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FLOW AND HYDRAULIC EFFICIENCY OF VERTICAL INTAKE STRUCTURES

Adam Auckland

Submitted under the supervision of:
Dr. Ioan Nistor and Dr. Ronald Townsend

In partial fulfillment of the requirements for the degree of
Master of Applied Science in Civil Engineering



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ABSTRACT

This thesis presents the results of an extensive experimental investigation into the hydraulic efficiency of a vertically-oriented water intake. Water supplied from rivers and reservoirs is usually drawn through intakes. Under low submergence conditions, the operation of an intake is associated with the formation of surface vortices, which result in flow reduction and the downstream entrainment of air and swirl.

The experimental work considered the fact that vortex formation is governed by the geometrical characteristics of the intake (e.g. diameter, shape, submergence, surrounding boundary, etc.) and the approaching flow conditions. Therefore, the experimental study was conducted to investigate the influence that the local shape and the proximity to boundaries each have on the hydraulic performance of a water intake.

The results of the present experimental program have lead to a better understanding of the phenomena that govern the flow in such structures and to the elaboration of improved design guidelines.

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LIST OF SYMBOLS

The following symbols are used in this paper:

α	= swirl angle (degrees)
Γ	= circulation (m^2/s)
ϵ	= eddy viscosity (m^2/s)
μ	= kinematic viscosity (m^2/s)
ν_e	= effective viscosity = $\mu + \epsilon$ (m^2/s)
ρ	= density (kg/m^3)
T	= surface tension (N/m)
$\vec{\Omega}$	= vorticity vector, $[u, v, w]$ (m/s)
ϕ	= parameter accounting for the influence of the intakes physical orientation (non-dimensional)
ξ	= parameter accounting for the influence of the local shape of the intake (non-dimensional)
ψ	= parameter describing the intakes location with respect to its boundaries (non-dimensional)
θ_V	= V-notch weir angle [90° for present experiment] (degrees)
ω	= angular velocity (rad/s)
σ_Q	= standard deviation of discharge, Q (m^3/s)
σ_h	= standard deviation of intake submergence depth, h (m)
A	= area (m^2)
B_1	= width of channel approaching V-notch weir (m)
c	= circulation constant (m^2/s) = $\frac{\Gamma}{2\pi}$
C_d	= coefficient of discharge = 0.578 for 90° V-notch weir (non-dimensional)
d	= diameter of intake (m)
Fr	= intake Froude number = $\frac{V}{\sqrt{gd}}$ (non-dimensional)
g	= gravitational acceleration ($9.81 \text{ m}/\text{s}^2$)
h	= intake submergence (m)
h_{cr}	= critical intake submergence (m)
h_m	= temporally averaged intake submergence (m)
h_w	= head above V-notch weir (m)
h_1	= head above V-notch weir (m)
$\left(\frac{h}{d}\right)$	= relative intake submergence (non-dimensional)
$\left(\frac{h}{d}\right)_{cr}$	= critical relative intake submergence (non-dimensional)
$\left(\frac{h}{d}\right)_m$	= mean relative intake submergence (non-dimensional)

L_1	= upstream distance of the point where the V-notch depth (h_1 or h_w) is measured (m)
n	= number of revolutions of a swirl meter per unit time (rev/t)
N	= number of data points recorded
N_S	= swirl number = $\frac{\Gamma d}{Q}$ (non-dimensional)
N_Γ	= circulation number = $\frac{\Gamma d}{Q}$ (non-dimensional)
p	= pressure (N/m ²)
p_1	= depth of water below the invert of the V-notch weir (m)
Q	= intake discharge (m ³ /s)
Q_m	= temporal average of intake discharge (m ³ /s)
r	= radial coordinate (m)
$\bar{r}$	= dimensionless radius = r/R (non-dimensional)
r_b	= radius of pipe bend used in experimental study (m)
R	= radius of interface between 'forced' and 'free' vortex regions (m)
Re	= intake Reynolds number = $\frac{Vd}{\mu}$ (non-dimensional)
Rr	= radial Reynolds number = $\frac{Q}{\mu h}$ (non-dimensional)
T	= surface tension (N/m)
u	= tangential velocity (m/s)
$\vec{u}$	= velocity vector, $[u, v, w]$ (m/s)
u_{max}	= maximum tangential velocity (m/s)
u_s	= tangential velocity as calculated by swirl meter (m/s)
v	= axial velocity (m/s)
V	= cross-sectional average velocity through intake = $\frac{Q}{A} = \frac{4Q}{\pi d^2}$ (m/s)
w	= radial velocity (m/s)
We	= intake Weber number = $V\sqrt{\rho d/T}$ (non-dimensional)
z	= axial coordinate (m)
$\bar{z}$	= dimensionless depth = z/h (non-dimensional)

LIST OF ABBREVIATIONS

The following abbreviations are used in this paper:

ARL Alden Research Laboratory

PIV Particle Image Velocimetry

USBR United States Bureau of Reclamation

1. INTRODUCTION

Water is used by humans for countless purposes. At large scales, it is typically drawn through *intakes* from rivers and reservoirs for irrigation and use by power generation facilities, and domestic and industrial supply systems. Furthermore, vertical intakes can be used to transport water vertically, such as in a *shaft* or *morning glory spillway*, or in a *drop structure*.

The placement of an intake near the free water surface may, at first, seem to be economically and operationally beneficial, as it would reduce both its construction cost and make it more accessible for maintenance. However, under low submergence conditions, vortices are likely to form, resulting in a decrease in the hydraulic efficiency of the intake and an increase in air and swirl entrainment. The latter phenomena can, in turn, have undesirable effects on downstream hydraulic systems or machinery (Jain *et al.*, 1978). For example, reductions of up to 80% in discharge capacity have been observed due to the presence of vortices (Jain *et al.*, 1978). In terms of hydraulic machinery, Denny and Young (1957) reported that air entrainment with a magnitude of 1% (by volume) can result in as much as a 15% decrease in the efficiency of a pump. An example of a typical free-surface intake vortex observed at a power generation station is provided in Figure 1.1.

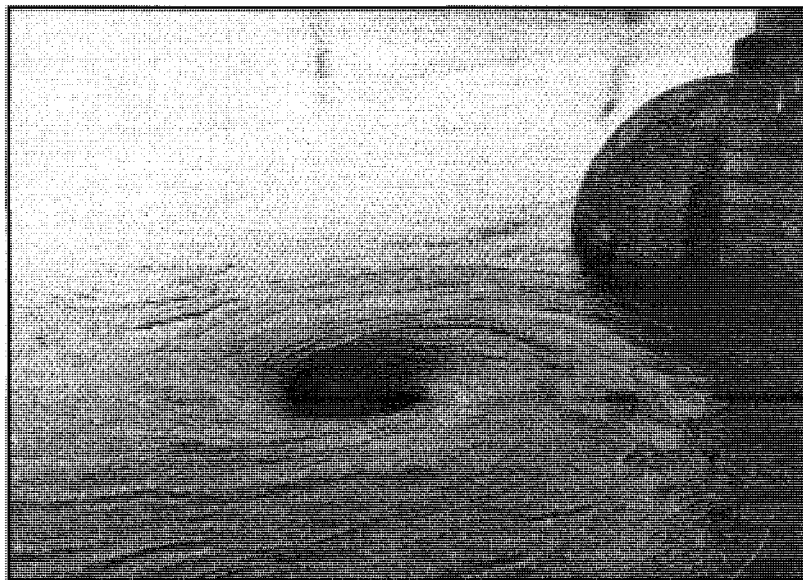


Figure 1.1: Intake vortex at Laufenburg power station on river Rhine (Vischer and Hager, 1998)

In this study the performance of a vertically downwards intake located on the horizontal floor of a rectangular basin is experimentally evaluated. In particular, the influence that the intake's local entrance shape and its proximity to nearby boundaries have on its overall flow rate, and therefore, its *hydraulic efficiency* is investigated.

1.1 NOVELTY OF STUDY

Over the years there has been an extensive amount of research conducted regarding intake vortices. However, vortex behavior is influenced by many factors; therefore, the research base is sparsely distributed, with few topics being investigated in great detail. In particular, little study has been focused on the influence that the local geometrical conditions have on the formation of vortices and flow through an intake. In fact, in the closing paragraph of his conclusion to the text, *Swirling Flows Problems at Intakes*, George E. Hecker states in his recommendations for future work that (G.E. Hecker, 1987):

"Rather than continuing experiments to define the basic features of surface vortices, and to quantify scale effects of air-core vortices, it is recommended that research on the analytical prediction of circulation be conducted. If the overall flow pattern around an intake can be defined, appropriate boundary conditions to analytical models would be available, and reasonable predictions of vortex intensity would be possible. However, due to the influence of the local geometry, additional work is also necessary on basic geometrical effects."

In this study, the effect that the geometrical parameters have on not only the formation of vortices, but also on their behavior and the overall flow through a vertical intake located inside a rectangular structure is investigated. The geometrical parameters examined herein include the local shape of the intake entrance and the intake's proximity to its surrounding solid boundaries.

In general, vortex formation is caused by circulation occurring in the flow. Most previous experimental studies regarding vortex formation at vertically downwards intakes have been performed by inducing a controlled, consistent amount of circulation to the flow. In reality however, circulation is dependent on the approaching flow conditions and the surrounding and upstream geometry. Therefore, circulation is not consistent and cannot be analytically estimated with sufficient certainty. In the present experimental study, circulation is not induced but rather allowed to develop naturally. To the author's knowledge, there has been no such investigation into vortex behavior under these conditions or inside the type of structure examined in the current study. The rectangular geometry of the intake structure used in this study is typical of flow regulators employed in urban storm sewer systems (e.g. city of Ottawa system).

In terms of the intake entrance shape, there is also novelty in the testing of some shapes under fully submerged (orifice-type) flow conditions. For example ogee profiles have been adapted from the United States Bureau of Reclamation's (USBR) *Design of Small Dams*. These profiles, as developed by the USBR, assume that the head above the crest of the ogee weir is comparatively small considering the current experimental study and orifice-type flow is not considered. Therefore, as such an examination has not been previously performed, there is novelty in the testing of these profiles under fully submerged conditions.

It is hoped that, through this study, the influence that the local entrance shape and surrounding geometrical conditions have on intake flow will be better understood and that some practical design recommendations for similar intake structures can be established.

1.2 SIGNIFICANCE OF STUDY

As the physical characteristics of an intake govern the amount of water that it can pass, a study aimed at developing criteria for optimal intake design can, in turn, provide substantial benefits, not only from a hydraulic view-point, but from economic and social perspectives as well.

1.2.1 HYDRAULIC PERSPECTIVE

An efficient intake will allow for the passing of the maximum amount of water. It will minimize frictional losses and both air and swirl entrainment. As hydraulic transport structures, such as drop structures, are principally designed to maximize flow capacity while minimizing its size/cost, an efficient intake to such a structure is essential. For example, minimizing the amount of air entrained into a series of sewer drop structures will allow for the design of a smaller, more efficient pipe system.

As urban areas become more intensively developed, a hardening of the ground surface occurs where soil and vegetation are covered by buildings, roads, parking lots and other mostly non-permeable surfaces. This urbanization has the effect of increasing surface runoff from rain and thus, also increasing storm sewer inflow. Also, many existing sewer systems suffer from reduced performance due to structural deterioration. Therefore, these systems may need to be improved in order to increase their efficiency and meet the rising hydraulic demand. In such works, proper measures should be taken to maximize discharge capacity and to minimize vortex formation and the subsequent entrainment of air.

1.2.2 ECONOMIC AND SOCIAL PERSPECTIVES

Reduced flow rates and air/swirl entrainment can produce significant economic problems. For instance, substantial profits can be lost by power plant operators if inflow rates are reduced. Economic disturbances can develop particularly when the overall demand for hydraulic power is high and the available supply is low. Such circumstances could arise from the presence of intake vortices as a substantial decrease in inflow could result in a significant decrease in power generation. Such a scenario may occur in hot, dry months, when temperatures are high and reservoir water levels are low. A poorly designed intake under such conditions could result in significant disruption of the local supply of power. Monetary losses can also be caused by reduced efficiency or increased maintenance of hydraulic machinery, both by-products of vortex occurrence.

From a social view-point, vortex occurrence at intakes can cause significant water supply problems, especially in tropical areas where fresh water can be in short supply. In such a case, during a dry season for example, if the minimum required depths cannot be maintained, vortices may prevail, effectively reducing the overall supply of water. As noted by Rajagopal (1980), another example where proper intake design is of extreme importance is in the containment of a nuclear reactor. Vortex formation in the recirculation pump sump of an Emergency Core Cooling System can give rise to the possibility of disastrous consequences.

1.3 OBJECTIVES OF STUDY

An extensive literature review revealed several problems associated with the design and functioning of basic water intakes. These problems provided the motivation behind the experimental study and are as follows:

- Intake vortex formation is fundamentally driven by an asymmetric velocity distribution relative to the location of the intake, the production of which is governed by the surrounding boundaries and the velocity distribution of the approaching flow.
- In prior studies, the effect of local intake entrance geometry (e.g. shape, angle, etc.) on intake performance has not been investigated (Knauss, 1987).
- Previous attempts to develop universal design guidelines for such intakes have proven to be ineffective. This is because vortex behavior is governed by geometrical parameters and therefore tends to be strongly site specific. (Gulliver *et al.*, 1983).
- If intake conditions are conducive to vortex formation, aside from increasing the size or submergence of the intake, there is little that can be done to prevent it.

Accordingly, the present study was undertaken with the following objectives

- Provide a summary of previous research on vortex formation at intakes with particular attention being paid to an understanding of the mechanisms that induce and drive flow circulation.
- Perform an experimental investigation on the influence of the basic geometrical properties on the performance and formation of vortices at vertical intakes. The geometrical properties studied in the present work include the entrance shape of the intake (e.g., straight, rounded, etc) and its proximity to nearby boundaries.
- Provide some practical engineering design recommendations, based on the experimental results, the theoretical mechanics of circulation and vortex behavior. These recommendations are intended to be general enough in nature that they can be universally applied.

1.4 SCOPE OF STUDY

In the literature review portion of the study, numerous sources were sought and considered with the objective of understanding why and how vortices form, and what factors influence their intensity. Although discussed briefly herein, the theoretical concepts and details regarding the actual fluid velocities associated with vortex flow are not examined in experimental study. This was due to the fact that, under unsteady conditions, the established vortices were variable in terms of strength and location (see Section 3.1.5.2); therefore, measurements of fluid velocity are difficult to obtain with sufficient accuracy.

