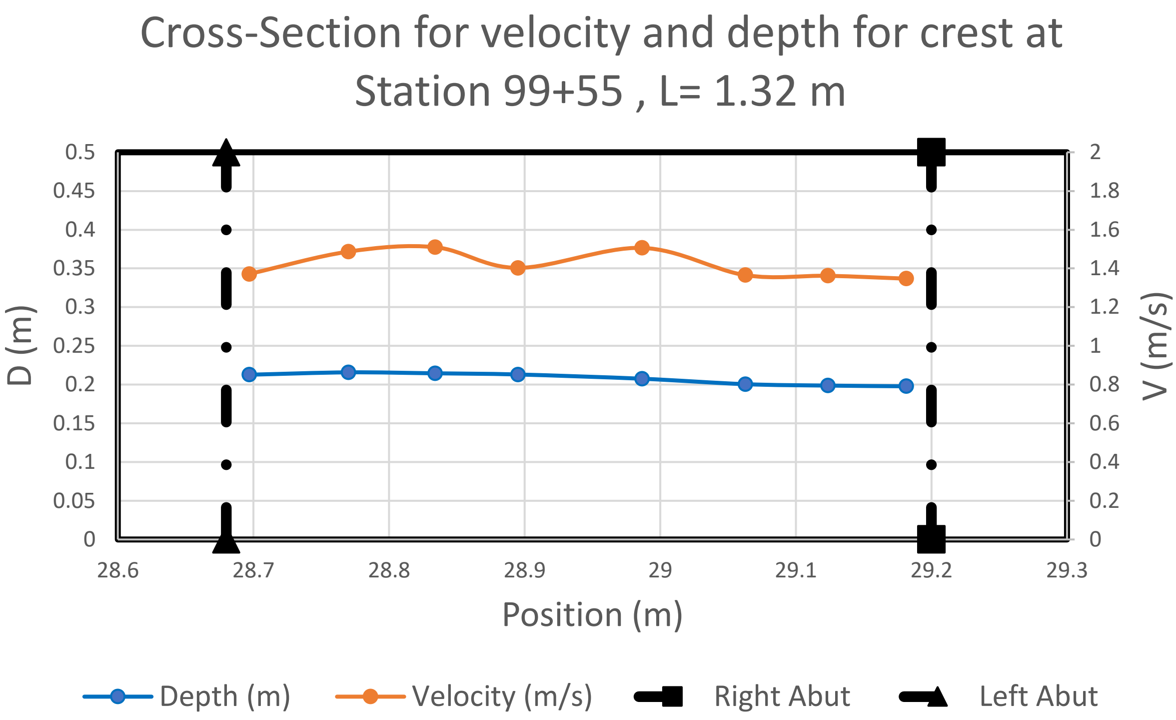
Figure 4-8. Flow turbulence zone caused by flow passing around the elliptical abutment of the left side of the spillway entrance. Note that, for this abutment form, a turbulence region also developed at the left abutment (viewer's left).


Cross-Section of station 99+40 for velocity and depth, L= 0.94 m (1.00 m = 3.28 ft.)
D (m)
V (m/s)
Position (m)
Depth (m)
Velocity (m/s)
Right Abut
Left Abut

(a)

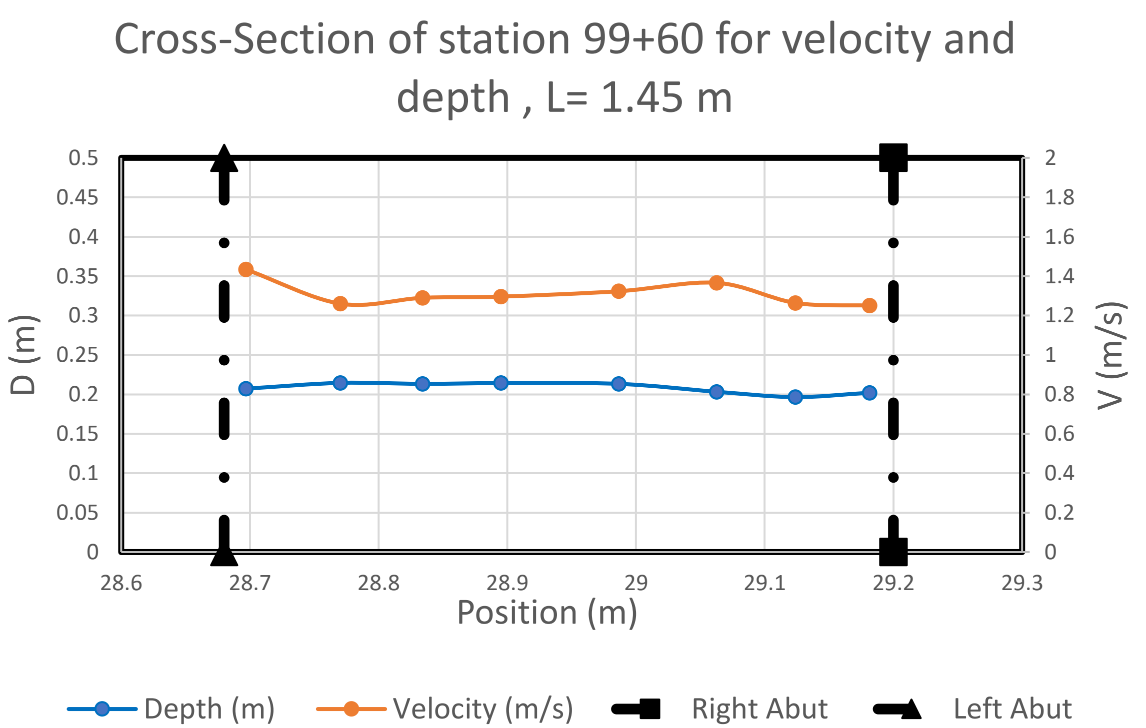

Cross-Section of station 99+50 for velocity and depth, L= 1.2 m
D (m)
V (m/s)
Position (m)
Depth (m)
Velocity (m/s)
Right Abut
Left Abut

(b)



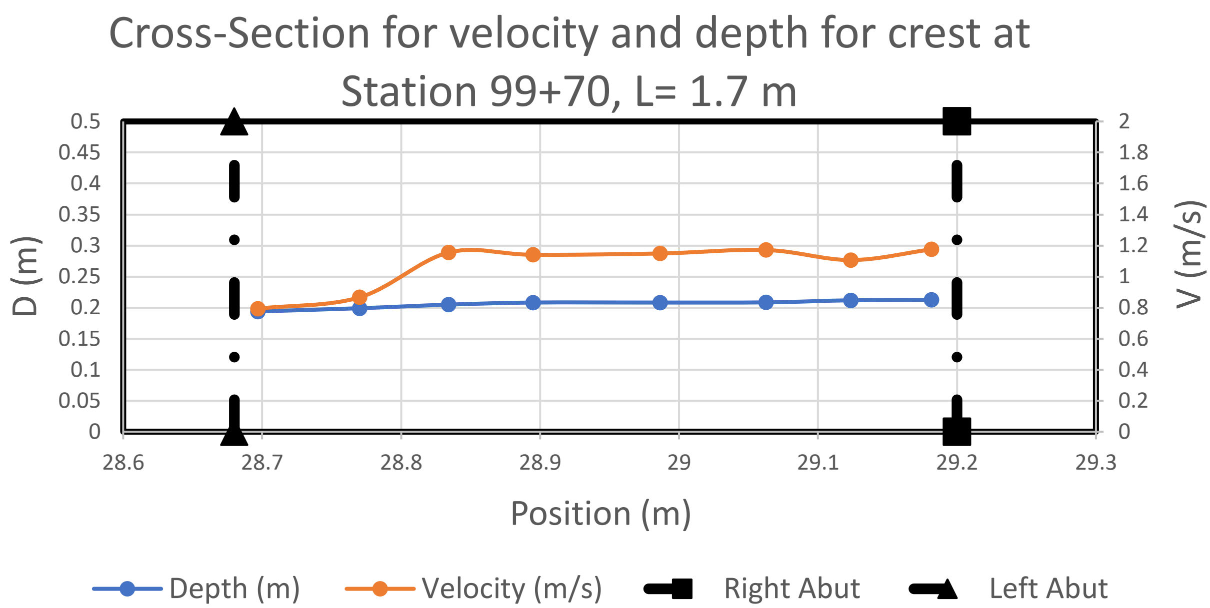
Cross-Section for velocity and depth for crest at Station 99+55 , L= 1.32 m
D (m)
V (m/s)
Position (m)
Depth (m)
Velocity (m/s)
Right Abut
Left Abut

(c)



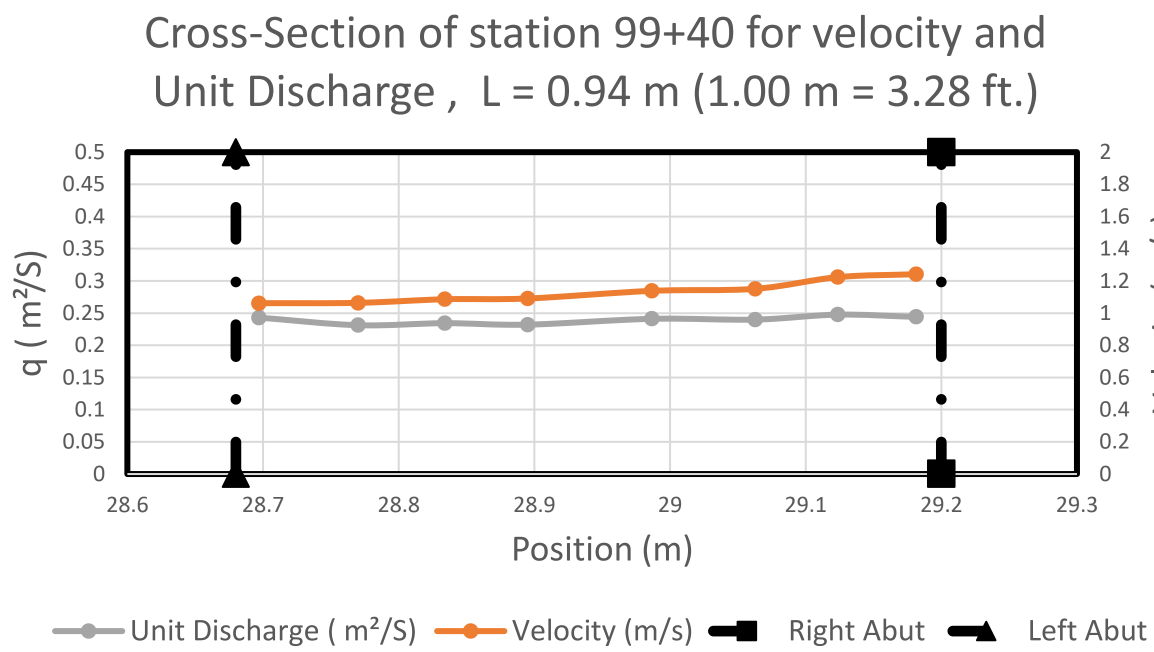
Cross-Section of station 99+60 for velocity and depth , L= 1.45 m
D (m)
V (m/s)
Position (m)
Depth (m)
Velocity (m/s)
Right Abut
Left Abut

(d)

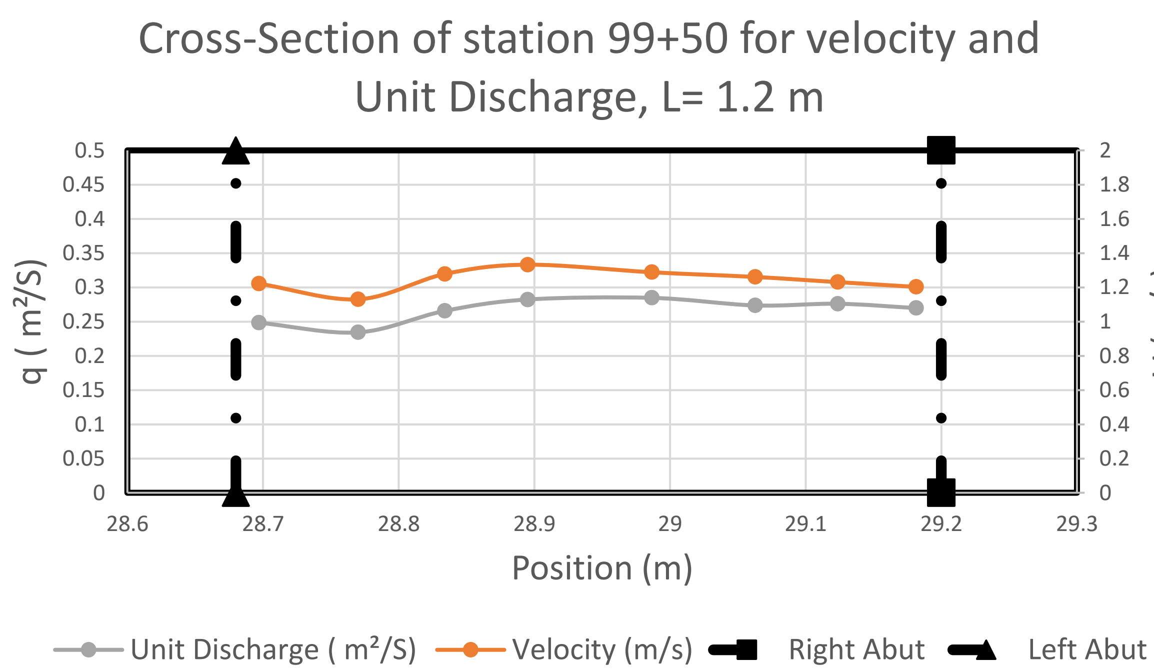


(e)