The physical experiments performed in this study were designed to investigate the efficiency of a vertical intake under different geometrical entrance conditions. This was accomplished by measuring the water depth above and flow through the various intake shapes considered. Efficiency, in this case, is defined by an intake's performance (flow rate) relative to the standard 'abrupt-entry' or 'straight-edged' intake, which is considered to be the hydraulically worst performing intake shape.

1.5 OUTLINE/ORGANIZATION

The present work has been organized into two main parts and six sections. The main parts, as identified in 1.3, are the literature review and the experimental study, respectively. The sections are as follows:

Section 1: Introduction – A brief introduction to the study is provided; the study's significance, novelty, scope and objectives are discussed

PART I – LITERATURE REVIEW

Section 2: General Overview – The different types of intake structures are described; important design considerations are discussed.

Section 3: Theoretical Background - An introduction to vortex theory is provided; terminology and governing equations are defined; vortex formation, behavior and characteristics are discussed; critical submergence and air/swirl entrainment and explained; simplified theoretical models are identified. The use of physical modeling to predict vortex behavior is investigated; dimensionless parameters are identified; problems and scaling effects are discussed.

PART II – EXPERIMENTAL STUDY

Section 4: Experimental Study – Experimental intake shapes and geometrical arrangements are identified; data acquisition methods and test methodology are discussed.

Section 5: Results and Analysis – The results from the experimental study are presented and discussed.

Section 6: Conclusions – The conclusions drawn from the study are summarized; design recommendations are provided.

PART I – LITERATURE REVIEW

2. GENERAL OVERVIEW

Intake structures are generally used for two main purposes, either to withdraw water from rivers or reservoirs for use or to transport flow vertically. In terms of hydraulic functionality, intake flow is usually driven by gravity and maintains the characteristic of a decreased pressure resulting from an increase in fluid velocity. The head above an intake is of particular importance because significantly different flows can occur depending on whether the head is low or high and the hydraulic problems associated with each type of flow are different (Vischer and Hager, 1998).

2.1 INTAKE CHARACTERISTICS

Variable in size and functionality, intakes can range from large scale installations (e.g. power plants, spillways, etc.) to smaller-sized structures (e.g. pump intakes, sewer system drop structures). Intakes can be found in several different forms and arrangements. To conceptualize the flow through an intake, it is first necessary to identify the intake's physical orientation with respect to the approaching flow. This classification is based on structural aspects, specifically, (i) the direction of the intake with respect to the flow (e.g. vertically downwards/upwards, inclined or horizontal), and (ii) whether the intake is located on the boundary (floor/walls) or projecting into the basin (Knauss, 1987). An illustrative representation of this classification scheme can be found in Figure 2.1. The present study is focused on the performance of a vertically downwards intake located on the floor of a rectangular basin.

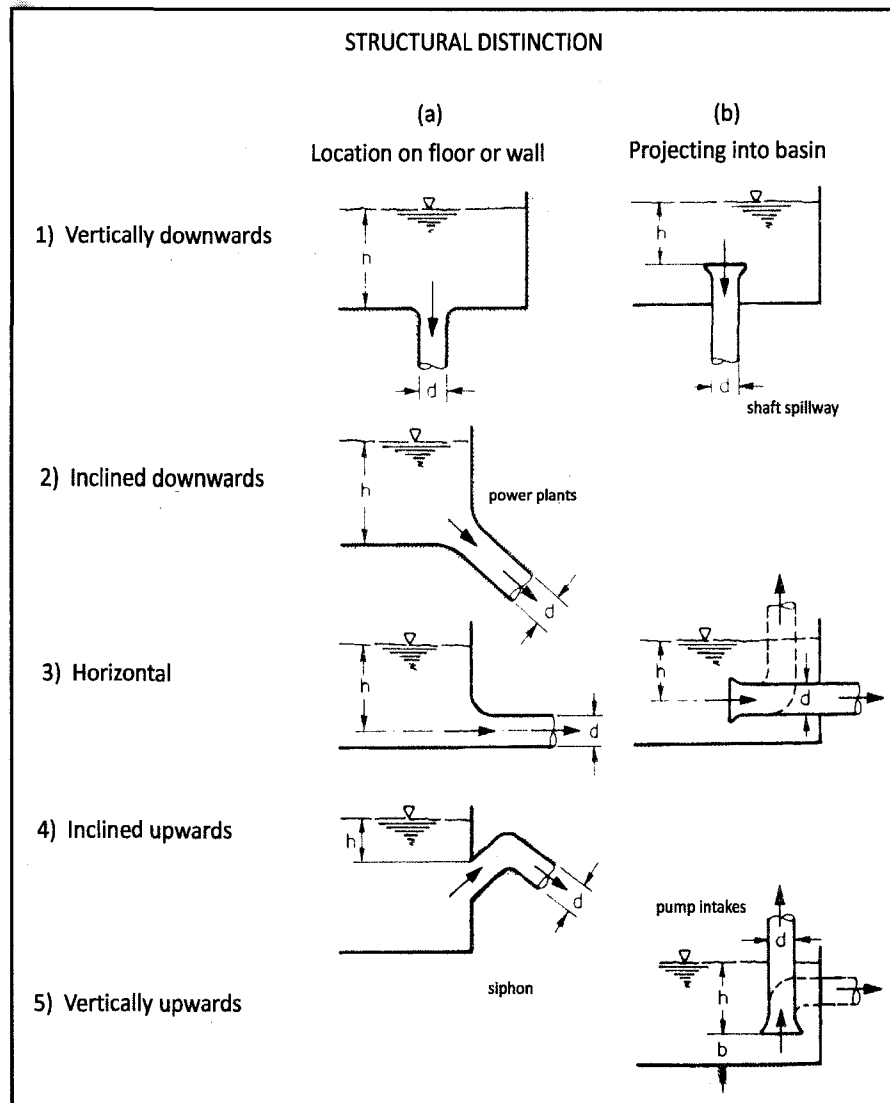


Figure 2.1: Structural classification scheme of intakes (Knauss, 1987)

2.2 DROP STRUCTURES

Intakes constitute an integral component of a basic *drop structure* (Figure 2.2). A drop structure is a hydraulic device used to transport water vertically between channels with different elevations. Typically, these structures are used by hydraulic designers in order to avoid installing channels/pipes with excessively steep slopes. Conceptually, the flow enters the intake structure where it is directed into a vertical shaft and falls by gravity until reaching

an outlet structure where excess flow energy is dissipated and the entrained air is removed prior to re-connecting with the rest of the supply system.

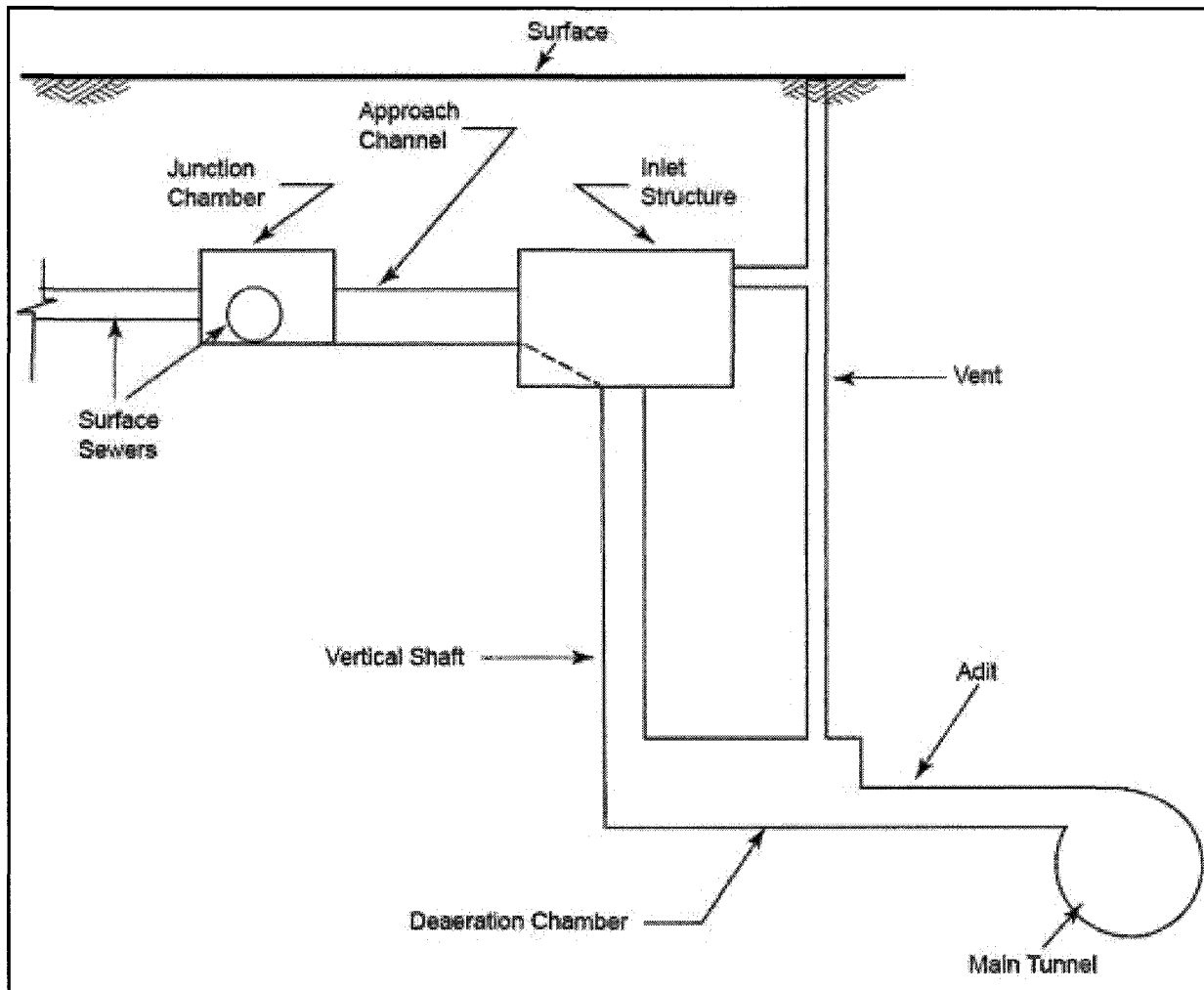


Figure 2.2: Typical drop structure (Williamson, 2001)

2.2.1 TYPES OF DROP STRUCTURES

Drop structures are distinguished by the characteristics of their intake structure. Two main types exist: (i) plunge-flow intakes (Figure 2.3) and (ii) vortex-flow intakes (Figure 2.4) (Jain and Kennedy, 1983). In a *plunge-flow* structure, the water flows uncontrolled into the

vertical shaft by gravity; whereas a *vortex-flow* structure uses a special type of inlet to impose angular momentum on the flow as it enters the structure. This momentum causes the water to spiral down the vertical shaft, clinging to its inner wall, while a stable, central air-core forms around its axis of rotation.

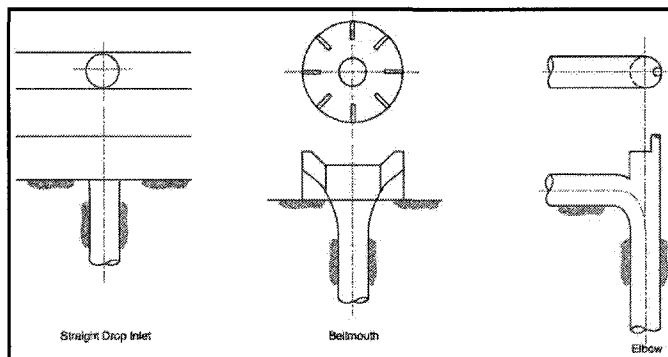


Figure 2.3: Plunge-flow intakes (Williamson, 2001)

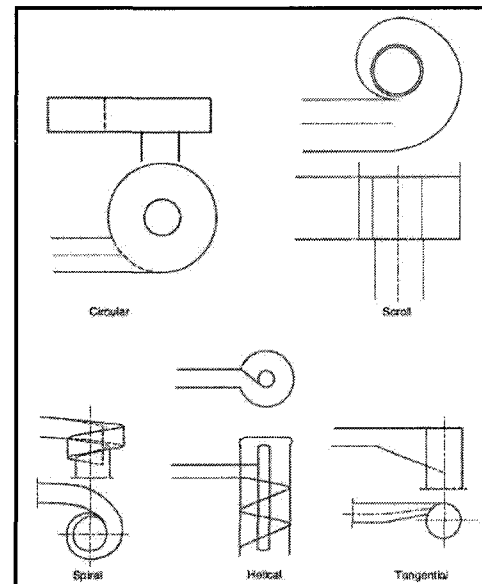


Figure 2.4: Vortex-flow intakes (Williamson, 2001)

Vortex-flow structures are generally considered to be superior to plunge-flow structures because they can establish and maintain a consistent flow pattern over a wider range of flows, ensure that the flow is aerated (thus avoiding cavitation by ensuring that atmospheric pressure exists throughout the drop shaft), and enhance energy dissipation through prolonged wall friction. Their main drawback is their relative high cost, which tends to make them impractical for smaller applications.

The experimental setup (Figure 2.5 and Figure 4.1-Figure 4.4) used in this study is analogous to a standard, straight inlet, plunge-flow drop structure and is subject to vortex formation and the subsequent entrainment of air and swirl.

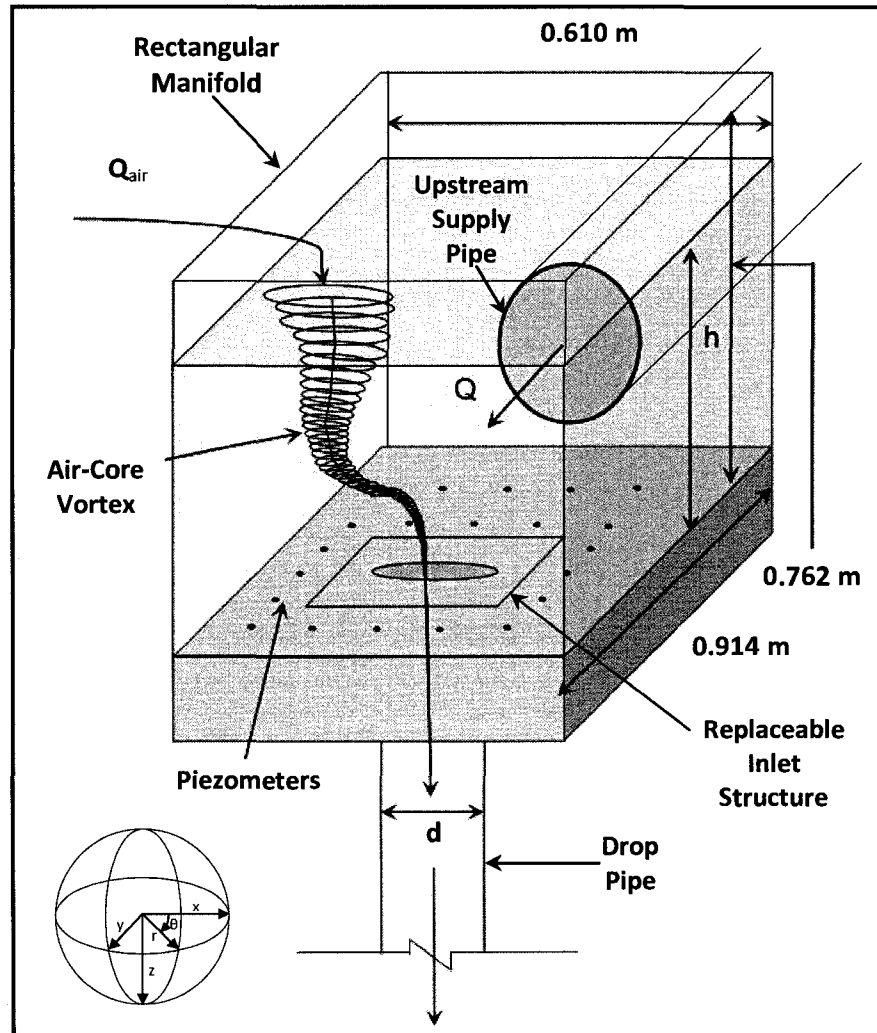


Figure 2.5: Experimental setup used in present study

2.3 DESIGN CONSIDERATIONS

Primarily, the hydraulic design of an intake consists of determining the necessary geometric form, dimensions and approach flow conditions required to provide the necessary discharge capacity (Jain and Kennedy, 1983). Uncontrolled air entrainment is the worst consequence for an intake structure; therefore, if the geometric and approach flow conditions are such that unwanted vortex formation cannot be avoided, the design should attempt to minimize the resulting amount of entrained air.

In the past, design guidelines have mainly been developed based on analytical solutions or observations of seemingly similar intakes and typically involve the prediction of the critical depth (or submergence) at which the entrainment of air first occurs. If this depth is maintained, the formation of air entraining vortices would be eliminated completely. However, this approach has proved to be ineffective; this is presumably because the mechanisms that govern vortex formation are geometrically dependent and are therefore strongly site specific (this concept is further explained in Section 3.1.3). Thus, there is a demand for more generic design criteria that considers the strong dependence of the vortex phenomena on the approaching flow and surrounding geometrical conditions of the intake.

Presently, an engineer has little information on which to develop an optimal intake design. As no completely reliable design guidelines exist, large scale installations require hydraulic model studies as an essential step in the design process (Hecker, 1987; Gulliver *et al.*, 1986; Jain *et al.*, 1978). Unfortunately, many smaller scale projects cannot bear the cost and delay that such a study requires. When hydraulic model studies cannot be performed, the designer's best judgment is relied upon, as a "wait and see" approach is used to design and construct the intake. In this scenario, it is imperative that the designer possess a solid understanding of the theoretical concepts pertaining to the formation and behavior of vortices. The next section attempts to provide a brief review and summary of these concepts.

3. THEORETICAL BACKGROUND

3.1 VORTEX THEORY

3.1.1 INTRODUCTION

The formation of *vortical structures* is a natural phenomenon of turbulent fluid flow. A common example of such a flow is a simple ‘bath-tub’ vortex. The largest scale vortical structures are found in the Earth’s upper atmosphere where they can reach up to 1000 km in diameter, with velocities in the order of 100 km/hr. In the oceans, structures up to 100 km in diameter and velocities of a few tens of km/hr can be observed (Petitjeans, 2003). At the smallest scale, the size of these structures is governed by the viscosity of the fluid. Below a certain size, internal viscous forces dissipate rotational energy as heat and coherent structures are unable to form (Petitjeans, 2003). Therefore, vortical structures scale with their boundaries on the large side, while the size of the smallest structures is dictated by the Kolmogorov scale.

3.1.2 TERMINOLOGY AND GOVERNING EQUATIONS

Vortices are coherent structures of turbulent rotational flow and are generated by circulation in the flow or, in other words, by flow that possesses vorticity.

Vorticity is a mathematical concept used in fluid dynamics to describe the rotation in a fluid (Lamb, 1962). It is a vector quantity, defined either as the curl of the velocity vector (equation 3.1), or as the circulation per unit area at a point in the fluid. For convenience, the equations in this section are presented in cylindrical coordinates, (θ, r, z) , where θ , r and z are, respectively, the tangential, radial and axial coordinates.

$$\vec{\Omega} = \text{curl}(\vec{u}) = \vec{\nabla} \times \vec{u} \quad [3.1]$$

where $\vec{\Omega}$ = vorticity vector and $\vec{u}$ = velocity vector (θ, r, z). If a fluid is assumed to be rotating as a solid (e.g. a cylinder), the vorticity of a fluid element is equal to twice its angular velocity (see Section 3.1.8.1). In general, any fluid element that is rotating about a fixed point is said to possess vorticity and accordingly, rotational fluid motion can also be referred to as *vortical* motion.

The *circulation*, Γ , around a closed curve is defined as the total vorticity inside the curve or as the line integral of a closed velocity curve. Vorticity and circulation are directly related to each other by the Stokes theorem. The Stokes theorem states that, the circulation around a surface periphery is equal to the vorticity integrated over the surface enclosed by that periphery (Carriveau, 2006), or mathematically,

$$\Gamma = \oint_C \vec{u} d\ell = \int_A \vec{\Omega} dA \quad [3.2]$$

where $d\ell$ = elementary vector tangent to the closed curve, C ; and A = area enclosed by curve C . This definition can be further simplified for a steady, 'free' vortex (see Section 3.1.8.1) following a circular curve of radius, r

$$\Gamma = 2\pi r u \quad [3.3]$$

The occurrence of intake vortices can be explained by the increased rotational velocity required by a converging water ring due to the conservation of angular momentum (Noguchi, 2003). The conservation of angular momentum states that the momentum along a closed ring is conserved. At the centre of each vortex is a *vortex line* which can be interpreted as the axis of rotation, as each fluid particle contained inside the vortex is considered to be circulating around the vortex line. Elongation of the vortex line (e.g. as the vortex is pulled into an intake) will lead to an intensification of the flow vorticity (Batchelor, 1967). This phenomenon, commonly termed as *stretching*, arises because, as the vortex line is extended, a reduction in the radii of the vortex rings occurs, leading to an amplification of the fluid's angular velocity by the conservation of angular momentum and thus, a confinement and intensification of the fluids vorticity (Petitjeans, 2003). This is analogous to a spinning figure

skater in which the skater first starts with a low, broad stance and begins spinning with a certain angular momentum (circulation). The skater then 'stretches' taller, narrowing his/her stance towards their axis of rotation. By the conservation of angular momentum, the rate of rotation (vorticity) of the skater is then increased (Carriveau, 2006).

The increase in rotational velocity associated with the development of a vortex results in a local drop in pressure at the surface. This decrease in pressure can cause a drop in the local water surface, the magnitude of which can range from a mere surface dimple to a fully developed air-core vortex. It is the latter of these consequences that is of particular concern in the design of intake structures.

Vorticity and circulation, although both used to describe rotational motion, are not the same. It is the circulation that is conserved by the conservation of angular momentum as the vorticity can either increase or decrease depending on its radius of rotation. The conservation of circulation can be expressed using a circulation constant. This constant, c , is defined as

$$c = \frac{\Gamma}{2\pi} \cong ru \quad [3.4]$$

Obtaining accurate estimates of flow circulation however, is not an easy task. As it cannot be directly measured, approximations must be made from other quantifiable data whose functional relationships with flow circulation are not necessarily well defined. Some of these quantities include maximum tangential velocity, surface depression depth, air-core diameter or swirl. In the past, some investigators have used sophisticated measurement techniques such as particle image velocimetry (PIV) (Noguchi *et al.*, 2003) and laser Doppler anemometers (Hite *et al.*, 1991) to measure fluid velocity near the vortex core but have also noted that this practice is difficult due to the temporal and spatial variability of unsteady vortices.

Swirl is defined as the ratio between the tangential and axial velocity components and is therefore present in axial flow if a non-zero tangential velocity component exists. Swirl is commonly used to indirectly estimate flow circulation because it can be measured by means

of a swirl meter (or vortometer). However, for reasons outlined in Section 4.5.4, a swirl meter was not used in the present study.

Throughout this study, the terms vorticity and circulation are used to describe the conditions above and upstream of the intake, while swirl is used to refer to the flow conditions downstream of the intake.

3.1.2.1 EQUATIONS OF MOTION

In this section, a free surface vertical vortex flow as depicted in Figure 3.1 is considered. If the fluid is assumed to be steady, axi-symmetric, incompressible and laminar, its motion can be represented by the continuity equation (3.5) and the Navier-Stokes equations (3.6-3.8).

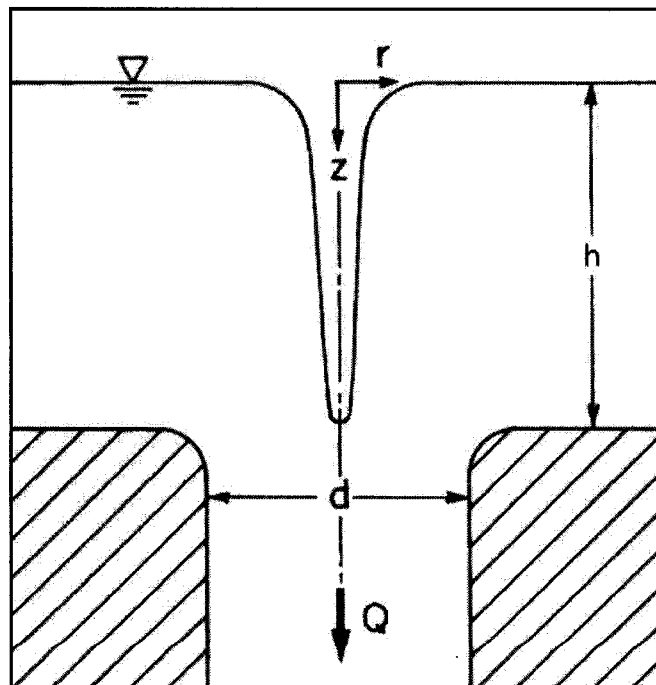


Figure 3.1: Definition sketch (Odgaard, 1986)

CONTINUITY EQUATION

$$\frac{1}{r} \frac{\partial}{\partial r} (rw) + \frac{\partial v}{\partial z} = 0 \quad [3.5]$$

NAVIER-STOKES EQUATIONS

Tangential Component, [u]

$$w \frac{\partial u}{\partial r} + v \frac{\partial u}{\partial z} + \frac{wu}{r} = \mu \left[\frac{\partial^2 u}{\partial r^2} + \frac{1}{r} \frac{\partial u}{\partial r} - \frac{u}{r^2} + \frac{\partial^2 u}{\partial z^2} \right] \quad [3.6]$$

Axial Component, [v]

$$w \frac{\partial v}{\partial r} + v \frac{\partial v}{\partial z} = -\frac{1}{\rho} \frac{\partial p}{\partial r} + \mu \left[\frac{\partial^2 v}{\partial r^2} + \frac{1}{r} \frac{\partial v}{\partial r} + \frac{\partial^2 v}{\partial z^2} \right] + g \quad [3.7]$$

Radial Component, [w]

$$w \frac{\partial w}{\partial r} + v \frac{\partial w}{\partial z} - \frac{u^2}{r} = -\frac{1}{\rho} \frac{\partial p}{\partial r} + \mu \left[\frac{\partial^2 w}{\partial r^2} + \frac{1}{r} \frac{\partial w}{\partial r} - \frac{w}{r^2} + \frac{\partial^2 w}{\partial z^2} \right] \quad [3.8]$$

where u , v , w = tangential, axial and radial components of the velocity field, respectively; z , r = axial and radial co-ordinates, respectively; g = gravitational acceleration (9.81 m/s^2); ρ = density; p = pressure; and μ = kinematic viscosity. For further discussion of equations 3.5-3.8, see Batchelor (1967).

These equations assume a laminar flow; an assumption that begins to fall apart with increasing circulation. The velocity gradient ($\partial u / \partial r$) near the core begins to produce turbulent effects as the circulation is increased. This turbulence generates internal shear stress, thereby increasing the effective viscosity near the core of the vortex. The motion of the vortex in this circumstance is therefore influenced by both the kinematic and eddy viscosities. *Eddy viscosity*, ϵ , is a parameter used to describe the turbulent shear stress. If it is assumed that the fluid maintains a constant circulation ($\partial u / \partial r = \text{constant}$), equations 3.5-3.8 can be roughly assumed to also govern turbulent flow if μ is replaced by $(\mu + \epsilon)$ (Odgaard, 1986).

It should be noted that these equations are presented simply to aid the reader in understanding various concepts discussed in this study and are for consideration purposes only. Due to the number of influential parameters and the complex, three-dimensional nature of the vortex flow, it is not possible to obtain a closed-form analytical solution that could satisfy completely both the continuity equation and the Navier-Stokes equations (Chen *et al.*, 2007). Thus, vortex motion is typically described using simplified analytical models. The most common of which is known as 'Rankine's combined vortex'. This model and others are introduced and discussed in Section 3.1.8.

3.1.3 MECHANISMS OF VORTEX FORMATION

The fundamental mechanisms that cause intake vortices are circulation and the axial stretching of the vortical structure. As noted by Quick (1970), circulation alone is not sufficient to produce an air-entraining vortex. He stated that the circulation in the flow must combine with a stretching mechanism to form what he referred to as a 'vortex-forming situation'. This stretching mechanism is driven by the axial intake velocity and its characteristics are therefore a function of the size and submergence of the intake.

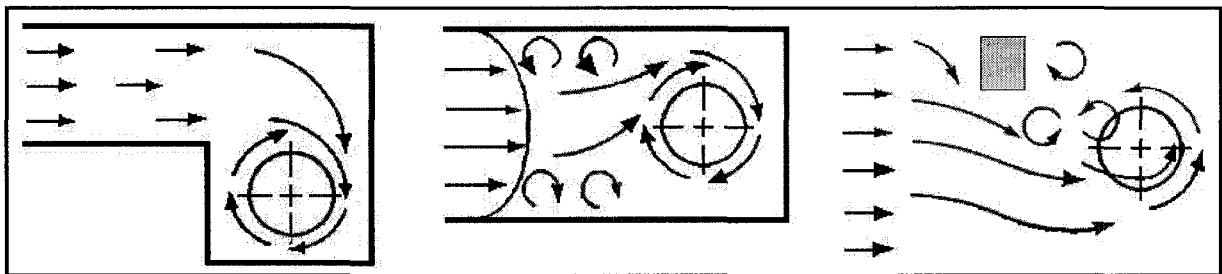


Figure 3.2: Primary sources of flow circulation (from left to right: i) eccentricity, ii) velocity gradient, and iii) obstruction) (Durgin and Hecker, 1978)

In general, circulation and vortex formation are caused by asymmetry in the approaching flow field relative to the location of the intake. This asymmetry is usually generated by the upstream and surrounding geometrical conditions. Circulation is driven primarily by three fundamental mechanisms of generating an asymmetric velocity distribution

relative to the location of the intake (Figure 3.2). These sources, as defined by Durgin and Hecker (1978), are:

- Eccentricity (with respect to the intake) in the approaching flow;
- Non-uniform velocity gradients (generated mainly by viscous interaction at boundaries);
- Rotational wakes formed behind physical obstructions.