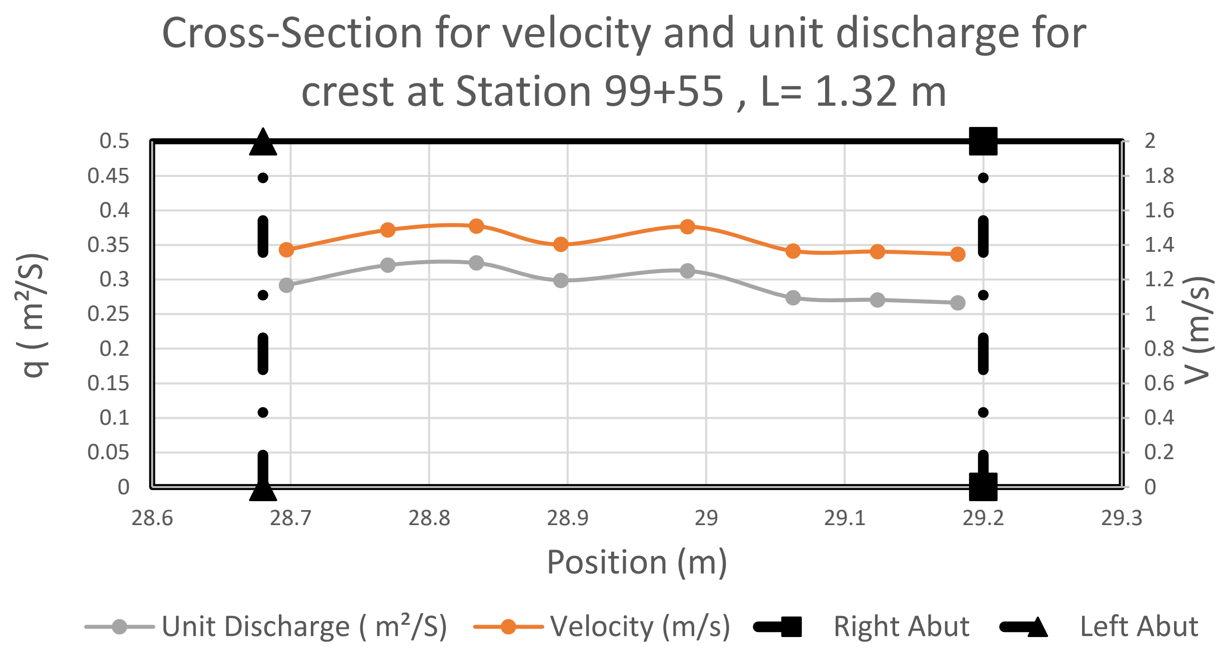
Figure 4-9. Distributions of depth (*d*) and depth-average velocity (*V*) for the elliptical abutment at the face of the ogee weir (model scale). The values of weir-face distance from spillway entrance (Station 9) were: (a) 0.94 m; (b) 1.2 m; (c) 1.32 m; (d) 1.45 m; and (e) 1.70 m. The values in (e) were affected by standing waves formed in the approach flow to the crest. (1.00 m = 3.28 ft.)


Cross-Section of station 99+40 for velocity and Unit Discharge , L = 0.94 m (1.00 m = 3.28 ft.)
q (m²/S)
Velocity(m/s)
Position (m)
Unit Discharge (m²/S)
Velocity (m/s)
Right Abut
Left Abut

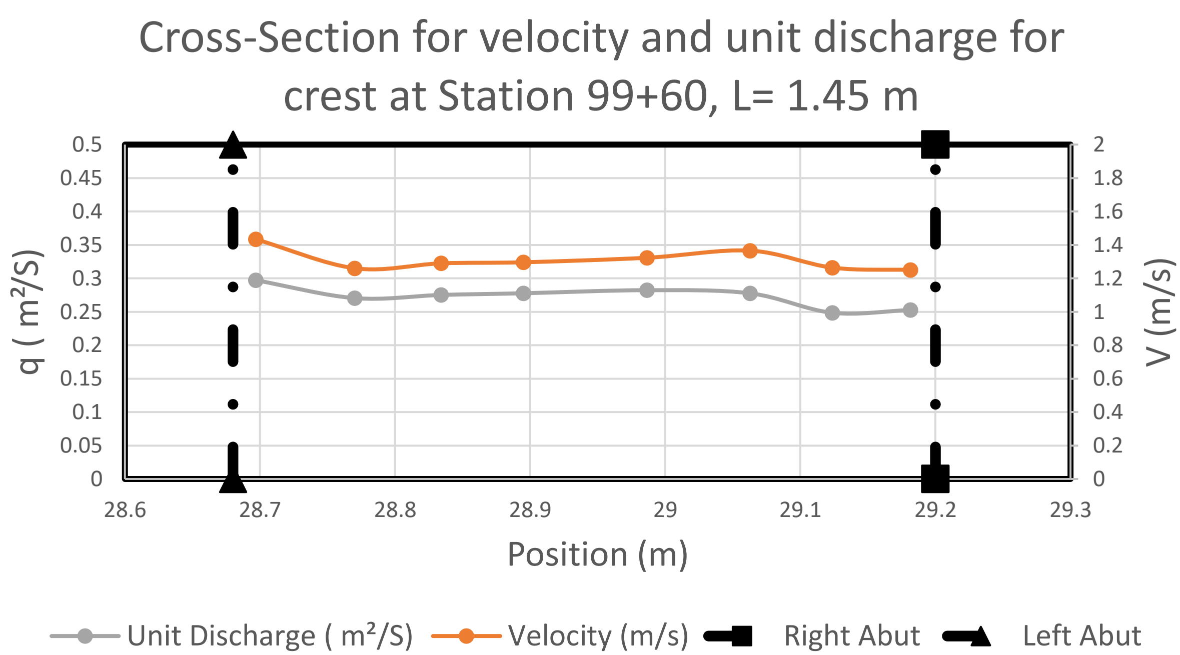
(a)


Cross-Section of station 99+50 for velocity and Unit Discharge, L= 1.2 m
q (m²/S)
V (m/s)
Position (m)
Unit Discharge (m²/S)
Velocity (m/s)
Right Abut
Left Abut

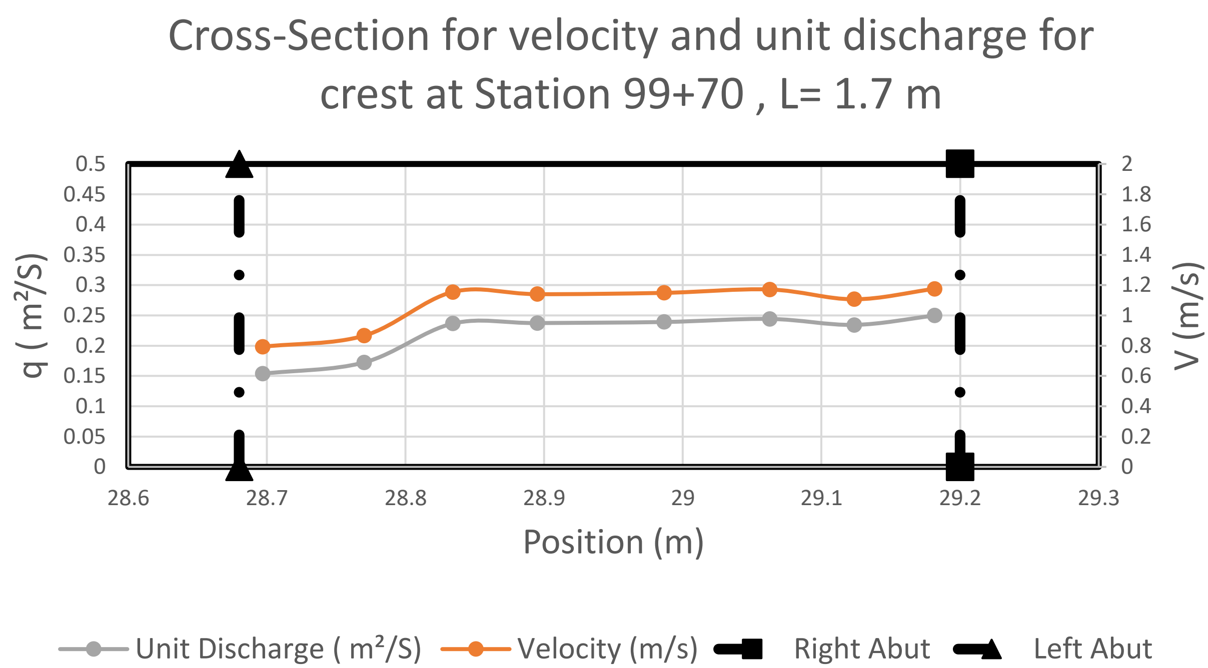
(b)


Cross-Section for velocity and unit discharge for crest at Station 99+55 , L= 1.32 m
q (m²/S)
V (m/s)
Position (m)
Unit Discharge (m²/S)
Velocity (m/s)
Right Abut
Left Abut

(c)


Cross-Section for velocity and unit discharge for crest at Station 99+60, L= 1.45 m
q (m²/S)
V (m/s)
Position (m)
Unit Discharge (m²/S)
Velocity (m/s)
Right Abut
Left Abut

(d)



(e)

Figure 4-10. Distributions of unit discharge (q) and depth-average velocity (*V*) for the elliptical abutment at the face of the ogee weir (model scale). The values of weir-face distance from spillway entrance (Station 9) were: (a) 0.94 m; (b) 1.2 m; (c) 1.32 m; (d) 1.45 m; and (e) 1.70 m. The values in (e) are affected by standing waves formed in the approach flow to the crest. (1.00 m = 3.28 ft.)

4.4 Discussion of Results

The results indicate that the crest of an ogee weir should be placed to ensure acceptable uniformity of flow and acceptable level of turbulence to ensure accurate development of the stage-discharge relationship for the spillway crest so as to control the outflow from a reservoir. In other words, the results generally suggest that the crest should be placed where the uniformity is high and water turbulence is at its lowest intensity. In this regard, the following points summarize the results:

- Placing the crest of the ogee weir furthest from the spillway entrance resulted in good water uniformity but led to high turbulence results, as indicated in Figures 4-6 (e), 4-10 (e), 4-12 (e), and 4-13(e).
- Placing the crest close to the spillway entrance resulted in unacceptable uniformity of water flow, but led to low standard deviation of turbulence, as indicated in Figures 4-6 (a), 4-10 (a), 4-12 (a), and 4-13(a).
- The design position (station 99+60, giving L = 4.43 ft, or 1.45 m, at model scale) gave an acceptable uniformity of water over the crest, this location yielded acceptable (low) standard deviation of water turbulence, as indicated in Figures 4-6 (d), 4-10 (d), 4-12 (d), and 4-13(d). This position best enables accurate operation of the crest for determining the outflow from the reservoir.
- The elliptical abutment provided better turbulence levels than did the circular abutment. However, the flow over the ogee crest was consistently more uniform than when the circular abutments were used rather than the elliptical abutments.
- Observations showed that turbulence in flow adversely affected the stage-discharge relationship of an ogee weir (outflow from the reservoir) because the water surface fluctuated on the crest of the ogee weir.

Also, the results suggest that the crest position of the ogee weir should not lead to a lower (or higher) than designed level of the reservoir, as indicated in Figures 4-11a.b for the circular and the elliptical abutments, respectively. This figure indicates, that for Los Vaqueros spillway, when L = 3.67 ft (or 1.20 m) from the spillway entrance; at model scale, the center water level matches the reservoir level, the design the reservoir level. For lesser values of L, ogee presence (i.e., the ogee weir is closer to the spillway entrance) leads to a mismatch with the design reservoir level, which would affect the rating curve applying to the ogee crest and outflow from the reservoir.