It should also be noted that, particularly in quiescent flow, it is possible for small vortical structures to be carried downstream with little dissipation. This is referred to as *residual vorticity* and may become significant if it approaches the intake and the flow is not dominated by another source of circulation.

Residual vorticity is considered to be a secondary source of circulation. Secondary sources are, for the most part, non-dominant, inconsistent, and generate circulation of a magnitude insufficient to evolve alone into a large-scale, air-core vortex. Another example of a secondary source is viscous shear at the interface between fluids moving with distinctly different velocities (e.g. countercurrents, wind). Although these sources are generally not considered to be significant by themselves, it is possible for the small vortices in which they generate to combine energy and produce a larger vortex capable of developing an air-core.

It has also been documented that vorticity can accumulate in volumes of stagnant water. When these small vortices enter stagnant water, because they have no local acceleration, they can become trapped. This allows for the accumulation of rotational flow energy, and thus, stagnant volumes of water can act as sinks of vorticity (Hecker, 1987). The formation of an air entraining vortex, according to Quick (1970) depends on three fundamental requirements:

- There must be vorticity in the flow approaching the intake.
- The submergence of the intake must be less than the critical submergence.
- The intake must be in a vortex forming situation which is a function of the flow geometry and the steadiness, or organization time, of the flow.

3.1.3.1 EFFECT OF THE CORIOLIS FORCE

There is a popular misconception that vortices are a result of the Coriolis force. The *Coriolis force* is caused by the rotation of the Earth. It is exerted on every free-moving object on the Earth's surface and will cause an object to veer slightly to the right in the northern hemisphere and to the left in the southern hemisphere.

In actuality, the influence that the Coriolis force has on small scale fluid vorticity is much less than that of the more significant sources of circulation (Levi, 1972). The minor significance of this force was confirmed by the carefully controlled experiments of Shapiro (1962). In his experiment, water in a large cylindrical tank (radius = 1.83 m) was allowed to settle for at least 24 hours thereby eliminating any residual vorticity. A small drain hole (diameter = 0.953 cm) was then opened at the bottom of the tank. It was only after 12-15 min. of draining that a perceptible counterclockwise rotation began to appear (experiments conducted at MIT in Massachusetts). The experiment was repeated by Trefethen *et al.* (1965) at the University of Sydney, Australia, and after a similar length of time, clockwise rotation was visually observed. These experiments indicate that vorticity can be developed by the Coriolis force but only in relatively minor quantities (Marris, 1967), therefore, at small scales, it is not considered to be a significant source. It has been suggested by Marris (1967) that this vorticity is generated in the bottom boundary layer and that sufficient time is required for it to diffuse upwards throughout the fluid.

3.1.4 CRITICAL SUBMERGENCE

Whether a surface vortex is air entraining or not depends very much on the depth of water above the intake under consideration. The critical submergence associated with an intake is known to increase as the circulation strength increases. Swirl entrainment is independent of air ingestion and increases with a decrease in submergence (Knauss, 1987). Figure 3.3 provides a simple illustration of the basic relationship between circulation strength, submergence and air and swirl entrainment.

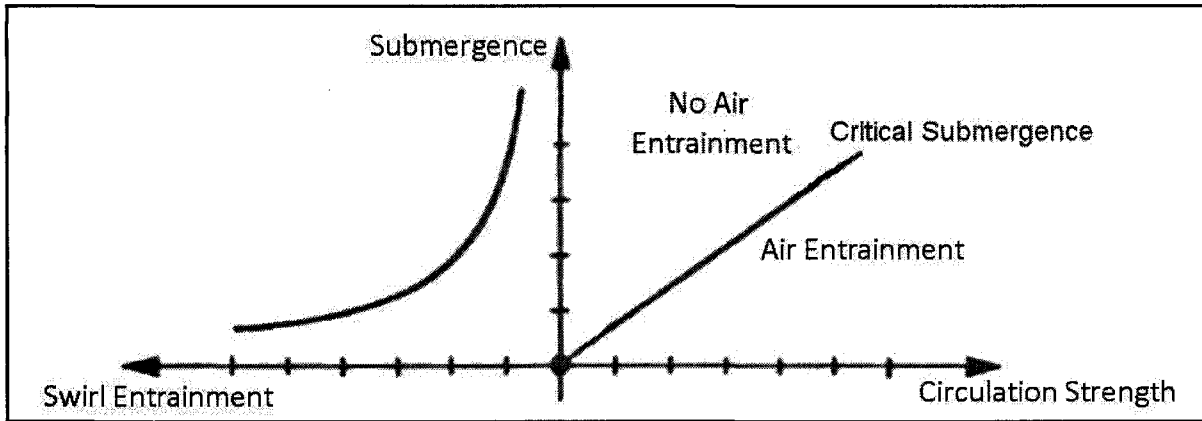


Figure 3.3: Basic relationship between circulation, submergence and air and swirl entrainment (Knauss, 1987)

The *critical submergence* (or *critical depth*), h_{cr} , of an intake is defined as the depth at which the circulation and the effect of the stretching mechanism are sufficient enough to induce an air entraining vortex. If this minimum submergence is maintained, no air entrainment will occur. Further lowering of the fluid surface will result in almost continuous air-entrainment, often producing an audible sucking noise (Jain *et al.* 1978). Figure 3.4 provides an illustration of the various stages of vortex development.

The critical submergence is dependent on numerous factors with whom its functional relationship is not well defined. The most important consideration is the amount of circulation that can be developed given the particular surrounding geometrical and approaching flow conditions of the intake. Therefore, the critical submergence is strongly site specific and is difficult to predict analytically with sufficient accuracy for design purposes.

The functional relationship of an intake's critical submergence can be expressed as

$$h_{cr} = f(V, d, \Gamma, \phi, \xi, \psi, g, T, \mu, \rho) \quad [3.9]$$

where h_{cr} = critical submergence depth; V = cross-sectionally averaged velocity across intake; d = diameter of the intake; T = surface tension and ϕ, ξ, ψ = parameters used to account for the influence of i) the physical orientation ϕ of the intake (e.g. vertically

downwards, horizontal, etc.), ii) the local shape ξ of the intake, and iii) the intake's location ψ with respect to its surrounding boundaries (Ranga Raju and Garde, 1987).

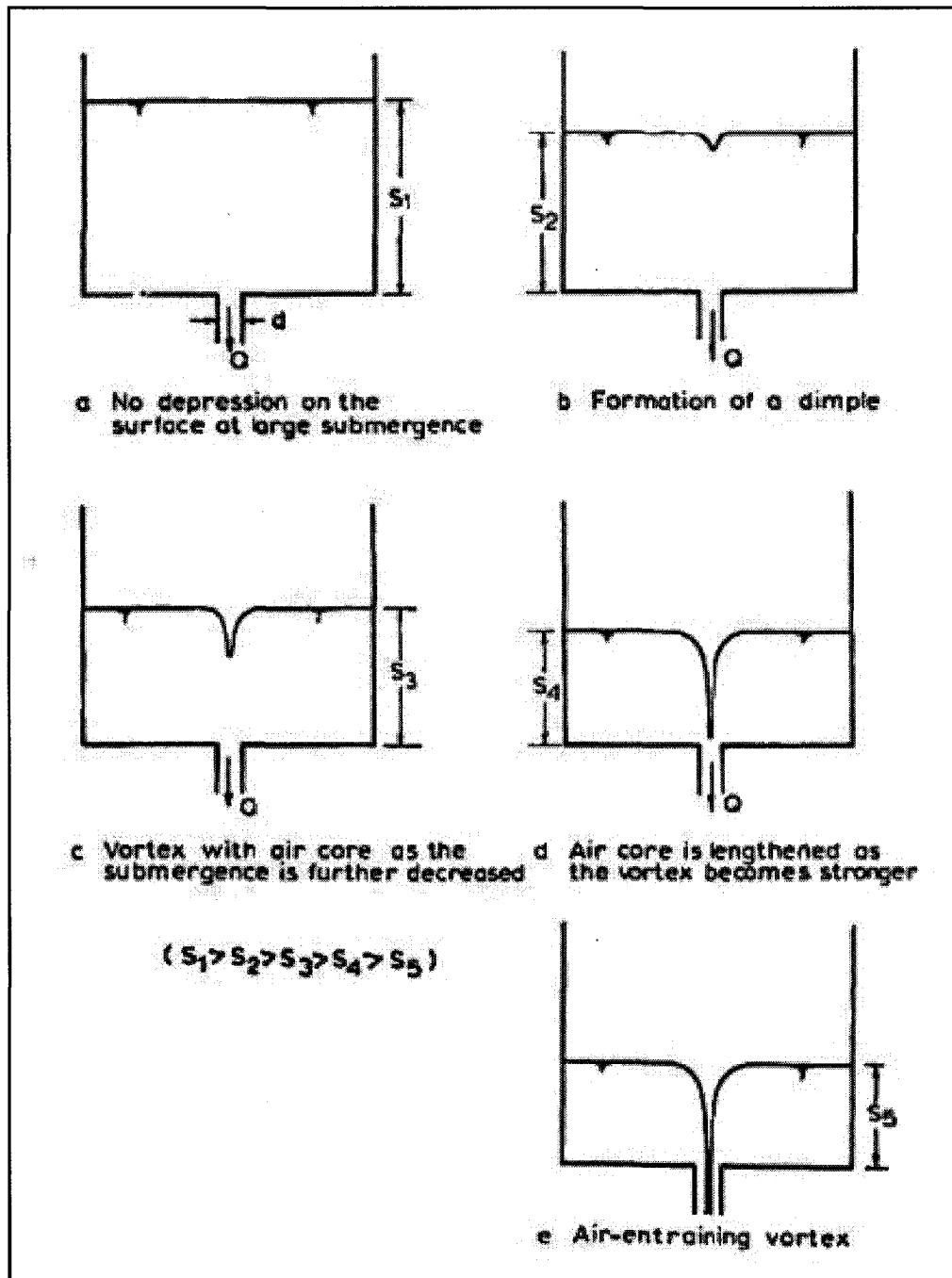


Figure 3.4: Stages of vortex development (Jain *et al.*, 1978)

By inspection of equation 3.9 it is apparent that the development of a closed form analytical solution would be a difficult and uncertain task. This difficulty is mainly due to two factors; first, many of the dependant variables (e.g. Γ , ϕ , ξ , ψ) cannot be analytically predicted with sufficient certainty, and secondly, the inter-relationships between the gradients of the dependent variables are not well understood. In other words, the effect or consequence of a change in one parameter on the other parameters cannot be accurately predicted (Knauss, 1987).

As maintenance of the critical submergence would completely eliminate the possibility of air entrainment due to vortex formation, an important question in design is how to predict the necessary depth to which the intake should be submerged. Accordingly, design guidelines have been devised with the goal of predicting this depth. This is usually accomplished either by using indirect measurements or approximations of circulation as inputs to analytical solutions, or by comparison to apparently similar intakes whose flow characteristics have already been established. This approach however, presumably due to the dependence of the flow circulation on both the surrounding and upstream geometry of the intake, has proven to be ineffective.

Based on experimental studies, some researchers have attempted to develop empirical solutions to predict critical submergence. Daggett and Keulegan (1974) and Jain *et al.* (1978) both performed such studies on vertically downwards intakes. Daggett and Keulegan (1974) found that for large Reynolds numbers (see Section 3.2.2.2):

$$\left(\frac{h}{d}\right)_{cr} = \frac{300}{Fr} \left[\frac{c}{\sqrt{g}d^{(\frac{3}{2})}} \right] \quad [3.10]$$

The results obtained by Jain *et al.* (1978) can be expressed as

$$\left(\frac{h}{d}\right)_{cr} = 88 Fr^{0.139} \left[\frac{c}{\sqrt{g}d^{(\frac{3}{2})}} \right]^{0.724} \quad [3.11]$$

where Fr = intake Froude number = $\frac{V}{\sqrt{gd}}$; and c = circulation constant = $\frac{\Gamma}{2\pi}$. These expressions have been transformed from their original formulation for comparison by Knauss (1987) and suggest that the critical submergence is primarily governed by the flow circulation and the intake Froude number. By inspection of the above empirical formulations it can be observed that they contradict each other in terms of Froude number dependence. In the expression provided by Daggett and Keulegan (1974), assuming constant circulation, the critical submergence is found to decrease with an increase in the Froude number while the solution given by Jain *et al.* (1978) indicates the opposite. This finding further shows the uncertainty involved in critical submergence prediction, even under controlled laboratory conditions.

Unfortunately, the experimental studies performed by Daggett and Keulegan (1974) and Jain *et al.* (1978) were carried out using cylindrical basins and by imparting a controlled (constant) amount of circulation to the flow. In reality, circulation is dependent on the approaching flow conditions and the surrounding and upstream geometry. Therefore, it is typically not consistent and cannot be analytically estimated with sufficient certainty. Thus, the use of such empirical solutions for design purposes is not reliable. In the present experimental study, circulation is not induced but rather allowed to develop naturally. The experiment is also performed in a rectangular basin; hence, due to geometric differences and unknown circulation, the aforementioned expressions cannot be used for comparison. Unfortunately, to the author's knowledge, there has been no such investigation into the critical submergence of the type of structure examined in the current study; therefore, a comparison of the results to previous studies cannot be made.

Evidence that the critical submergence of an intake is influenced by the proximity of its surrounding boundaries has been provided by Denny and Young (1957) and Anwar and Amphlett (1980). These studies both showed that, for a vertically upwards intake, the critical submergence is reduced as the clearance of a vertical or slightly sloping boundary is decreased and that the magnitude of the reduction increases with the initial circulation

strength. Denny and Young (1957) reported that a boundary will influence the critical submergence if it is within $10d$ of the intake. With respect to the entrance shape of the intake, Denny and Young (1957) found that it has very little effect on vortex formation.

Experimental investigations on differently oriented intakes similar to those of Daggett and Keulegan (1974) and Jain *et al.* (1978) have been performed by Anwar *et al.* (1978) and Anwar and Amphlett (1980) on horizontal and vertically upwards intakes, respectively. Through these studies, it was found that the orientation of the intake also influences the critical submergence.

Prediction of the critical submergence depth and circulation through numerical modeling has also proven to be ineffective when compared to results obtained through hydraulic model studies (Hecker, 1987). As circulation is heavily dependent on approach geometry, numerical prediction of circulation has been found to be sensitive to grid size and must include calculations far from the intake. In addition to this, numerical models have also been found to be sensitive to the chosen eddy viscosity value which varies with flow conditions. Furthermore, the unsteady nature of vortex occurrence can also present difficulty in calculating circulation as a function of time. It should be noted however that, considering recent improvements in numerical modeling, given cases involving relatively simple geometry (such as that used in the current study), it may now be possible to estimate circulation with reasonable certainty through the use of a three-dimensional unsteady numerical model. In fact, the results from the current study may be used as validation for such a model.

To date, there is no completely satisfactory solution to the prediction of the critical submergence of an intake and design guidelines that use this approach should be regarded as unreliable. If it is important that vortices be avoided altogether, the most reliable approach to design is through the use of a hydraulic model study (Jain *et al.*, 1978 Gulliver *et al.*, 1986; Hecker, 1987). It should be noted that hydraulic model studies are also not free from uncertainty as inaccuracy can be introduced in the form of scaling effects. These effects and the prediction of critical submergence through hydraulic modeling are discussed in further detail in Section 3.2.

3.1.5 VORTEX CLASSIFICATION

Vortices, once established, can be generally described using three main criteria: (i) their location relative to the intake, (ii) their time dependency and (iii) their physical characteristics.

3.1.5.1 LOCATION

As illustrated in Figure 3.5, vortex formation can occur either underwater, between the intake and a nearby boundary, or from the free water surface. These phenomena are known as *subsurface (or submerged) vortices* and *surface vortices*, respectively (Figure 3.6).

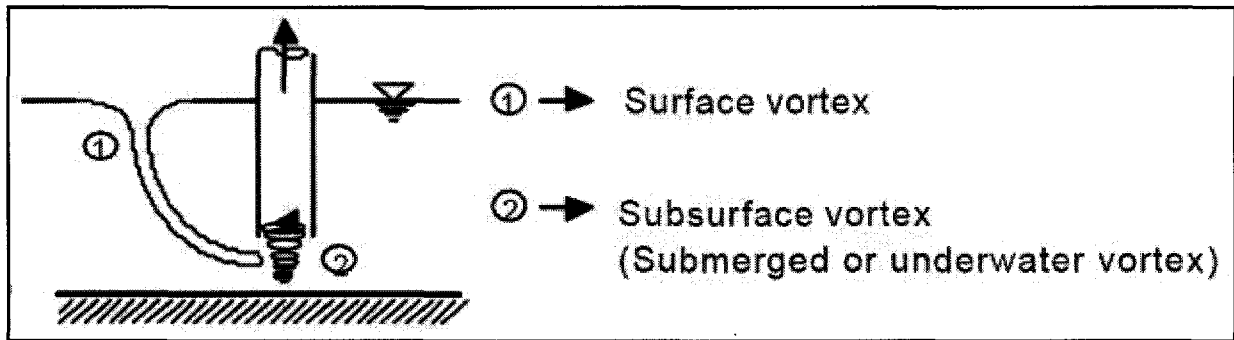


Figure 3.5: Locations of vortex formation (Borghei, 2000)

Subsurface vortices can lead to swirl entrainment downstream of the intake, while surface vortices can induce the entrainment of both swirl and air. Although both forms of entrainment can have undesirable downstream effects, the majority of vortex-related intake problems, however, are associated with the entrainment of air (see Section 3.1.6).

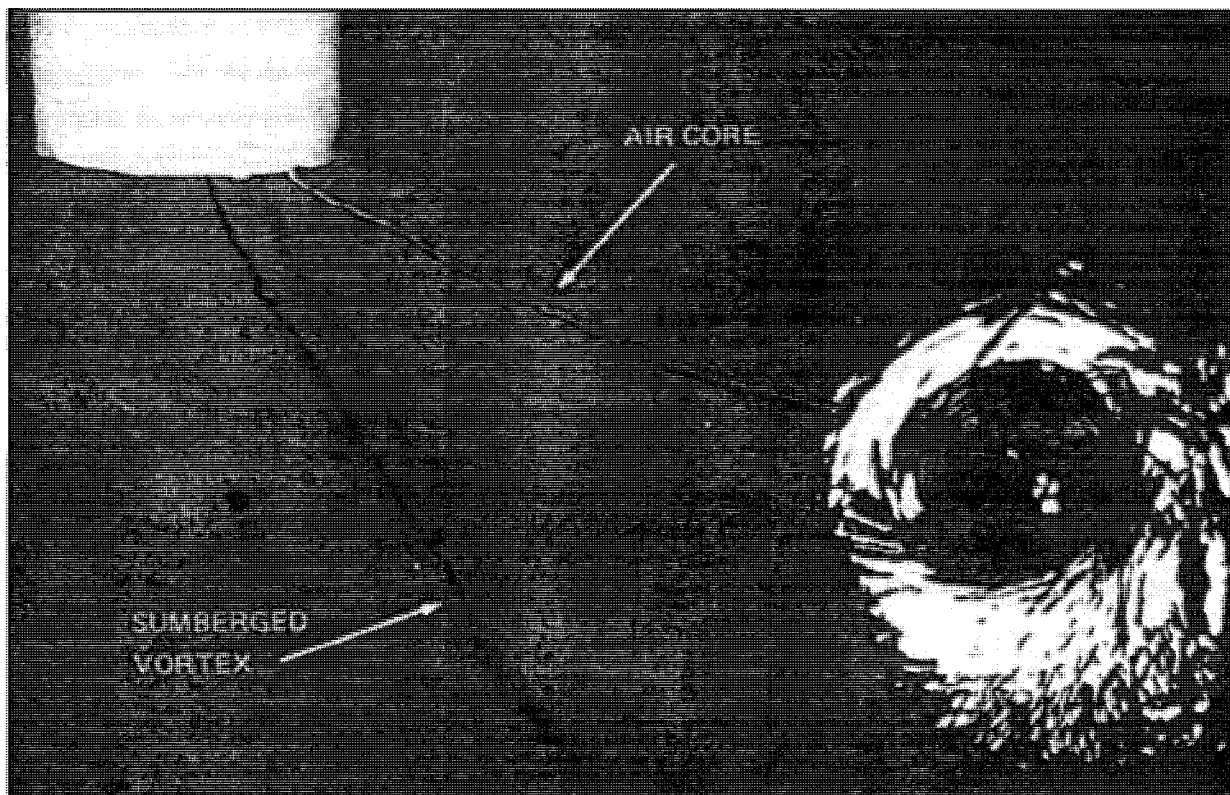


Figure 3.6: Intake with surface and subsurface vortices (Hecker, 1987)

3.1.5.2 TIME DEPENDENCY

The next distinction considers the time dependency of the vortex formation process. In general, the stability of an induced vortex is controlled by the amount of circulation in the approaching flow and the submergence of the intake, with more stable vortices occurring under conditions of increased circulation or decreased submergence (Blaisdell, 1958; Noguchi *et al.*, 2003).

Stable or *steady vortices* are characterized by a well-developed structure, and a constant strength. *Unstable vortices* (also known as, *intermittent*, *transient* or *unsteady vortices*), on the other hand, are marked by an inconsistent structure and strength as well as the intermittent entrainment of air. As noted by Blaisdell (1958), the variation in vortex strength causes flow to be erratic and therefore, no reliable prediction of flow can be made in the presence of such vortices. Unstable vortices occur at intermediate submergence

conditions (below critical) and the degree of their unsteadiness tends to decrease as the submergence is reduced. Noguchi *et al.* (2003) also found that the position of the axis of this type of vortex fluctuates about the axis of the intake as shown in Figure 3.7; therefore unstable vortices are also spatially variable.

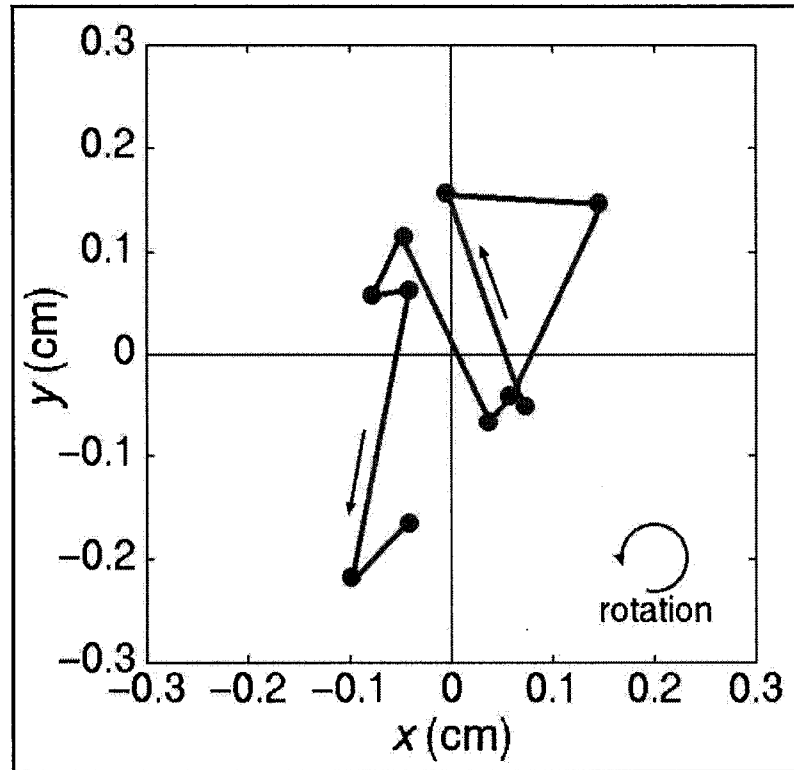


Figure 3.7: Movement of vortex axis (Noguchi *et al.*, 2003)

The intermittency of unstable vortices is generated by the variation of many flow parameters, such as turbulence intensity, approach flow distribution and local energy dissipation. These are inherent flow features defined by the interaction between the flow and the physical boundaries. In general, the intensity and stability of the flow circulation will increase if the area above the intake that is prone to circulation increases (Knauss, 1987).

The unsteadiness of the vortex formation process is also, in itself, a cause of flow instability. This is because air entrainment is intermittent; thus, the flow through the intake is subject to large fluctuations. If the reservoir is relatively small, this can create a variable water depth and, consequently, an unsteady amount of circulation in the flow. Systematically, air

entrained by surface vortices hinders the hydraulic efficiency of the intake causing the fluid to be stored inside the intake structure. The resulting increase in depth effectively reduces the circulation in the flow and thus, significantly weakens the vortex. Reducing circulation strength will eventually lead to the complete dissipation of the vortex structure. Once a vortex has been reduced in strength or has dissipated, it takes some time for the flow to 'reorganize' itself and generate enough circulation for the vortex to reform (Hecker 1987).

3.1.5.3 STRENGTH/INTENSITY

In practice, in order to avoid having to make poor approximations of parameters such as the mean vortex type or maximum vortex strength, it is desirable to measure and analyze the temporal variation of the vortex strength. However, difficulties occur in quantifying the strength of a vortex. This difficulty lies in the inability to accurately measure the flow parameters that are most intimately related to circulation strength, mainly the maximum tangential velocity and the radius of the air core, both of which occur in the central region of the vortex. Measurement of these parameters is problematic because unstable-vortex occurrence is both temporally and spatially variable, making the positioning of measuring instrumentation difficult. Additionally, to obtain accurate measurements, the measurement technique must be non-intrusive, as an object inserted into the flow may significantly alter its vortical characteristics.

To date, the solution to this problem has laid in one of two possibilities: (i) the measurement of some other quantity that is related either directly or indirectly to the vortex strength or, (ii) the use of a visual classification system.

With respect to the first option, quantities related to vortex strength could be the amount of air ingestion or the magnitude of swirl in downstream of the intake. The main arguments against this technique are that, (i) due to the complex nature of the flow, the correlation between the vortex strength and the chosen variable may be weak, ambiguous or vary with changes in other parameters (Hecker, 1987) or (ii) the chosen quantity also cannot be measured with sufficient accuracy.

The second option for the quantification of vortex strength is the use of a visual classification system. The obvious problems with this approach are (i) it is labor intensive, as someone is physically required to make constant visual observations, and (ii) it is a subjective technique. The benefits, however, that a consistent classification would have in alternative design evaluation and comparing intake performances were apparent and accordingly, a visual classification system was developed by the Alden Research Laboratory (ARL) at the Worcester Polytechnic Institute in New England, USA (Borghei, 2000). It defines six vortex types based on their visual appearance. The ARL classification system is illustrated in Figure 3.8. Application of this technique, however, is extremely difficult because, aside from a full air-core vortex, vortex types 1 through 5 occur only for brief instances and differentiating between them is problematic.

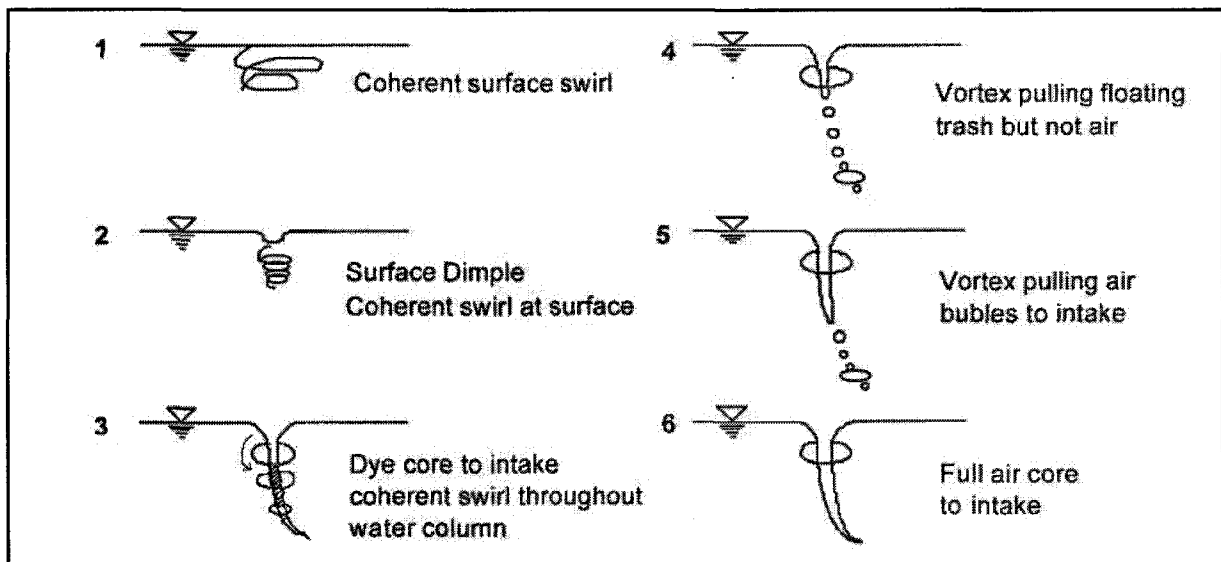


Figure 3.8: Visual classification system for vortex strength (Borghei, 2000)

In general, the strength and stability of a surface vortex is a function of circulation strength and will increase with a decrease in intake submergence or an increase in the area above the intake (Knauss, 1987). Altering these parameters can be troublesome after installation, thus a 'wait-and-see' approach to design and construction should be avoided. The strength of a subsurface vortex is dependent on the distance between the intake and the

boundary with which it has formed in such a way that the strength of the vortex will increase if this distance is reduced (Hecker, 1987).