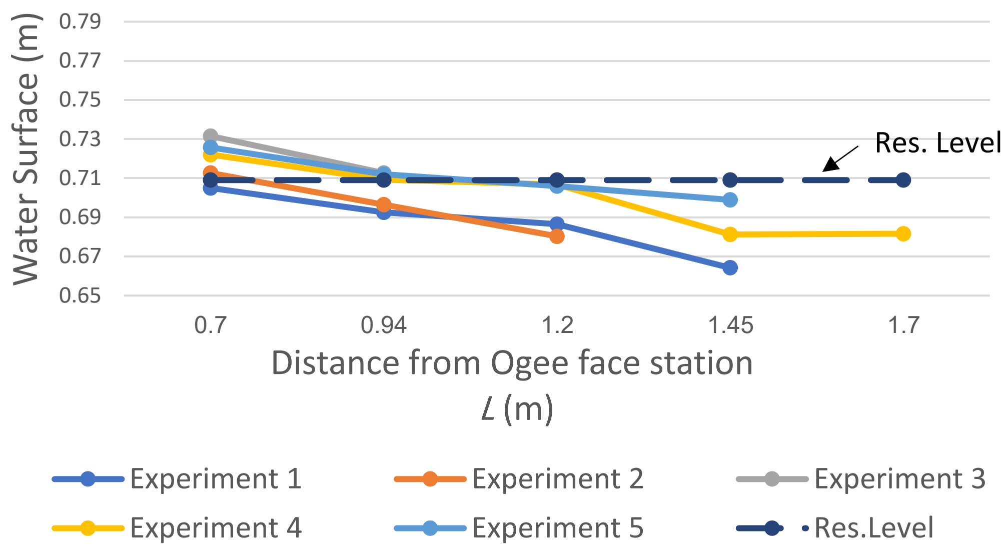
From the weir equation given in Chapter 2,

$$Q = CLH_0^{3/2} \tag{4-1}$$

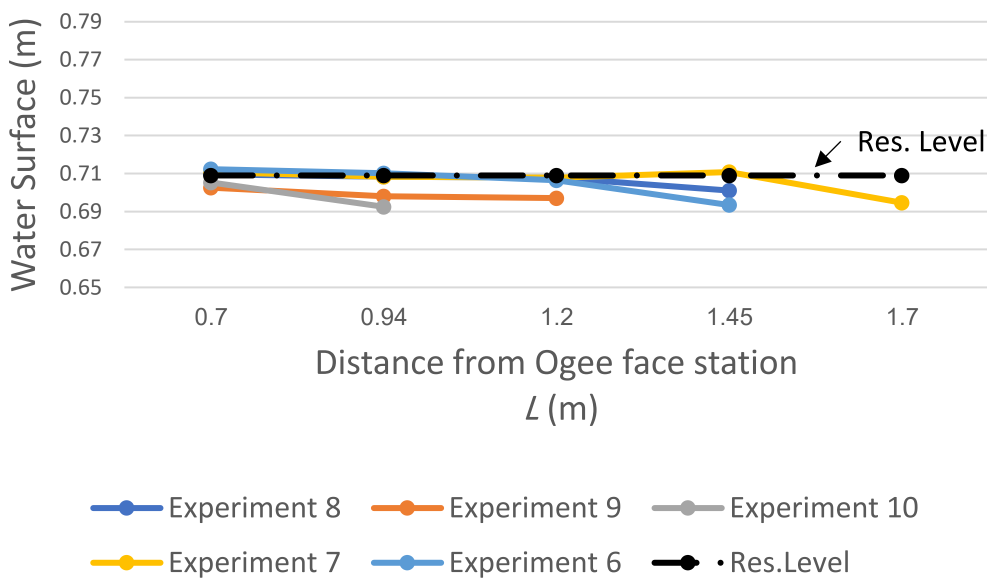
where H_0 is here taken as the reservoir level, it can be shown for the circular abutments that increasing H_0 about 0.07 ft (0.02 m) results in about a 5% decrease of discharge coefficient, *C*, for the weir. This reduction in weir performance is small. The fluctuations of the water surface would be more problematic. For the elliptical abutments, no rise in the reservoir water level was observed.

The mismatch could be resolved by adjusting the width of the spillway. The latter action would increase the cost of the spillway, as widening the spillway would involve a larger spillway. The crest height matches the reservoir level for which no spilling of water occurs.

Figures 4-12 and 4-13 show the standard deviation of turbulence for the circular and elliptical abutments and the ogee crest at the range of locations investigated. The values correspond to the maximum value of the standard deviation for the velocity as obtained from the ADV measurements.

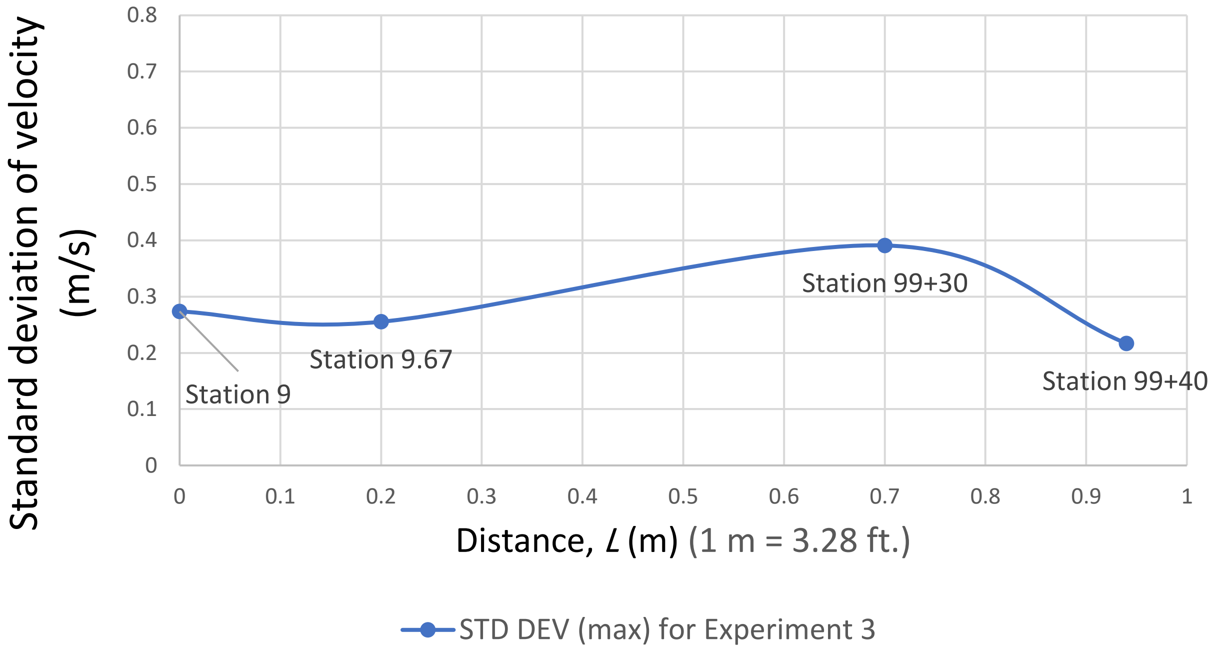


(a)

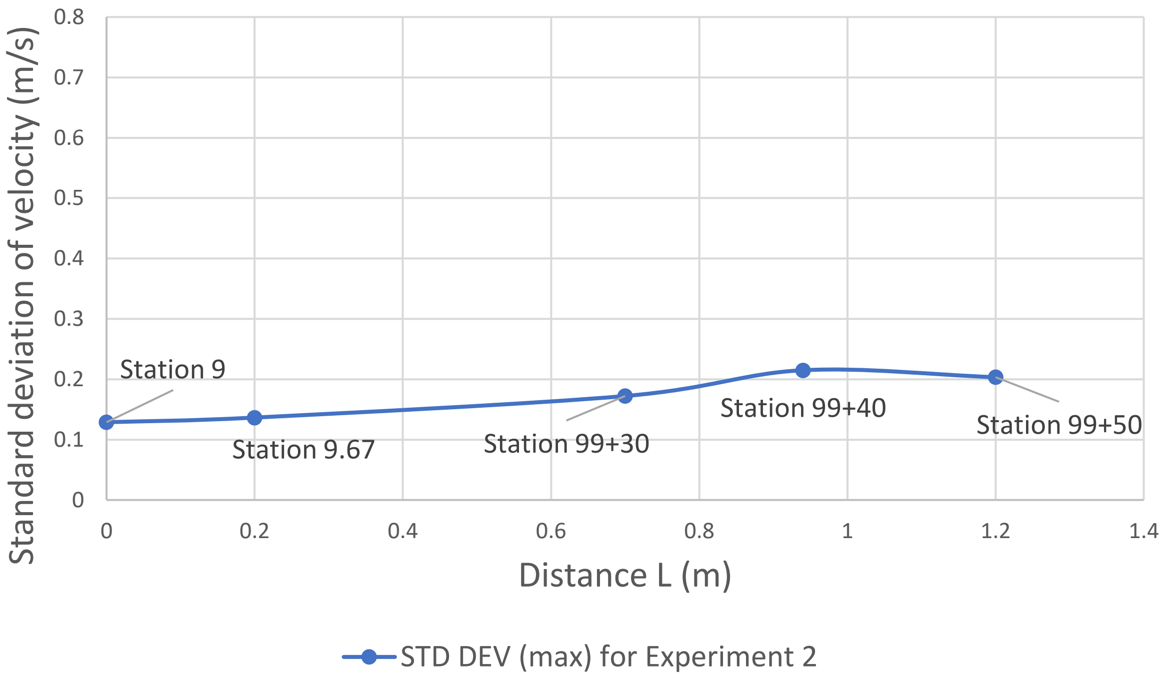


(b)

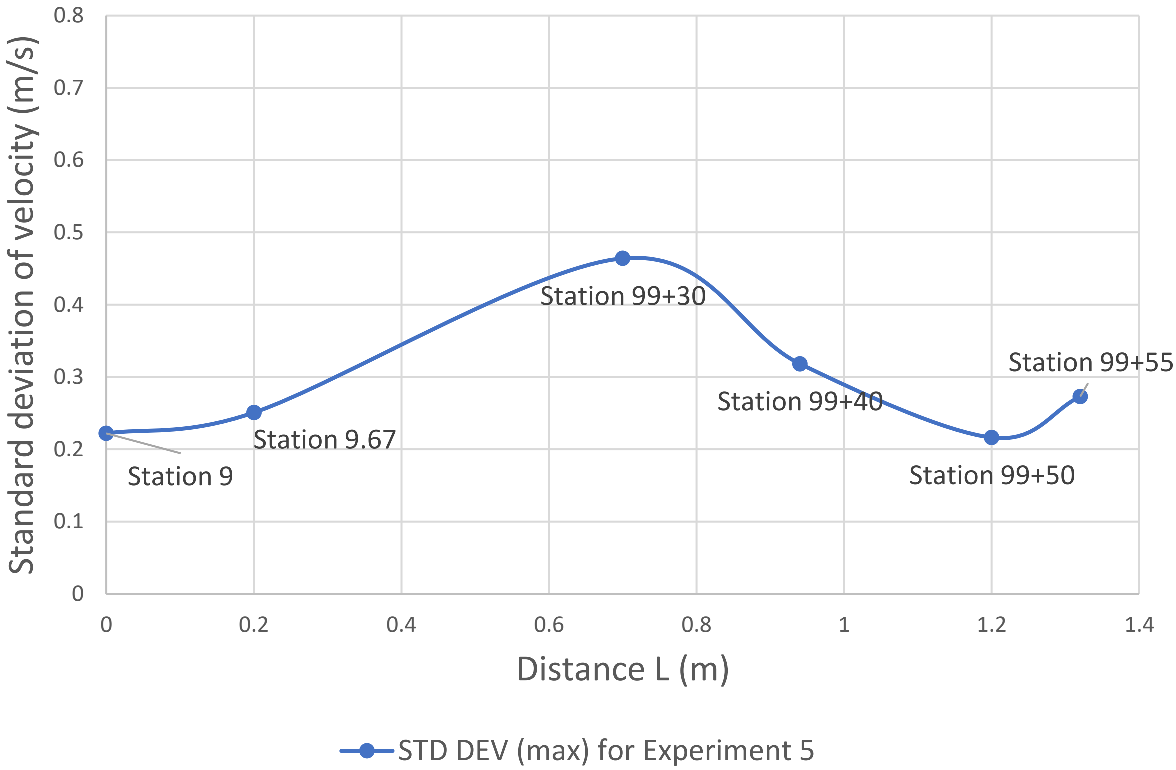
Figure 4-11. Level of water-surface at spillway entrance for the locations of ogee weir: (a) circular abutments; and (b) elliptical abutments. Also indicated here is the design level of the reservoir. (1.00 m = 3.28 ft.)


Standard deviation of velocity (m/s)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Distance, L (m) (1 m = 3.28 ft.)
Station 9
Station 9.67
Station 99+30
Station 99+40
STD DEV (max) for Experiment 3

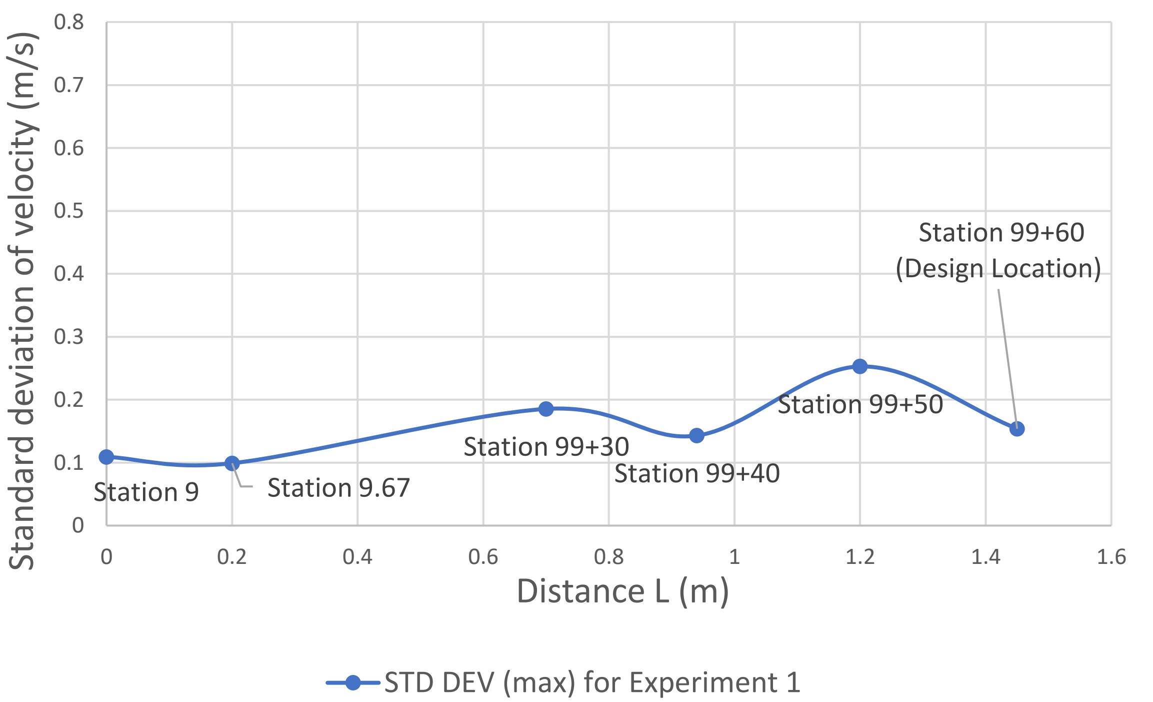
(a)


Standard deviation of velocity (m/s)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Distance L (m)
Station 9
Station 9.67
Station 99+30
Station 99+40
Station 99+50
STD DEV (max) for Experiment 2

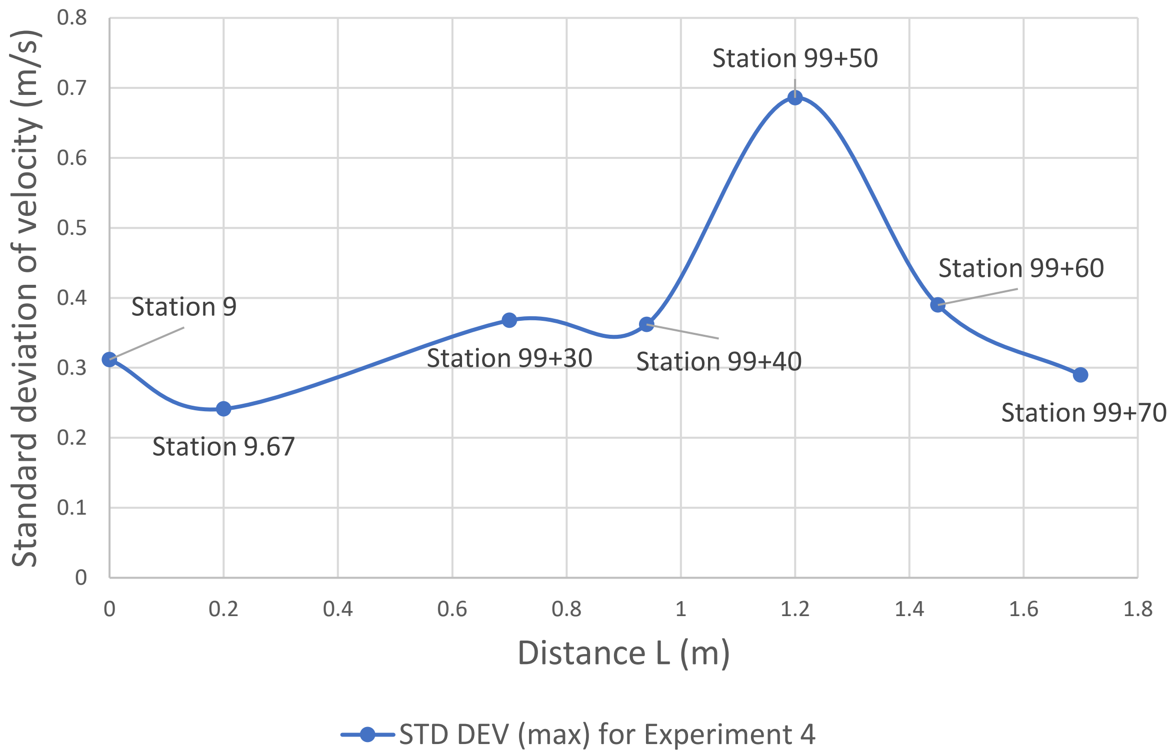
(b)


Standard deviation of velocity (m/s)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Distance L (m)
Station 9
Station 9.67
Station 99+30
Station 99+40
Station 99+50
Station 99+55
STD DEV (max) for Experiment 5

(c)

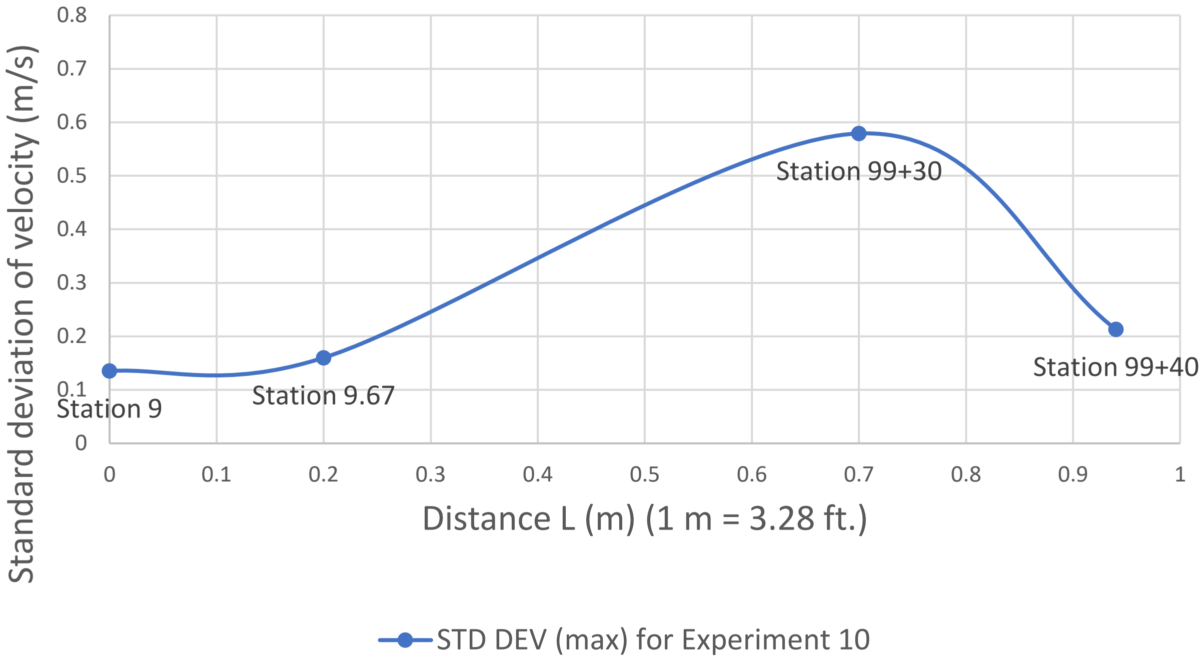

Standard deviation of velocity (m/s)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Distance L (m)
Station 9
Station 9.67
Station 99+30
Station 99+40
Station 99+50
Station 99+60
(Design Location)
STD DEV (max) for Experiment 1

(d)



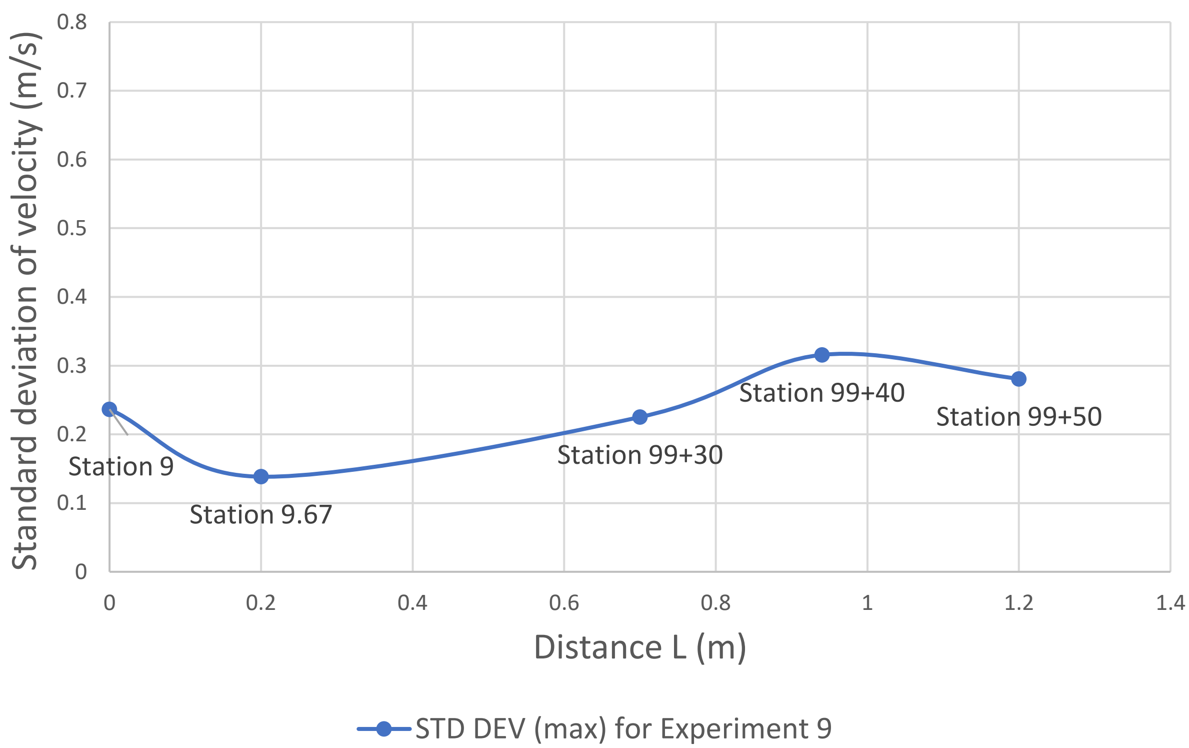
(e)

Figure 4-12. Distributions of maximum standard deviation of velocity (σ_V) and distance to experiment stations (L) for the circular abutment form. The values of weir-face distance from spillway entrance (Station 9) were: (a) 0.94 m; (b) 1.2 m; (c) 1.32 m; (d) 1.45 m; and (e) 1.70 m. (1.00 m = 3.28 ft.)