3.1.6 AIR/SWIRL ENTRAINMENT

As previously discussed, the velocity associated with fluid rotation will cause a local reduction in pressure and possibly a depression in the free water surface. Whether this phenomenon results in the entrainment of air or not, as confirmed by Anwar (1966), depends on the maximum tangential velocity (a measure of circulation strength).

The entrainment of air and swirl caused by vortex formation can generate an array of hydraulic problems. The majority of which can be differentiated by three considerations, specifically, (i) decreased hydraulic performance of the intake itself, (ii) undesirable impact on the performance and operation of hydraulic machinery, and (iii) harmful air-water interaction effects in downstream closed channel systems. The following provides a summary of some of the important hydraulic problems associated with the entrainment of air by surface vortices (Knauss, 1987).

3.1.6.1 DISCHARGE CONSIDERATIONS

- The overall flow rate through the intake will be significantly decreased, either due to (i) a reduction in flow capacity caused by the presence of the additional volume of entrained air, or (ii) to modified operating conditions employed in order to reduce air and swirl intrusion.
- The suction associated with surface vortices may result in the ingestion of floating debris. The reoccurrence of which can lead to an increase in operational problems and required maintenance.
- Head losses imparted to the fluid by the intake are increased by the 'choking' effect of the vortex. This results in a significant decrease of the hydraulic efficiency.
- Swirl entrained downstream of the intake causes the water to spiral down the vertical shaft resulting in prolonged wall contact and increased head loss due to frictional dissipation.

3.1.6.2 HYDRAULIC MACHINERY CONSIDERATIONS

- Vortices can trigger vibration and cavitation both of which can cause damage/wear to hydraulic machinery (e.g. bearings, impeller blades, etc).
- The operational efficiency of hydraulic machinery may be significantly reduced as a result of either (i) decreased flow or (ii) having to operate of the machines under non-ideal conditions in order to reduce the probability of vortex formation.
- Undesirable operating conditions can arise from the development of *slug-flow*; a two-phase flow pattern characterized by long gas 'slugs', also known as 'Taylor' bubbles, that nearly fill the entire cross-section. The slugs are separated volumes of fluid that travel successively with the flow.
- Vortex induced fluctuations in flow and variations in pressure distribution create 'rough' operating conditions for hydraulic machinery. Operating machinery under such conditions can result in substantial fluctuation in efficiency and expedite mechanical wear.
- Finally, swirl intrusion can result in the 'off-design' or uneven loading of mechanical components (e.g. impeller blades), possibly adversely affecting the performance of a machine or accelerate its deterioration.

3.1.6.3 CLOSED CONDUIT CONSIDERATIONS

- The rapid escape of accumulated air in closed conduit systems can cause flow surging which, in turn, can result in structural damage (Jain and Kennedy, 1983).

Air entrainment is governed primarily by flow circulation which, in turn, is influenced by the intake submergence in such a way that, at large depths, air entrainment is small and vice versa. Acknowledging that in some instances the formation of surface vortices is unavoidable, the role of the design engineer is to minimize the operational problems generated by air and swirl entrainment.

3.1.7 INFLUENCE OF VISCOSITY AND SURFACE TENSION

3.1.7.1 VISCOSITY

Jain *et al.* (1978) used a chemical additive called 'cepol' to increase the kinematic viscosity of water by a factor of 16.5. Through this experiment, a significant decrease in critical submergence was observed in the more viscous fluid. This can be observed by Figure 3.9 and is indicative of a decrease in flow circulation.

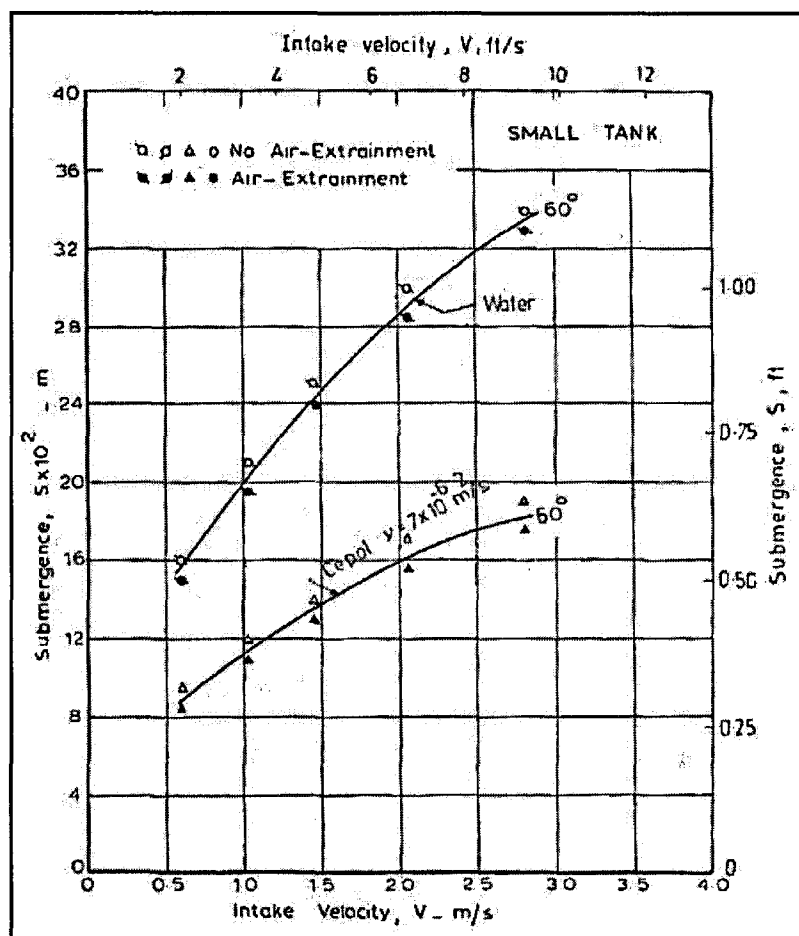


Figure 3.9: Effect of viscosity on critical submergence (Jain *et al.*, 1978)

Generally, in a fluid with a higher viscosity, particles are more tightly 'bound' together and internal shearing forces between particles are greater. Turbulence and subsequent internal shearing causes increased energy dissipation in more viscous fluids resulting in

decreased velocities and circulation. Therefore, for highly viscous fluids, a larger amount of circulation is required to produce an air-core vortex.

The influence that viscosity has on vortex flow can be described using the Reynolds number which relates the viscous forces to the inertial forces in a moving fluid (see Section 3.2.2). As the Reynolds number is increased, the effect that viscous forces have on the flow is decreased. Hence, above a certain Reynolds number, the influence of viscous forces can be ignored (Chang and Prosser, 1987). This is discussed further in Section 3.2.2.2.

3.1.7.2 SURFACE TENSION

In general, the effect of surface tension on the formation and behavior of vortices has been considered to be negligible relative to the influence the gravitational and viscous forces (Chang and Prosser, 1987). Surface tension effects are typically defined using the Weber number, which relates the surface tension forces to the inertial forces acting on a fluid (see Section 3.2.2). Past experimental investigations into the effect of surface tension have been carried out by Daggett *et al.* (1974) and Jain *et al.* (1978).

Daggett *et al.* (1974) used fluids that shared a common viscosity but had surface tension values which varied by a factor of 3 (0.024 N/m to 0.072 N/m). Through this investigation, it was determined that surface tension has a negligible effect on vortex strength. Jain *et al.* (1978) added isoamyl alcohol to water to lower its surface tension and found that the critical submergence of a vertical intake is independent of the surface tension within the range of Weber numbers tested. In their experiments, surface tension values ranged between 0.024 N/m and 0.072 N/m, and Weber numbers ranged between 11 and 184. This observation is illustrated in Figure 3.10. Therefore, considering these studies, it can be assumed that, within the above mentioned range, the effect of surface tension on the formation and behavior of vortices can, for practical purposes, be ignored.

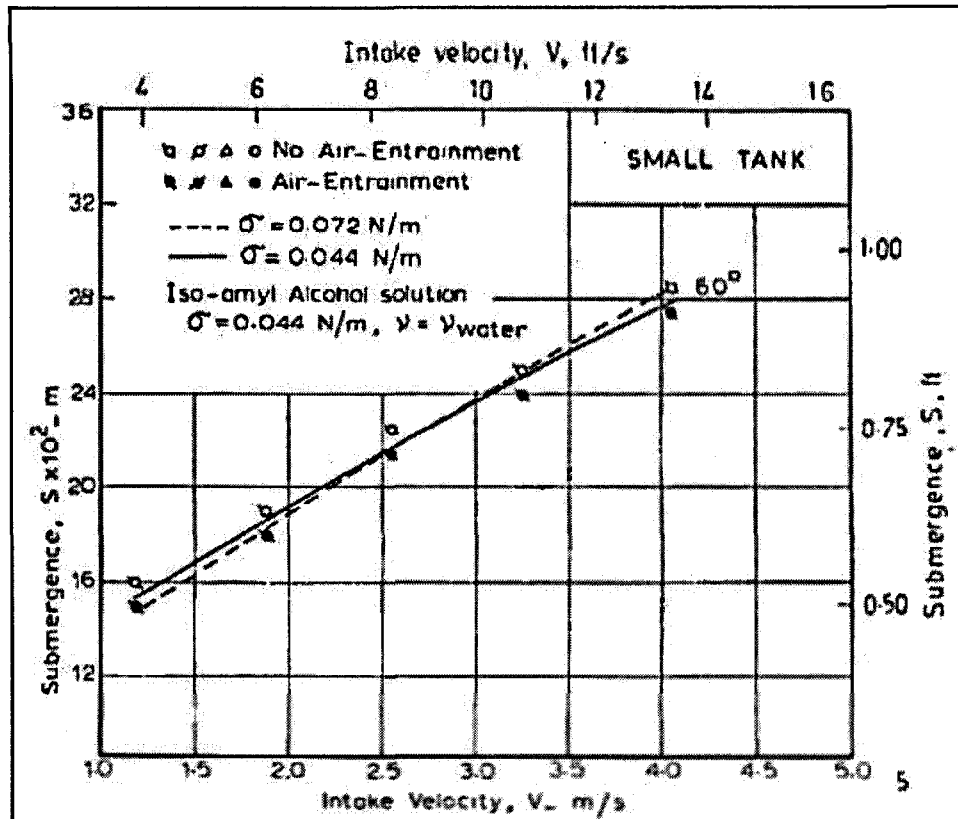


Figure 3.10: Effect of surface tension on critical submergence (Jain *et al.*, 1978)

3.1.8 VELOCITY

The distribution of velocity in an air core vortex has been the subject of many experimental studies (Anwar, 1965; Daggett and Keulegan, 1974; Hite *et al.*, 1991). It has also been the subject of much theoretical consideration (Odgaard, 1986; Hite *et al.*, 1994; Chen *et al.*, 2007). A proper theoretical description would require the full solution of the equations of motion (3.5-3.8).

A solution to the equations of motion of vortex flow however, is not easily obtained. This is partly due to the complexity of the equations and to their dependence on knowledge of the surrounding flow field. As such, vortex flow is typically described using simplified analytical models (Hecker, 1987). One of the simplest and most commonly used models was

developed in the mid-nineteenth century by William J. Rankine and is known as '*Rankine's combined vortex*'.

3.1.8.1 RANKINE'S COMBINED VORTEX

The Rankine vortex model (Figure 3.11) divides the flow into two regions and considers only tangential velocities. The flow regions include a viscous inner circular core assumed to be rotating as a solid body and an inviscid outer region extending radially from the inner core which is free from vorticity. These flows are known as '*forced*' vortex and '*free*' vortex flow, respectively and intersect at radius R .