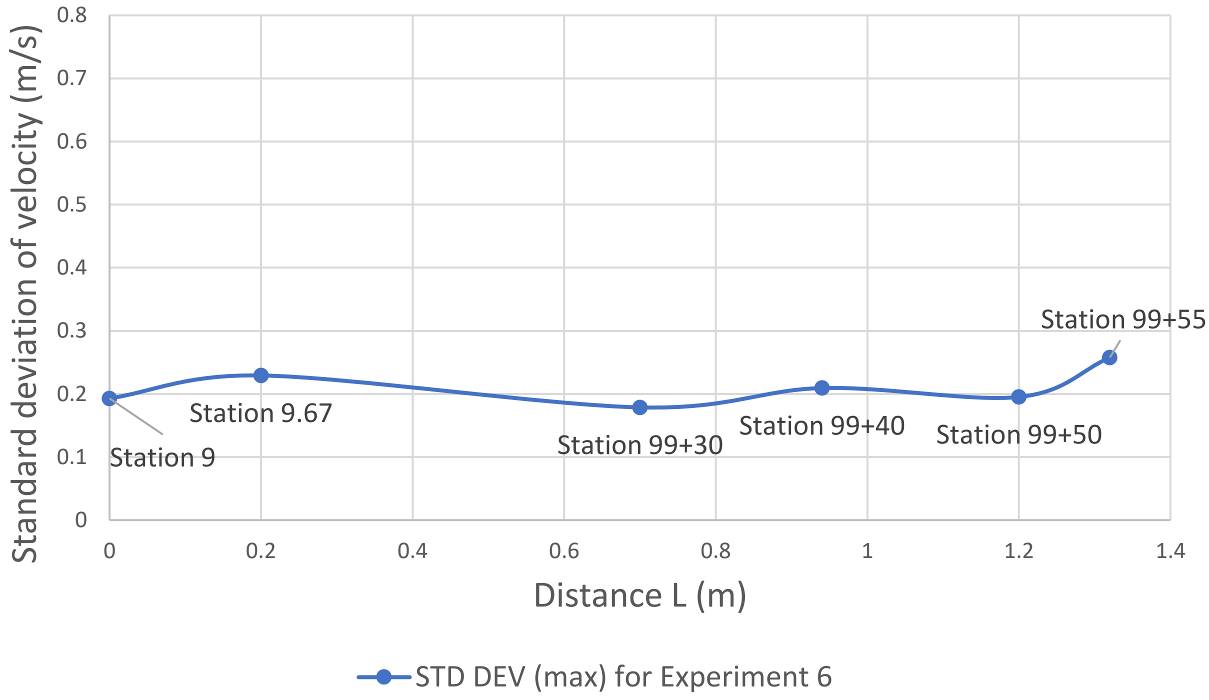
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Standard deviation of velocity (m/s)
Station 9
Station 9.67
Station 99+30
Station 99+40
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Distance L (m) (1 m = 3.28 ft.)
STD DEV (max) for Experiment 10

(a)



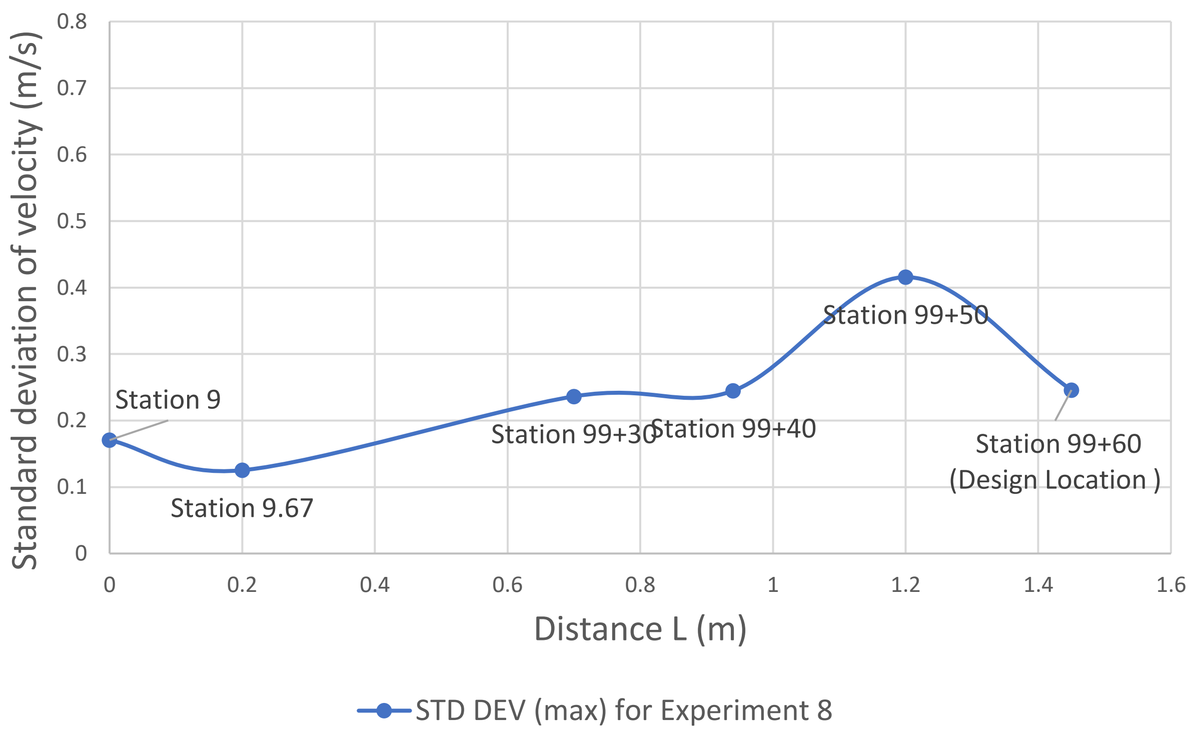
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Standard deviation of velocity (m/s)
Station 9
Station 9.67
Station 99+30
Station 99+40
Station 99+50
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Distance L (m)
STD DEV (max) for Experiment 9

(b)



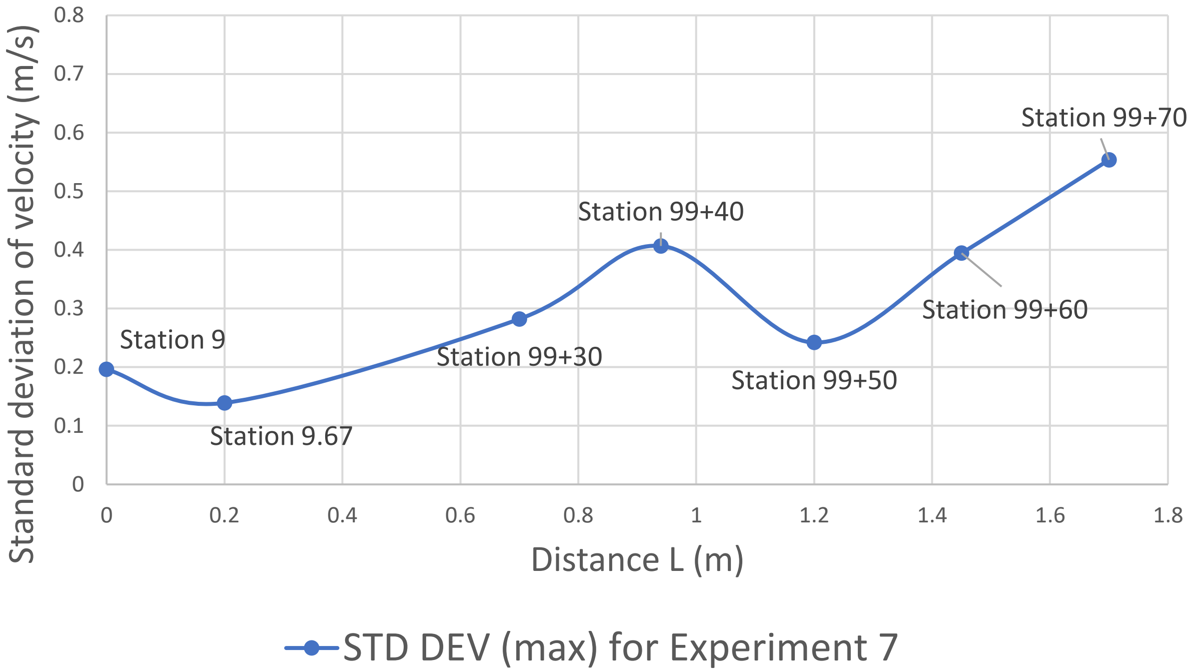
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Standard deviation of velocity (m/s)
Station 99+55
Station 9.67
Station 9
Station 99+30
Station 99+40
Station 99+50
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Distance L (m)
STD DEV (max) for Experiment 6

(c)



0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Standard deviation of velocity (m/s)
Station 99+50
Station 9
Station 99+30
Station 99+40
Station 99+60
(Design Location)
Station 9.67
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
Distance L (m)
STD DEV (max) for Experiment 8

(d)



(e)

Figure 4-13. Distributions of maximum standard deviation of velocity (σ_V) and distance to experiment stations (L) for the elliptical abutment form. The values of weir-face distance from spillway entrance (Station 9) were: (a) 0.94 m; (b) 1.2 m; (c) 1.32 m; (d) 1.45 m; and (e) 1.70 m. (1.00 m = 3.28 ft.)

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This study investigated the effects of spillway-crest location relative to spillway entrance, and the influence of spillway-abutment shape, on uniformity of approach flow, flow acceleration, and turbulence level approach flow, to flow over the ogee-weir crest of a spillway. Circular and elliptical shapes of abutments were used. The base spillway used for the study entailed the use of a hydraulic model (length scale 1:12) of the heightened spillway being developed for Los Vaqueros Dam on Kellogg Creek near Brentwood, California. The flow approach to this heightened spillway was typical of many, relatively shallow over-flow spillways that involve an ogee crest.

For relatively shallow approach flows to the ogee crests of spillway, the distance of the crest to the spillway entrance is an important variable, because of considerations of approach-flow uniformity and turbulence in the approach flow. These considerations are especially affected by the shape of a spillway's entrance abutments. Relatively shallow approach flows are those flows for which flow depth, Y, is less than about four times the height of the ogee crest, Y_C, (i.e., $Y/Y_C < 4$; USBR, 1987). Spillways with shallow approaches are becoming increasingly common when earthfill dams are heightened so that their spillways are placed on the shallowing shoulders of these dams.

5.2 Conclusions

From the approach taken to address the objectives outlined in Chapter 1 of this thesis, the study arrived at the following conclusions:

1. The present study revealed the importance of ogee-weir location relative to the entrance of a spillway. The weir location affected the uniformity of flow and turbulence level of flow immediately approaching the weir.
2. A new finding from this study was the importance of turbulence level in the approach flow to a spillway's ogee weir. Flow turbulence primarily affected the temporal variability of the water surface at the ogee crest, and therefore influenced the accuracy of the stage-discharge relationship for estimating the rate of flow going down a spillway.
3. Flow immediately within the spillway (at Section 9+30) was non-uniformly distributed (the ratio of peak value to minimum value of unit discharge was about 10% of the mean value of the unit discharge) and developed turbulence as it passed around the spillway's abutments. Flow entering a relatively spillway was affected by the spillway's abutments, which may create a zone of substantial turbulence downstream of the entrance. The zone of turbulence, located downstream of an abutment, can be created by several causes: the manner whereby flow enters the spillway; and flow separation from spillway's abutments.
4. Non-unform distribution of flow entering a spillway caused flow to be non-uniform as it approached the crest of an ogee weir as the location of the crest became close to the spillway entrance. Such non-uniformity also adversely affected the accuracy of the stage discharge relationship developed for the ogee crest. The maximum value of flow-depth non-uniformity was about 10% at Section 9 +30.

5. The position of the crest of an ogee weir should maximize, to an acceptable level of uniformity, the uniformity of the unit discharge of the flow passing over the ogee crest. Additionally, the crest location should minimize, to an acceptable level, the turbulence in flow passing over the ogee crest.
6. The location of the ogee crest should not increase the design value of the water level in the reservoir. This consideration can be overcome by adjusting the width of the spillway and its ogee weir, but may result in a more expensive spillway.
7. The circular spillway-abutments produced a more uniform distribution of flow at the ogee crest than did the elliptical abutments, because the circular abutments produced the greatest reservoir water-level rise and velocity decreases (about 5% at Section 9 + 30) when the weir location was shortened.
8. The elliptical abutments reduced the area extent of turbulence zone formed by the right abutment than did the circular abutments. The reduction in surface area of the turbulence zone was about 50%.
9. Generally, the results of this study suggest that ogee crests be located about $b/L \approx 1.5$ downstream from the entrance of a spillway. However, this value of $b/L \approx 1.5$ should be verified for other approach-flow bathymetries.

5.3 Recommendations for Further Research

This study led to the following recommendations regarding several topics in need of further research:

1. The results of this study should be generalized for other earthfill dams, besides the heightened dam for Los Vaqueros Reservoir.

2. The bathymetry of the approach flow from the reservoir to the spillway entrance should be varied so that flow approaches the spillway abutments from several directions and there are a variety of approach flow fields. This task may be more readily undertaken using a three-dimensional flow numerical model.
3. Further measurements should be taken on top of the ogee weir. Such measurements may entail the use of a velocity probe alternative to the ADV, which requires a significant depth of flow to be used, as was found for the present study.
4. More research should be done to quantify flow distribution and flow turbulence. That research entails more extensive flow measurements than the present study could avail.

REFERENCES

Bai, Y., et al. (2022). Flow non-uniformity mitigation in a trapezoidal spillway intake using a semi-elliptical control pier. Journal of Hydroinformatics, 24(3), 759-773.

Bollaert, E., et al. (2014). Flow distribution at intake structures. Journal of Hydraulic Research, 52(4), 475-485.Bung, D. B. (2015). Hydraulic design of spillways. ICE Publishing.

California Department of Water Resources. (2004). Los Vaqueros Project: Draft environmental impact statement/environmental impact report. Author.

Chanson, H. (2004). Hydraulics of spillways and energy dissipators. CRC Press.

Chow, V. T., Maidment, D. R., & Mays, L. W. (1988). Applied hydrology. McGraw-Hill.

de Vos, C., et al. (2021). Influence of intake geometry on flow non-uniformity at embankment dams. Water, 13(4), 525.

El Naggar, H. M., et al. (2019). Flow distribution at intake structures: Influence of submergence and discharge. Journal of Hydraulic Engineering, 145(6), 04019015.

Froehlich, D. C., & Yarnell, J. L. (2011). Engineering flow and heat exchange. Springer Science & Business Media.

Garde, R. J., et al. (2016). Experimental and numerical study of flow distribution at intake structures. Journal of Irrigation and Drainage Engineering, 142(8), 04016007.

Haun, S., et al. (2015). Flow distribution at intake structures: Influence of upstream flow conditions. Journal of Irrigation and Drainage Engineering, 141(9), 04015004.

Hong, J., et al. (2018). Influence of flow non-uniformity on cavitation damage in spillway intakes. Journal of Hydraulic Engineering, 144(6), 04018014.

Hu, Z., et al. (2020). Experimental investigation of flow distribution at intake structures with side bays. Journal of Hydroinformatics, 22(5), 1289-1302.

Jeyapandiyan, J., et al. (2023). Measurement of flow distribution in a trapezoidal intake using particle image velocimetry. Water Resources Management, 37(1), 35-51.

Kang, S., et al. (2016). Investigation of sediment transport in intake channel: Effect of flow non-uniformity. Journal of Hydraulic Engineering, 142(4), 04015069.

Li, Y., et al. (2022). Study on the flow non-uniformity at rectangular side inlets. Journal of Hydrodynamics, 34(1), 128-137.

Los Vaqueros Reservoir and Watershed Authority. (2019). Los Vaqueros Reservoir expansion project: Final environmental impact report/environmental impact statement. Author.

Ma, H., et al. (2019). Optimizing flow distribution in intakes using flow control devices. Journal of Hydraulic Engineering, 145(2), 04018089.

Miao, C., et al. (2022). Cavitation characteristics in a trapezoidal spillway intake with different submergence ratios. Journal of Hydraulic Engineering, 148(2), 04021058.

Mofidi, A., et al. (2017). Flow distribution at multi-bay intakes: Experimental investigation. Journal of Hydraulic Research, 55(6), 816-827.

Novak, P., Moffat, A. I. B., Nalluri, C., & Narayanan, R. (2010). Hydraulic structures. CRC Press.

Pellicer, E., & Gómez, M. (2004). Flow measurements in open channels. Taylor & Francis.

Tarek, M. A., & Amin, M. M. (2020). Sediment deposition at an irrigation intake structure: Experimental investigation. Journal of Irrigation and Drainage Engineering, 146(1), 04019043.

Thota, S., et al. (2022). Experimental investigation of flow non-uniformity in gated spillway intakes. Journal of Hydroinformatics, 24(1), 42-54.

Thornton, C.I., Ettema, R., Ellis, J., Volt, C. and Hogan, T. (2022). Los Vaqueros Reservoir Expansion: hydraulic model study of spillway and sluice. CSU Hydraulics Laboratory Report Submitted to AECOM, Denver, and AECOM San Francisco.

Tullis, J. P. (2001). Hydraulic engineering: Design principles and practices. Wiley.

U.S. Army Corps of Engineers. (1990). Hydraulic Design of Spillways. Engineer Manual No. 1110-2-1603, Department of the Army. Errata #1, 31 August 1992.

U.S. Bureau of Reclamation. (2019). Spillway design and spillway gates. Water Measurement Manual, USBR.

Verwey, A., et al. (2017). Physical modelling of flow distribution at intake structures. Proceedings of the Institution of Civil Engineers-Water Management, 170(4), 179-190.

Wang, Y., et al. (2023). Numerical simulation of flow distribution in a side intake with flow control devices. Journal of Hydraulic Research, 61(1), 137-151.

Water Environment Federation. (2013). Design of municipal wastewater treatment plants: WEF manual of practice No. 8. McGraw-Hill Education.

Zarrati, A. R., et al. (2018). Investigation of approach flow effects on the distribution of flow entering circular channels. Journal of Irrigation and Drainage Engineering, 144(11), 04018060.

Zhang, H., et al. (2022). Flow distribution at a side intake with non-uniform approach flow. Journal of Hydrodynamics, 34(2), 380-389.

Zhang, H., et al. (2021). Experimental study of flow distribution at an intake with screens. Journal of Hydraulic Engineering, 147(10), 04021058.

Zhao, Y., et al. (2019). Experimental study on flow distribution in a trapezoidal intake with flow control devices. Journal of Hydroinformatics, 21(6), 1097-1110.

Zhao, Y., et al. (2021). Flow-induced vibration in intake conduits: Effect of flow non-uniformity. Journal of Fluids and Structures, 106, 103232.

APPENDIX

Table. A-1. Distributions of velocity and unit discharge entering the headtank and spillway. The flow was non-uniform. Here, *L* is the distance from the spillway entrance (Station 9) to Experiment 1 stations. The last station in the table is the ogee crest's current (or design) position.

Station 9 *L* = 0 m	Stations across the headtank (m)	27.081	26.853	26.548	26.304	26.030	25.756	25.490	25.295
	Velocity (m/s)	0.486	0.445	0.369	0.271	0.217	0.144	0.115	0.103
	Depth (m)	0.305	0.323	0.332	0.326	0.328	0.332	0.331	0.327
	Unit Discharge (m²/S)	0.148	0.144	0.122	0.088	0.071	0.048	0.038	0.034
	Standard deviation	0.109	0.061	0.056	0.058	0.046	0.058	0.081	0.060

Station 9.67 *L* = 0.20 m	Stations across the headtank (m)	26.853	26.548	26.304	26.030	25.756	25.490
	Velocity (m/s)	0.589	0.481	0.324	0.173	0.138	0.101
	Depth (m)	0.309	0.314	0.317	0.322	0.328	0.326
	Unit Discharge (m²/S)	0.182	0.151	0.103	0.056	0.045	0.033
	Standard deviation	0.083	0.099	0.061	0.066	0.064	0.077

Station 99+30 *L*= 0.70 m	Stations across the spillway (m)	29.182	29.063	28.895	28.770
	Velocity (m/s)	0.829	0.794	0.770	0.760
	Depth (m)	0.290	0.293	0.291	0.291
	Unit Discharge (m²/S)	0.240	0.233	0.224	0.221
	Standard deviation	0.185	0.144	0.120	0.109

Station 99+40 *L*= 0.94 m	Stations across the spillway (m)	29.182	29.063	28.895	28.770
	Velocity (m/s)	1.107	1.007	0.925	0.894
	Depth (m)	0.250	0.270	0.280	0.277
	Unit Discharge (m²/S)	0.276	0.272	0.259	0.248
	Standard deviation	0.137	0.124	0.130	0.143

Station 99+50 *L*= 1.2 m	Stations across the spillway (m)	29.182	29.063	28.895	28.770
	Velocity (m/s)	0.987	0.942	0.906	0.907
	Depth (m)	0.283	0.288	0.276	0.282
	Unit Discharge (m²/S)	0.279	0.271	0.250	0.256
	Standard deviation	0.188	0.253	0.147	0.140

Station 99+60 *L*= 1.45 m	Stations across the spillway (m)	29.182	29.063	28.895	28.770
	Velocity (m/s)	1.359	1.367	1.351	1.353
	Depth (m)	0.177	0.176	0.179	0.181
	Unit Discharge (m²/S)	0.240	0.241	0.242	0.245
	Standard deviation	0.145	0.116	0.114	0.154

Table. A-2 Distributions of velocity and unit discharge entering the headtank and spillway. The flow was non-uniform. Here, *L* is the distance from the spillway entrance (Station 9) to Experiment 2 stations. The last station in the table is the ogee crest's current (or design) position.

Station 9 *L*= 0 m	Stations across the headtank (m)	27.081	26.853	26.548	26.304	26.030	25.756	25.490	25.295
	Velocity (m/s)	0.481	0.443	0.367	0.262	0.112	0.126	0.043	0.118
	Depth (m)	0.329	0.311	0.338	0.330	0.334	0.339	0.338	0.333
	Unit Discharge (m²/S)	0.158	0.138	0.124	0.086	0.037	0.043	0.015	0.039
	Standard deviation	0.081199	0.0672858	0.0604405	0.0580247	0.1288387	0.1266697	0.0719501	0.061848

Station 9.67 *L*= 0.20 m	Stations across the headtank (m)	26.853	26.548	26.304	26.030	25.756	25.490
	Velocity (m/s)	0.639	0.475	0.388	0.111	0.106	0.082
	Depth (m)	0.317	0.320	0.325	0.331	0.335	0.334
	Unit Discharge (m²/S)	0.203	0.152	0.126	0.037	0.036	0.027
	Standard deviation	0.1365113	0.0778543	0.071555	0.1064294	0.0833396	0.1112593

Station 99+30 *L*= 0.70 m	Stations across the spillway (m)	29.182	29.124	29.063	28.986	28.895	28.834	28.770	28.697
	Velocity (m/s)	0.811	0.805	0.811	0.765	0.745	0.739	0.744	0.732
	Depth (m)	0.295	0.296	0.298	0.298	0.297	0.297	0.299	0.310
	Unit Discharge (m²/S)	0.239	0.238	0.241	0.228	0.221	0.219	0.222	0.227
	Standard deviation	0.1222638	0.1287168	0.1548945	0.1559274	0.1192118	0.1309975	0.1336226	0.1722495

Station 99+40 *L*= 0.94 m	Stations across the spillway (m)	29.182	29.124	29.063	28.986	28.895	28.834	28.770	28.697
	Velocity (m/s)	1.090	1.023	0.994	0.936	0.880	0.866	0.865	0.863
	Depth (m)	0.264	0.275	0.280	0.283	0.289	0.288	0.287	0.288
	Unit Discharge (m²/S)	0.288	0.281	0.279	0.265	0.254	0.250	0.248	0.249
	Standard deviation	0.2149456	0.1243818	0.1503257	0.1600665	0.1327915	0.1164239	0.1131897	0.1135829

Station 99+50 *L*= 1.2 m	Stations across the spillway (m)	29.182	29.124	29.063	28.986	28.895	28.834	28.770	28.697
	Velocity (m/s)	1.379	1.373	1.415	1.429	1.374	1.385	1.367	1.309
	Depth (m)	0.185	0.193	0.197	0.204	0.203	0.208	0.211	0.212
	Unit Discharge (m²/S)	0.256	0.265	0.279	0.292	0.279	0.288	0.288	0.278
	Standard deviation	0.2017903	0.1867354	0.1832497	0.1854742	0.1849424	0.1931841	0.178682	0.2033989

Table. A-3 Distributions of velocity and unit discharge entering the headtank and spillway. The flow was non-uniform. Here, *L* is the distance from the spillway entrance (Station 9) to Experiment 3 stations. The last station in the table is the ogee crest's current (or design) position.