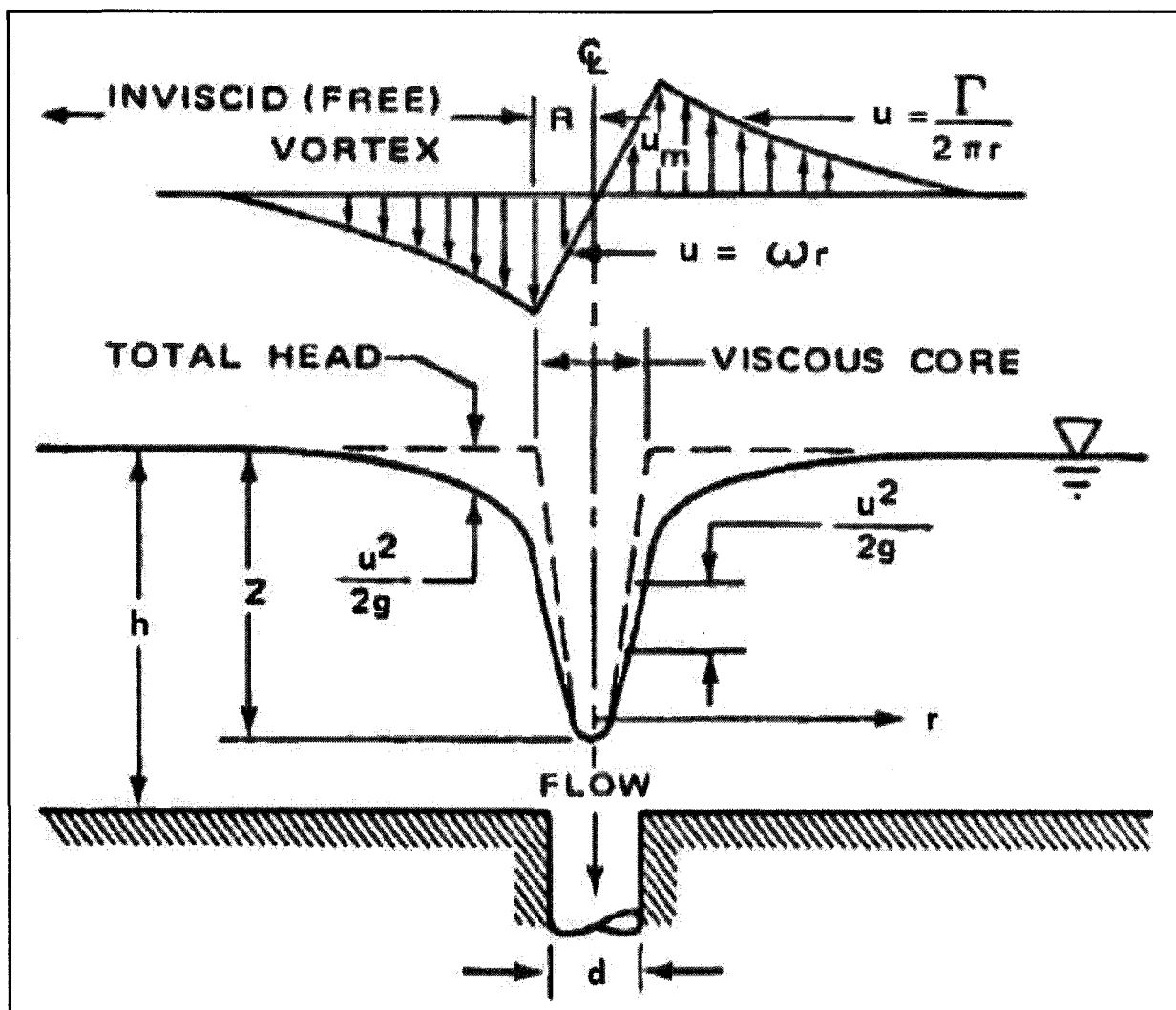


Figure 3.11: Rankine's combined vortex (Durgin and Hecker, 1978)

In the *forced vortex* region, the core is assumed to be rotating circularly as a solid-body with a tangential velocity that varies linearly with the radial coordinate.

For $r < R$:

$$u = \omega r = \frac{\Gamma r}{2\pi R^2} \quad [3.12]$$

where ω = angular velocity in radians per unit time. This flow has a vorticity of twice the angular velocity, 2ω .

In the *free vortex* region, the flow is assumed to be irrotational and the tangential velocity varies directly with the circulation and inversely with the radial coordinate.

For $r > R$:

$$u = \frac{\Gamma}{2\pi r} = \frac{\omega R^2}{r} \quad [3.13]$$

This equation is an exact solution of the two-dimensional, axisymmetric Navier-Stokes equations of vortex flow (Granger, 1966).

The radius, R , at which the two flow regions meet is proportional to the intake radius (Hecker, 1987). As the intensity of the vortex increases, the radius of this interface also increases, such that for a strong (air-core) vortex over a vertically downwards intake, the interface radius may be almost equal to the intake radius (Hecker, 1987). Vischer and Hager (1995) give a typical value of $R = \frac{3}{8}d$. It is at this interface where the maximum tangential velocity, u_{max} , is observed. This can be observed in Figure 3.12 which depicts the two-dimensional distribution of the tangential velocity vectors in a Rankine vortex. In this figure, the solid circle represents the interface between the forced and free vortex regions.

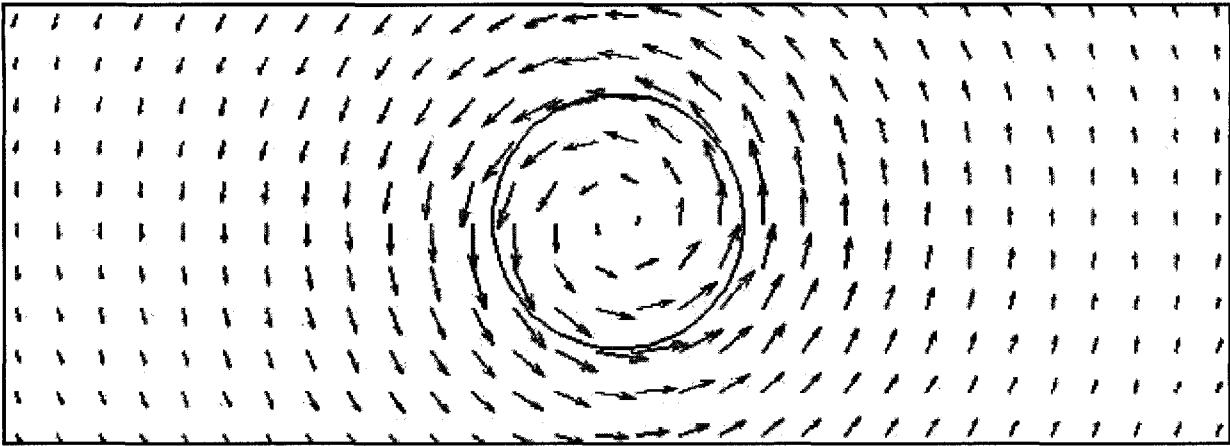


Figure 3.12: Tangential velocity vectors in a Rankine vortex (Harris and Durran, 2003)

Unfortunately, due to its simplicity, Rankine's vortex cannot be used to accurately predict the distribution of velocity and circulation in an actual three-dimensional air-core vortex. However, in more recent years, it has been used as a basis for more complex models developed to account for parameters not considered by Rankine (e.g. radial and axial velocities, etc.). These more advanced analytical models consider much of the previously identified experimental work. These works considered not only the distribution of tangential velocities but also that of the radial and axial velocities.

3.1.8.2 TANGENTIAL VELOCITY

Perhaps the most unique characteristic of vortex flow is its high tangential velocity near its axis of rotation. This velocity increases as the centre of the vortex is approached radially and results in a significant decrease in pressure. This has been observed in many experimental studies (Anwar, 1965; Daggett *et al.*, 1974) and is shown in Figure 3.13. In this figure, the maximum tangential velocity observed by Daggett *et al.* (1974) is plotted against the relative radius, r/r_0 , where r_0 = area of the intake. It should be noted, again, that these experimental studies were performed by imparting a controlled amount of circulation on the flow, thus the strength of the vortices generated in these studies was constant.

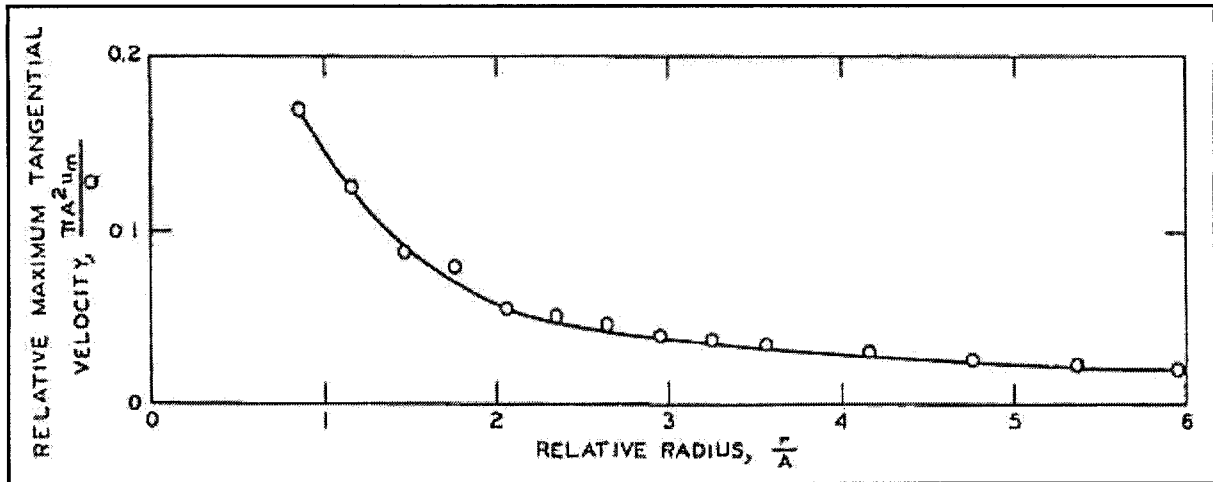


Figure 3.13: Variation of maximum tangential velocity with radial coordinate (Daggett *et al.*, 1974)

It has also been experimentally observed that the value of ur remains nearly constant for all radial coordinates (Daggett *et al.*, 1974). This finding, as shown in Figure 3.14, serves to validate equation 3.4 and the assumption of constant circulation.

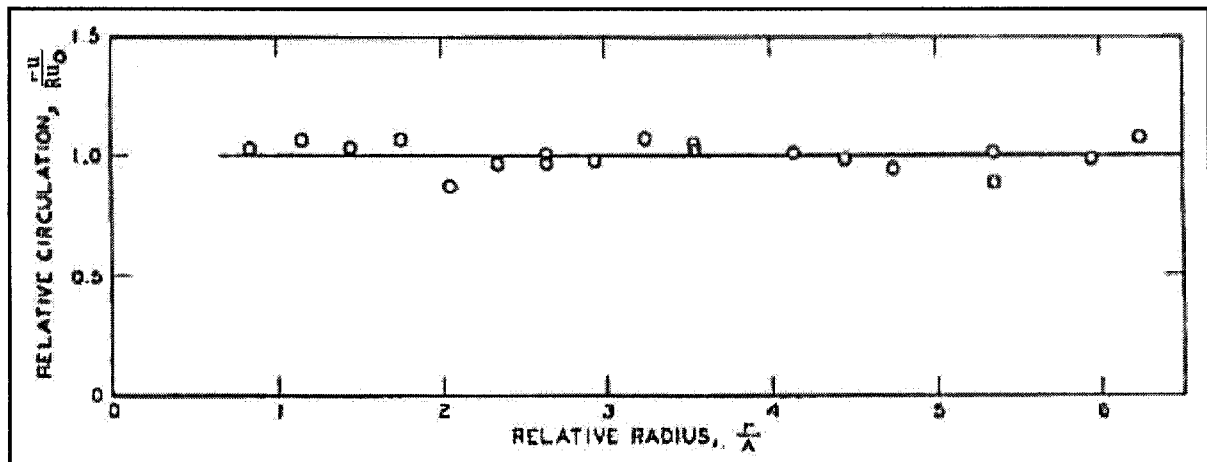


Figure 3.14: Variation of ru with radial coordinate (Daggett *et al.*, 1974)

The tangential velocity has also been found to vary, although slightly, with depth. As noted by Daggett *et al.* (1974), the tangential velocity remains nearly uniform throughout the flow depth except for a small region of boundary layer development near the bottom of the tank. This observation is illustrated by Figure 3.15.

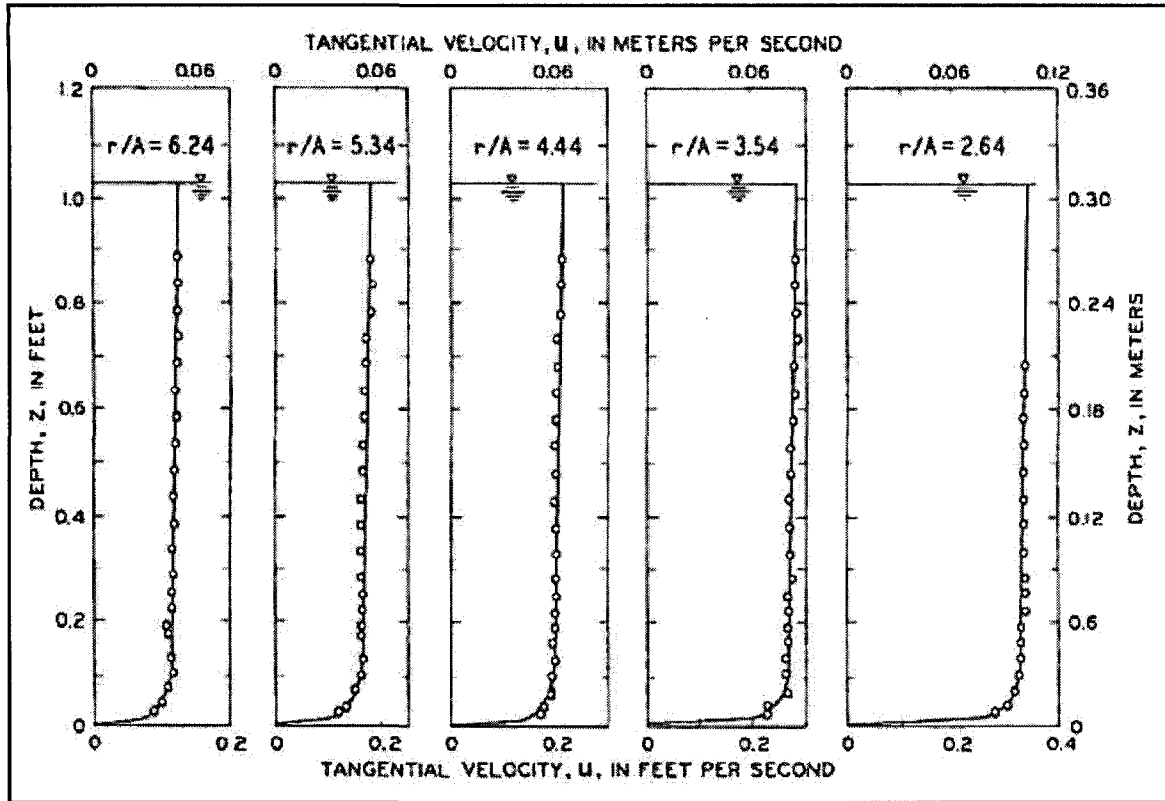


Figure 3.15: Variation of tangential velocity with depth (Daggett *et al.*, 1974)

To develop an analytical model that also considers both the radial and axial velocity components in addition to the tangential component, Odgaard (1986) derived a solution from Rankine's vortex model (equations 3.12-3.13) using the continuity equation (3.5) and the Navier-Stokes equations (3.6-3.8) and by superimposing a radial flow on the vortex flow. Based on observations that, near the air core of the vortex, the radial velocity is nearly linear (Anwar, 1965; Daggett *et al.*, 1974), he obtained for the tangential velocity component:

$$u = \frac{\Gamma}{2\pi r} \left[1 - \exp\left(-1.25 \frac{r^2}{R^2}\right) \right] \quad [3.14]$$

Although equation 3.14 was found to compare well with experimental data, its integration leads to a type of exponential integral that has no known closed-form solution (Hite *et al.* 1994). Hite *et al.* (1991) suggested the use of a more mathematically amenable empirical formula for prediction of the tangential velocities. This formula is expressed as:

$$u = \frac{\Gamma}{2\pi} \frac{2r}{R^2 + 2r^2} = \frac{\Gamma}{2\pi R} \frac{2\bar{r}}{1 + 2\bar{r}^2} \quad [3.15]$$

where $\bar{r} = r/R$ = dimensionless radius.