Station 9 *L*= 0 m	Stations across the headtank (m)	27.08148	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042	25.29535
	Velocity (m/s)	0.447843	0.378108	0.377414	0.102476	0.235499	0.169467	0.107023	0.108946
	Depth (m)	0.320345	0.338938	0.345034	0.339242	0.340766	0.346862	0.346862	0.341681
	Unit Discharge (m²/S)	0.143464	0.128155	0.130221	0.034764	0.08025	0.058782	0.037122	0.037225
	Standard deviation	0.078827	0.2738	0.08678	0.181935	0.042637	0.054564	0.086678	0.057139

Station 9.67 *L*= 0.20 m	Stations across the headtank (m)	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042
	Velocity (m/s)	0.624652	0.416457	0.26461	0.074983	0.094303	0.010343
	Depth (m)	0.324307	0.331622	0.332232	0.337718	0.341986	0.339242
	Unit Discharge (m²/S)	0.202579	0.138106	0.087912	0.025323	0.03225	0.003509
	Standard deviation	0.179085	0.169794	0.255389	0.180014	0.105338	0.021381

Station 99+30 *L*= 0.70 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.773771	0.769388	0.78307	0.751011	0.611738	0.739829	0.710704	0.753308
	Depth (m)	0.305105	0.305684	0.30541	0.305105	0.3048	0.304495	0.305105	0.317297
	Unit Discharge (m²/S)	0.236081	0.23519	0.239157	0.229137	0.186458	0.225275	0.216839	0.239022
	Standard deviation	0.122783	0.14401	0.178746	0.172631	0.391008	0.150922	0.246548	0.152698

Station 99+40 *L*= 0.94 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	1.438962	1.37833	1.348261	1.35819	1.335418	1.31301	1.311503	1.310826
	Depth (m)	0.210617	0.214884	0.218542	0.221285	0.224028	0.225552	0.222199	0.220066
	Unit Discharge (m²/S)	0.30307	0.296181	0.294651	0.300547	0.299171	0.296152	0.291415	0.288468
	Standard deviation	0.216832	0.199904	0.194413	0.172241	0.186135	0.170186	0.178089	0.196839

Table. A-4 Distributions of velocity and unit discharge entering the headtank and spillway. The flow was non-uniform. Here, *L* is the distance from the spillway entrance (Station 9) to Experiment 4 stations. The last station in the table is the ogee crest's current (or design) position.

Station 9 *L*= 0 m	Stations across the headtank (m)	27.08148	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042	25.29535
	Velocity (m/s)	0.454955	0.336755	0.384047	0.097288	0.237506	0.17653	0.138547	0.100918
	Depth (m)	0.323088	0.338328	0.345034	0.340766	0.344119	0.349606	0.349301	0.344424
	Unit Discharge (m²/S)	0.14699	0.113934	0.132509	0.033152	0.08173	0.061716	0.048395	0.034759
	Standard deviation	0.081732	0.311784	0.091215	0.073434	0.047685	0.055969	0.061591	0.069705

Station 9.67, *L*= 0.20 m	Stations across the headtank (m)	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042
	Velocity (m/s)	0.636027	0.449381	0.197533	0.011631	0.177619	0.134548
	Depth (m)	0.32766	0.329794	0.332842	0.341376	0.345338	0.34351
	Unit Discharge (m²/S)	0.208401	0.148203	0.065747	0.00397	0.061339	0.046219
	Standard deviation	0.185431	0.083689	0.241356	0.072863	0.064418	0.068552

Station 99+30 *L*= 0.70 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.794414	0.797746	0.710041	0.599875	0.705584	0.729534	0.728118	0.707388
	Depth (m)	0.306934	0.305714	0.308458	0.307848	0.308762	0.278587	0.309677	0.32065
	Unit Discharge (m²/S)	0.243832	0.243883	0.219018	0.18467	0.217858	0.203239	0.225481	0.226824
	Standard deviation	0.141726	0.176252	0.26169	0.367729	0.169068	0.117699	0.12525	0.186974

Station 99+40 *L*= 0.94 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	1.023096	0.984007	0.949087	0.89845	0.830632	0.75771	0.703837	0.776856
	Depth (m)	0.277673	0.286512	0.291998	0.296266	0.300533	0.299314	0.298094	0.301447
	Unit Discharge (m²/S)	0.284086	0.28193	0.277132	0.26618	0.249632	0.226793	0.20981	0.234181
	Standard deviation	0.165472	0.149625	0.176562	0.256601	0.205474	0.305714	0.361937	0.246679

Station 99+50 *L*= 1.2 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.907387	0.897158	0.889931	0.799104	0.788545	0.77136	0.822318	0.85165
	Depth (m)	0.302971	0.305105	0.295656	0.295351	0.299923	0.302362	0.29779	0.299314
	Unit Discharge (m²/S)	0.274912	0.273727	0.263113	0.236016	0.236503	0.23323	0.244878	0.25491
	Standard deviation	0.224641	0.163738	0.214632	0.685764	0.535589	0.36949	0.238339	0.149938

Station 99+60 *L*= 1.45 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.894388	0.930107	0.919814	0.948303	0.947377	0.938106	0.967447	0.960795
	Depth (m)	0.283769	0.280416	0.284074	0.262128	0.284683	0.279502	0.287122	0.28895
	Unit Discharge (m²/S)	0.2538	0.260817	0.261295	0.248577	0.269702	0.262202	0.277775	0.277622
	Standard deviation	0.305185	0.211805	0.389732	0.188017	0.163722	0.164375	0.135961	0.125102

Station 99+70 *L*= 1.7 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	1.483235	1.505079	1.394396	1.445504	1.567581	1.559904	1.543527	1.503411
	Depth (m)	0.194767	0.194158	0.191414	0.193548	0.197815	0.199339	0.198425	0.199339
	Unit Discharge (m²/S)	0.288886	0.292223	0.266908	0.279774	0.310091	0.31095	0.306274	0.299689
	Standard deviation	0.289837	0.278508	0.222611	0.186687	0.254731	0.256892	0.24814	0.230584

Table. A-5 Distributions of velocity and unit discharge entering the headtank and spillway. The flow was non-uniform. Here, *L* is the distance from the spillway entrance (Station 9) to Experiment 5 stations. The last station in the table is the ogee crest's current (or design) position.

Station 9 *L* = 0 m	Stations across the headtank (m)	27.08148	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042	25.29535
	Velocity (m/s)	0.455974	0.434247	0.363824	0.236962	0.225024	0.17407	0.140609	0.11227
	Depth (m)	0.325526	0.341376	0.35113	0.344119	0.346558	0.363931	0.34991	0.345338
	Unit Discharge (m²/S)	0.148431	0.148242	0.127749	0.081543	0.077984	0.063349	0.0492	0.038771
	Standard deviation	0.074417	0.221964	0.08444	0.098689	0.063032	0.058071	0.069788	0.061634

Station 9.67 *L* = 0.20 m	Stations across the headtank (m)	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042
	Velocity (m/s)	0.625287	0.324095	0.206646	0.189726	0.170714	0.076019
	Depth (m)	0.328574	0.332537	0.336499	0.343205	0.347167	0.345948
	Unit Discharge (m²/S)	0.205453	0.107774	0.069536	0.065115	0.059266	0.026299
	Standard deviation	0.166903	0.237878	0.250766	0.080781	0.059799	0.111036

Station 99+30 *L* = 0.70 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.795539	0.81159	0.715851	0.663369	0.659456	0.671069	0.681479	0.678481
	Depth (m)	0.309982	0.307238	0.311201	0.311506	0.31181	0.31181	0.31303	0.322387
	Unit Discharge (m^2/S)	0.24442	0.252568	0.222992	0.206845	0.205625	0.209246	0.213323	0.218734
	Standard deviation	0.158473	0.184442	0.283328	0.464164	0.254307	0.209156	0.197706	0.179649

Station 99+40, *L* = 0.94 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	1.009832	0.97164	0.948163	0.855913	0.827594	0.829784	0.824659	0.796172
	Depth (m)	0.28194	0.28956	0.295351	0.299009	0.303581	0.301142	0.301142	0.305105
	Unit Discharge (m^2/S)	0.284712	0.281348	0.280041	0.255926	0.251242	0.249883	0.24834	0.242916
	Standard deviation	0.153496	0.156153	0.20768	0.318353	0.179155	0.134688	0.130885	0.176125

Station 99+50, *L* = 1.2 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.999845	0.983033	0.976268	0.975347	0.935977	0.922683	0.933932	0.91732
	Depth (m)	0.301142	0.289865	0.292608	0.294437	0.29779	0.300838	0.299314	0.298399
	Unit Discharge (m^2/S)	0.301096	0.284947	0.285664	0.287178	0.278724	0.277578	0.279539	0.273728
	Standard deviation	0.21624	0.172095	0.192138	0.188262	0.182132	0.191994	0.165379	0.169724

Station 99+55 *L* = 1.32 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	1.360294	1.353251	1.402785	1.447203	1.427823	1.401535	1.388547	1.314308
	Depth (m)	0.210312	0.214579	0.207874	0.213055	0.217627	0.21397	0.211226	0.209398
	Unit Discharge (m^2/S)	0.286086	0.29038	0.291602	0.308334	0.310733	0.299886	0.293298	0.275213
	Standard deviation	0.272914	0.247906	0.248983	0.245786	0.217064	0.210135	0.177594	0.220465

Table. A-6 Distribution of velocity and unit discharge entering the headtank and spillway. The flow was non-uniform. Here, *L* is the distance from the spillway entrance (Station 9) to Experiment 6 stations. The last station in the table is the ogee crest's current (or design) position.

Station 9 *L* = 0 m	Stations across the headtank (m)	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042	25.29535
	Velocity (m/s)	0.655677	0.433256	0.344737	0.211255	0.176621	0.162802	0.122891
	Depth (m)	0.331318	0.344729	0.340766	0.34351	0.35052	0.351739	0.345034
	Unit Discharge (m²/S)	0.217237	0.149356	0.117475	0.072568	0.061909	0.057264	0.042402
	Standard deviation	0.19286	0.174011	0.059274	0.139389	0.045023	0.055004	0.067579

Station 9.67 *L* = 0.20 m	Stations across the headtank (m)	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042
	Velocity (m/s)	0.854348	0.592965	0.117676	0.062971	0.186677	0.120195
	Depth (m)	0.306019	0.325222	0.332537	0.340766	0.346558	0.346558
	Unit Discharge (m²/S)	0.261447	0.192845	0.039132	0.021458	0.064694	0.041655
	Standard deviation	0.129274	0.114206	0.229281	0.166113	0.060561	0.087513

Station 99+30 *L* = 0.70 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	1.014928	0.944452	0.932317	0.887294	0.835347	0.830717	0.831436	0.848519
	Depth (m)	0.28956	0.291694	0.29657	0.298094	0.299618	0.29779	0.294132	0.286512
	Unit Discharge (m²/S)	0.296048	0.280097	0.277918	0.26585	0.250285	0.247379	0.244552	0.243111
	Standard deviation	0.141019	0.125361	0.161724	0.178635	0.160231	0.125218	0.135815	0.119181

Station 99+40, *L* = 0.94 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.909739	0.901185	0.912989	0.911036	0.856966	0.849427	0.823725	0.864733
	Depth (m)	0.293827	0.291084	0.292913	0.29718	0.308153	0.306019	0.302362	0.299314
	Unit Discharge (m²/S)	0.267306	0.26232	0.267426	0.270742	0.264077	0.259941	0.249063	0.258826
	Standard deviation	0.139363	0.152871	0.169672	0.186796	0.194363	0.176977	0.209333	0.122859

Station 99+50, *L* = 1.2 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.928935	0.925901	0.917617	0.946234	0.923546	0.915277	0.921467	0.933575
	Depth (m)	0.294742	0.299314	0.302057	0.295046	0.293827	0.292608	0.293827	0.297485
	Unit Discharge (m²/S)	0.273796	0.277135	0.277173	0.279183	0.271363	0.267817	0.270752	0.277724
	Standard deviation	0.15626	0.172175	0.195172	0.191792	0.163453	0.157716	0.143147	0.1412

Station 99+55, *L* = 1.32 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	1.347208	1.361964	1.365424	1.506156	1.402928	1.509671	1.486822	1.37167
	Depth (m)	0.197815	0.19873	0.200558	0.207569	0.213055	0.214579	0.215798	0.21275
	Unit Discharge (m²/S)	0.266498	0.270662	0.273847	0.312631	0.298901	0.323944	0.320854	0.291823
	Standard deviation	0.217716	0.204345	0.20035	0.240081	0.180699	0.257654	0.239883	0.205229

Table. A-7 Distributions of velocity and unit discharge entering the headtank and spillway. The flow was non-uniform. Here, *L* is the distance from the spillway entrance (Station 9) to Experiment 7 stations. The last station in the table is the ogee crest's current (or design) position.

Station 9, *L* = 0 m	Stations across the headtank (m)	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042	25.29535
	Velocity (m/s)	0.630949	0.429264	0.364985	0.159858	0.166931435	0.164784	0.117488
	Depth (m)	0.329489	0.344424	0.338633	0.341681	0.3477768	0.350215	0.34351
	Unit Discharge (m²/S)	0.207891	0.147849	0.123596	0.05462	0.05805488	0.05771	0.040358
	Standard deviation	0.102206	0.118559	0.063646	0.196063	0.043098703	0.048617	0.057075

Station 9.6 *L* = 0.20 m	Stations across the headtank (m)	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042
	Velocity (m/s)	0.811466	0.576602	0.355193	0.154777	0.123575442	0.116699
	Depth (m)	0.306934	0.324917	0.33528	0.338328	0.345948	0.344424
	Unit Discharge (m²/S)	0.249066	0.187348	0.119089	0.052365	0.042750677	0.040194
	Standard deviation	0.138978	0.11339	0.109036	0.094569	0.075677454	0.071417

Station 99+30 *L* = 0.70 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.999699	0.971074	0.925039	0.864065	0.851254872	0.832111	0.821234	0.860019
	Depth (m)	0.285902	0.289865	0.292913	0.29657	0.2959608	0.293218	0.28956	0.32065
	Unit Discharge (m²/S)	0.285816	0.28148	0.270956	0.256256	0.251938073	0.243989	0.237797	0.275765
	Standard deviation	0.173347	0.200782	0.168684	0.240414	0.172948018	0.170005	0.28209	0.141482

Station 99+40 *L* = 0.94 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.905896	0.89771	0.899281	0.874967	0.852131272	0.840028	0.860236	0.851007
	Depth (m)	0.297485	0.287426	0.291084	0.295351	0.3035808	0.302666	0.302362	0.29779
	Unit Discharge (m²/S)	0.26949	0.258026	0.261766	0.258422	0.258690693	0.254248	0.260102	0.253421
	Standard deviation	0.181283	0.145699	0.406724	0.199367	0.170700848	0.157171	0.132414	0.173579

Station 99+50 L = 1.2 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.885459	0.877467	0.889572	0.873533	0.838744807	0.835356	0.835656	0.827835
	Depth (m)	0.29657	0.303886	0.305105	0.296266	0.2935224	0.294132	0.296266	0.300533
	Unit Discharge (m^2/S)	0.262601	0.266649	0.271413	0.258798	0.246190389	0.245705	0.247576	0.248792
	Standard deviation	0.203621	0.170425	0.22891	0.205192	0.241979688	0.228806	0.176613	0.220429

Station 99+60 L = 1.45 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.903191	0.8904	0.922235	0.940763	0.915407279	0.912427	0.842846	0.893591
	Depth (m)	0.261945	0.279502	0.284074	0.291694	0.2907792	0.28255	0.287426	0.287731
	Unit Discharge (m^2/S)	0.236587	0.248868	0.261983	0.274415	0.266181396	0.257806	0.242256	0.257114
	Standard deviation	0.191364	0.217618	0.24839	0.184655	0.206891775	0.181696	0.394286	0.197787

Station 99+70 L = 1.7 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	1.175652	1.106665	1.17161	1.149064	1.140510181	1.15495	0.866319	0.793475
	Depth (m)	0.212446	0.211836	0.208483	0.208178	0.2081784	0.204826	0.199034	0.193853
	Unit Discharge (m^2/S)	0.249762	0.234432	0.244261	0.23921	0.237429585	0.236563	0.172427	0.153817
	Standard deviation	0.242176	0.169012	0.164327	0.189108	0.553509474	0.193271	0.393589	0.356591

Table. A-8 Distributions of velocity and unit discharge entering the headtank and spillway. The flow was non-uniform. Here, *L* is the distance from the spillway entrance (Station 9) to Experiment 8 stations. The last station in the table is the ogee crest's current (or design) position.

Station 9 *L* = 0 m	Stations across the headtank (m)	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042	25.29535
	Velocity (m/s)	0.621527	0.443296	0.2449	0.252683	0.168984162	0.151945	0.124054
	Depth (m)	0.327355	0.343205	0.338938	0.342595	0.3483864	0.348691	0.345643
	Unit Discharge (m²/S)	0.20346	0.152141	0.083006	0.086568	0.058871784	0.052982	0.042878
	Standard deviation	0.094732	0.162598	0.170663	0.074041	0.045227151	0.069298	0.072301

Station 9.67 *L* = 0.20 m	Stations across the headtank (m)	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042
	Velocity (m/s)	0.803221	0.568348	0.433065	0.257965	0.121323236	0.120774
	Depth (m)	0.30419	0.321869	0.329489	0.336499	0.3453384	0.343814
	Unit Discharge (m²/S)	0.244332	0.182933	0.14269	0.086805	0.041897572	0.041524
	Standard deviation	0.125251	0.094088	0.080222	0.107719	0.104994446	0.091075

Station 99+30 *L* = 0.70 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	1.003412	0.968926	0.949622	0.880026	0.82851876	0.831229	0.825772	0.830097
	Depth (m)	0.285293	0.287731	0.291998	0.295351	0.2953512	0.294437	0.290779	0.284988
	Unit Discharge (m²/S)	0.286266	0.27879	0.277288	0.259917	0.24470401	0.244744	0.240117	0.236568
	Standard deviation	0.154888	0.211522	0.236202	0.23628	0.180780679	0.15811	0.149164	0.152605

Station 99+40 *L* = 0.94 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.903806	0.904337	0.909176	0.885606	0.82993706	0.850414	0.849646	0.858751
	Depth (m)	0.292303	0.287731	0.290779	0.295351	0.3035808	0.305105	0.299923	0.297485
	Unit Discharge (m²/S)	0.264185	0.260206	0.26437	0.261565	0.251952957	0.259465	0.254828	0.255465
	Standard deviation	0.199244	0.199893	0.21274	0.18154	0.244813472	0.162768	0.159399	0.152363

Station 99+50 *L* = 1.2 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	0.904079	0.90557	0.888267	0.845381	0.797830516	0.810609	0.857848	0.861027
	Depth (m)	0.295351	0.300533	0.300533	0.296266	0.2938272	0.294437	0.29779	0.299923
	Unit Discharge (m²/S)	0.267021	0.272153	0.266953	0.250457	0.234424307	0.238673	0.255458	0.258242
	Standard deviation	0.188232	0.201223	0.201699	0.259158	0.351038814	0.415622	0.168397	0.130158

Station 99+60 *L* = 1.45 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.77007	28.69692
	Velocity (m/s)	1.250333	1.264214	1.365914	1.323186	1.296152425	1.289832	1.260525	1.433777
	Depth (m)	0.202082	0.196596	0.203302	0.21336	0.2142744	0.21336	0.214579	0.207264
	Unit Discharge (m²/S)	0.25267	0.248539	0.277693	0.282315	0.277732283	0.275199	0.270482	0.29717
	Standard deviation	0.209431	0.199754	0.236703	0.245898	0.178478152	0.223455	0.194087	0.201333

Table. A-9 Distributions of velocity and unit discharge entering the headtank and spillway. The flow was non-uniform. Here, *L* is the distance from the spillway entrance (Station 9) to Experiment 9 stations. The last station in the table is the ogee crest's current (or design) position.

Station 9 *L* = 0 m	Stations across the headtank (m)	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042	25.295352
	Velocity (m/s)	0.633239	0.45525	0.281153	0.227851	0.16593304	0.151236	0.0933701
	Depth (m)	0.324002	0.33589	0.333146	0.335585	0.3441192	0.3429	0.3386328
	Unit Discharge (m²/S)	0.205171	0.152914	0.093665	0.076463	0.057100745	0.051859	0.031618178
	Standard deviation	0.098809	0.105356	0.236635	0.073135	0.055571761	0.056104	0.079849958

Station 9.67 *L* = 0.20 m	Stations across the headtank (m)	26.85288	26.54808	26.30424	26.02992	25.7556	25.49042
	Velocity (m/s)	0.819749	0.589079	0.438603	0.279852	0.163150561	0.093796
	Depth (m)	0.29779	0.317602	0.325831	0.331927	0.3416808	0.337109
	Unit Discharge (m²/S)	0.244113	0.187092	0.14291	0.09289	0.055745414	0.03162
	Standard deviation	0.138371	0.100786	0.078129	0.122234	0.080740213	0.087596

Station 99+30 *L* = 0.70 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.770072	28.69692
	Velocity (m/s)	1.050033	1.009728	0.965119	0.911624	0.857462778	0.865511	0.870223772	0.881255584
	Depth (m)	0.278587	0.280721	0.284988	0.288341	0.2874264	0.285902	0.2822448	0.2755392
	Unit Discharge (m²/S)	0.292526	0.283452	0.275047	0.262858	0.246457439	0.247452	0.245616134	0.242820459
	Standard deviation	0.205164	0.210277	0.172463	0.22517	0.182227477	0.132676	0.160159856	0.124438427

Station 99+40 *L* = 0.94 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.770072	28.69692
	Velocity (m/s)	0.947483	0.945981	0.952762	0.93158	0.842980231	0.887962	0.887168159	0.890279743
	Depth (m)	0.272186	0.276454	0.280416	0.284988	0.292608	0.299009	0.2959608	0.292608
	Unit Discharge (m²/S)	0.257892	0.26152	0.26717	0.265489	0.24666276	0.265508	0.262566998	0.260502975
	Standard deviation	0.184418	0.201541	0.219496	0.187702	0.315681607	0.180042	0.155521899	0.158035129

Station 99+50 *L* = 1.2 m	Stations across the spillway (m)	29.18155	29.12364	29.06268	28.98648	28.89504	28.83408	28.770072	28.69692
	Velocity (m/s)	1.202368	1.23045	1.260599	1.288092	1.332338443	1.278022	1.130105002	1.221564245
	Depth (m)	0.224333	0.224333	0.217018	0.22098	0.211836	0.207874	0.207264	0.2033016
	Unit Discharge (m²/S)	0.269731	0.27603	0.273572	0.284643	0.282237246	0.265667	0.234230083	0.248345966
	Standard deviation	0.280841	0.21642	0.20449	0.235214	0.182392046	0.162977	0.178535387	0.180351168

Table. A-10 Distributions of velocity and unit discharge entering the headtank and spillway. The flow was non-uniform. Here, *L* is the distance from the spillway entrance (Station 9) to Experiment 10 stations. The last station in the table is the ogee crest's current (or design) position.

Station 9 *L* = 0 m	Stations across the headtank (m)	26.853	26.548	26.304	26.030	25.756	25.490	25.295
	Velocity (m/s)	0.616	0.447	0.366	0.237	0.184	0.136	0.092
	Depth (m)	0.325	0.340	0.336	0.340	0.346	0.347	0.340
	Unit Discharge (m²/S)	0.200	0.152	0.123	0.080	0.064	0.047	0.031
	Standard deviation	0.135231644	0.105912559	0.08449	0.08268	0.057853	0.068159	0.073984

Station 9.67 *L* = 0.20 m	Stations across the headtank (m)	26.853	26.548	26.304	26.030	25.756	25.490
	Velocity (m/s)	0.817	0.581	0.406	0.243	0.167	0.062
	Depth (m)	0.304	0.320	0.329	0.336	0.342	0.340
	Unit Discharge (m²/S)	0.248	0.186	0.133	0.082	0.057	0.021
	Standard deviation	0.155708864	0.098333761	0.160014	0.078169	0.059198	0.085068

Station 99+30 *L* = 0.70 m	Stations across the spillway (m)	29.182	29.124	29.063	28.986	28.895	28.834	28.770	28.697
	Velocity (m/s)	1.069	1.051	0.951	0.927	0.875	0.855	0.860	0.826
	Depth (m)	0.282	0.285	0.288	0.291	0.291	0.289	0.286	0.279
	Unit Discharge (m²/S)	0.301	0.299	0.274	0.270	0.255	0.247	0.246	0.230
	Standard deviation	0.194415778	0.156901702	0.199119	0.189283	0.154455	0.149016	0.158959	0.579167

Station 99+40 *L* = 0.94 m	Stations across the spillway (m)	29.182	29.124	29.063	28.986	28.895	28.834	28.770	28.697
	Velocity (m/s)	1.242	1.223	1.151	1.138	1.091	1.086	1.064	1.062
	Depth (m)	0.197	0.202	0.208	0.212	0.213	0.216	0.217	0.229
	Unit Discharge (m²/S)	0.244	0.248	0.240	0.241	0.232	0.234	0.231	0.243
	Standard deviation	0.180048913	0.213010043	0.200316	0.203033	0.19148	0.172983	0.193352	0.169177