The equations obtained by Odgaard (1986) and Hite *et al.* (1991) however, both assume that the tangential and radial velocities u , and w , are independent of the axial coordinate, z . In other words, any change of the vortex flow field in the axial direction is not considered. This assumption has been proven, experimentally, to be incorrect (Daggett *et al.*, 1974). Therefore, the velocity components should not only be a function of the radial coordinate r , but also a function of the axial coordinate z (depth).

Accordingly, Chen *et al.* (2007), based on experimental results, extended the equations of Hite *et al.* (1991) to include variation in the axial direction. For the tangential velocity, their empirical equation is expressed in dimensionless form as:

$$u = \frac{\Gamma}{2\pi R} \frac{2\bar{r}}{1 + 2\bar{r}^2} (1 + ah\bar{z}) \quad [3.16]$$

where $\bar{z} = z/h$ = dimensionless depth and a = proportionality factor determined experimentally.

3.1.8.3 RADIAL VELOCITY

The radial velocity moves fluid particles towards the centre of the vortex. A steady vortex must have an inward radial velocity component in order to sustain its motion; otherwise the tangential velocity component will decay due to viscous dissipation. Without the inward radial component to the velocity, the fluid particles would continue to rotate

around the intake at a constant radius until all of its rotational energy is consumed by internal friction.

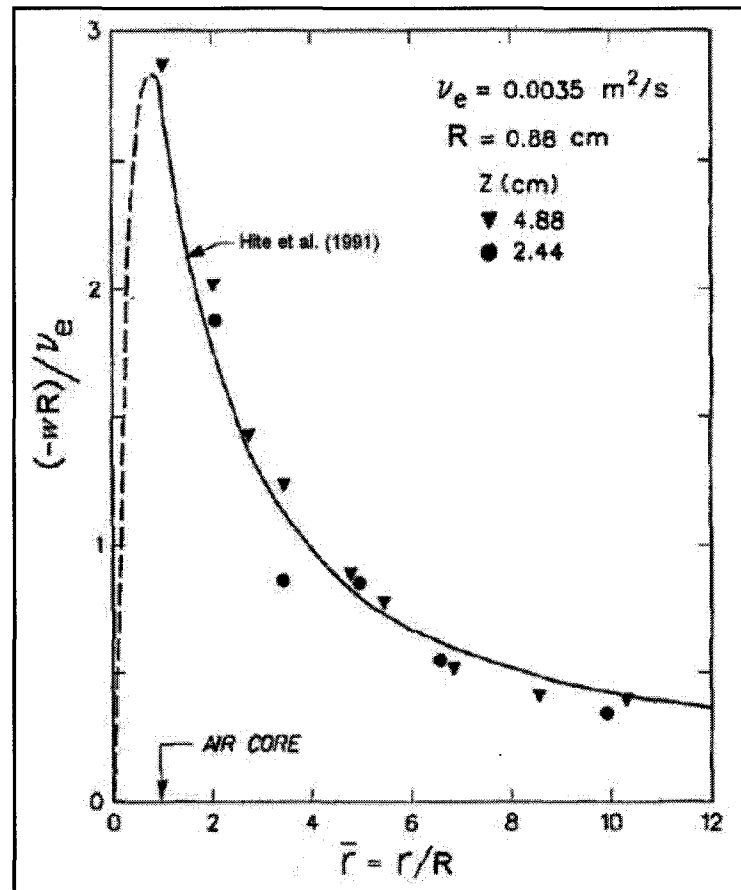


Figure 3.16: Variation of radial velocity with radial coordinate (Hite *et al.*, 1994)

As illustrated by Figure 3.16, experimental results (Hite *et al.*, 1994) have shown that, similar to the tangential velocity, the radial velocity component also increases as the axis of the vortex is approached radially.

Odgaard (1986) assumed that the radial velocity varies linearly with the radial coordinate near the center of the vortex and using a factor of proportionality, k_1 , and expressed the radial velocity as:

$$w \cong -k_1 r \quad (r < d/2; z \leq h) \quad [3.19]$$

Using their equation for tangential velocity (3.13), the radial component of the Navier-Stokes equation (3.8) and an order-of-magnitude analysis, Hite *et al.* (1991) expressed the radial velocity as:

$$w = -(\mu + \epsilon) \frac{8r}{R^2 + 2r^2} = -\frac{v_e}{R} \frac{8\bar{r}}{1 + 2\bar{r}^2} \quad [3.18]$$

where $v_e = \mu + \epsilon = \text{effective viscosity}$.

The radial velocity is frequently assumed to be uniform with depth in the previous theoretical developments (Odgaard, 1986; Hite *et al.* 1991). This assumption however is not entirely correct as confirmed by Anwar (1965) and Daggett *et al.* (1974). Through their analysis it was observed, as shown in Figure 3.17, that the radial velocity increases with the depth of flow and becomes quite large at the bottom of the tank near the centre of the vortex.

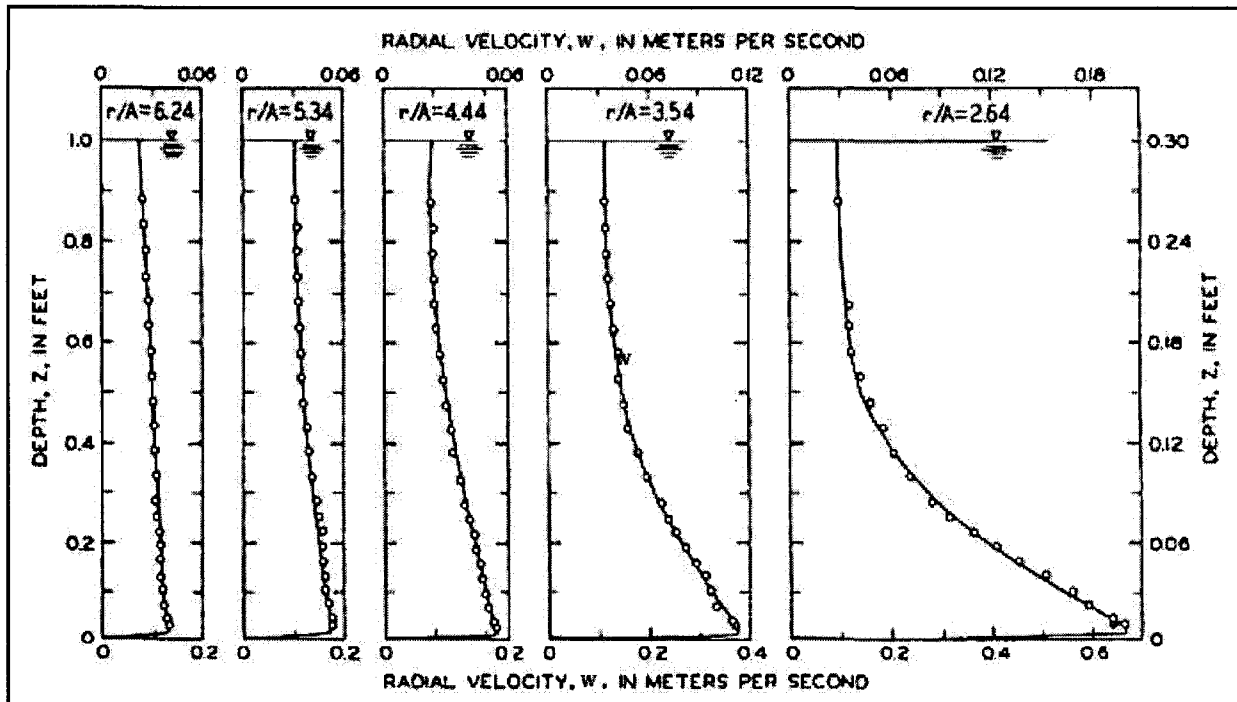


Figure 3.17: Variation of radial velocity with depth (Daggett *et al.*, 1974)

To consider the radial velocity variation in both the radial and axial directions, Chan *et al.* (2007) proposed the following equation:

$$w = -\frac{v_e}{R} \frac{8\bar{r}}{1+2\bar{r}^2} [1 + \ln(1 + ah\bar{z})] \quad [3.19]$$

By inspection of Figure 3.17, it can be seen that the radial velocity becomes significant near the bottom boundary of the intake. As noted by Anwar (1965) and Daggett *et al.* (1974), this velocity is indicative of a significant radial boundary layer flow. Therefore, as noted by Echavez and McCann (2002), the total outflow consists of both an axial component in the central area of the vortex that originates close to the free surface and a radial component that is confined to the bottom boundary layer. Echavez and McCann (2002) were able to separate these components experimentally by inserting a smaller 'bell-mouth' shaped pipe into the centre of the intake such that only the axial component passed through it. Through their experiments, Echavez and McCann (2002) found that the proportion of the total discharge associated with the bottom boundary flow varied between 15% and 70% and that this proportion increased with increasing vortex strength.

3.1.8.4 AXIAL VELOCITY

The radial velocity near the free surface turns into an axial velocity as it approaches the centre of the vortex (Hite *et al.* 1994). Therefore, as shown in Figure 3.18, significant axial velocity can only be observed near the axis of the vortex. The axial velocity has also been found to increase with depth (Hite *et al.* 1994).

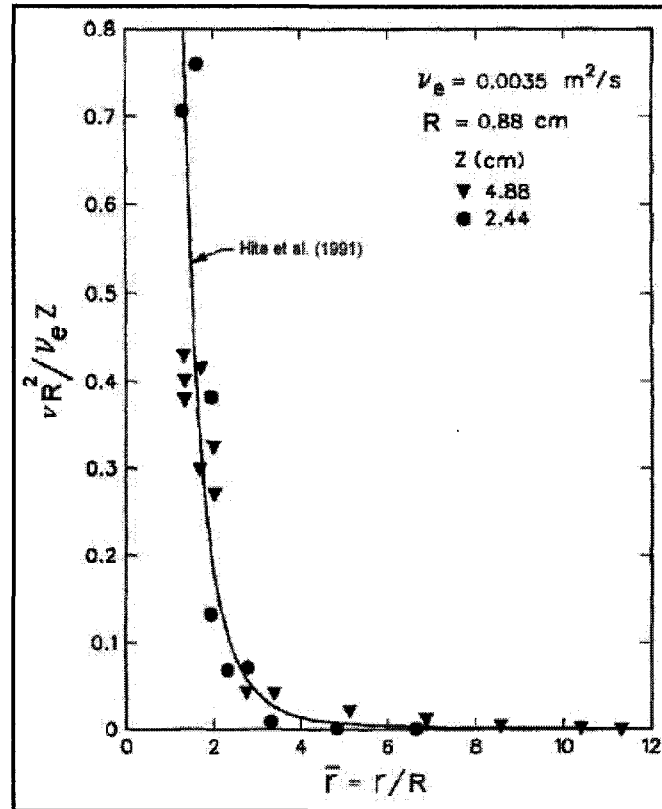


Figure 3.18: Variation of axial velocity with radial coordinate (Hite *et al.*, 1994)

Considering the link between the radial and axial velocities, Odgaard (1986) derived an equation for the axial velocity from the radial velocity equation (3.17) and the continuity equation (3.5) which is expressed as:

$$v = 2k_1 z \quad (r < d/2; z \leq h) \quad [3.20]$$

Also acknowledging the connection between radial and axial velocity as defined by the continuity equation (3.5), Hite *et al.* (1991) expressed the axial velocity as:

$$v = (\mu + \epsilon) z \frac{16R^2}{(R^2 + 2r^2)^2} = v_e \frac{z}{R^2} \frac{16}{(1 + 2\bar{r}^2)^2} \quad [3.21]$$

Tang (1999) applied a Particle Image Velocimetry (PIV) technique to measure the velocities in a vertical intake vortex (Chen *et al.*, 2007). Through this study, a 'multi-cycle' spiral flow (Figure 3.19) was observed in which fluid particles rotate several times around the axis of the vortex before entering the intake and the axial velocity increases as the fluid particles descend (Chen *et al.*, 2007).

The multi-cycle spiraling flow phenomenon was not considered in the theoretical models developed by Odgaard (1986) and Hite *et al.* (1991). Accordingly, the model developed by Chen *et al.* (2007) takes this observation into consideration and is able to reproduce the downward spiraling motion of the fluid particles. The axial velocity equation in this model is expressed as:

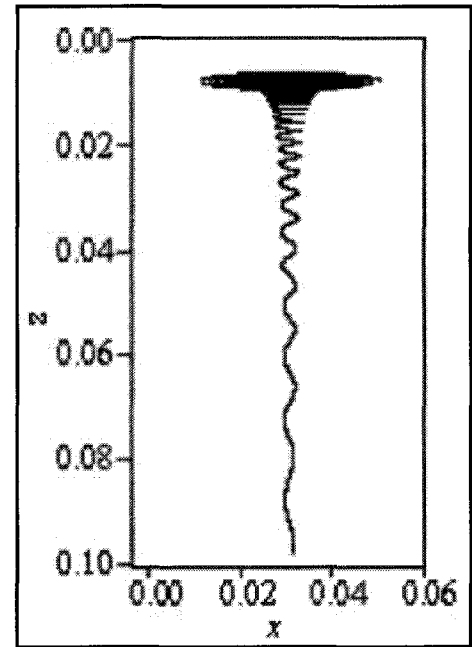


Figure 3.19: Multi-cycle spiral vortex flow (Chen *et al.*, 2007)

$$v = \frac{16v_e}{R^2(1+2\bar{r}^2)^2} \left[\frac{(1+ah\bar{z})}{a} \ln(1+ah\bar{z}) \right] \quad [3.22]$$

A summary of the equations presented in this section is provided in Table 3.1.

Table 3.1: Summary of velocity formulae for vertical vortex flow (Chen *et al.*, 2007)

	u	v	w
Rankine (1858) $r \leq R$	$\omega r = \frac{\Gamma r}{2\pi R^2}$	-	-
Rankine (1858) $r > R$	$\frac{\Gamma}{2\pi r} = \frac{\omega R^2}{r}$	-	-
Odgaard (1986)	$\frac{\Gamma}{2\pi r} \left[1 - \exp\left(-1.25 \frac{r^2}{R^2}\right) \right]$	$2k_1 z$	$-k_1 r$
Hite <i>et al.</i> (1991)	$\frac{\Gamma}{2\pi R} \frac{2\bar{r}}{1+2\bar{r}^2}$	$v_e \frac{z}{R^2} \frac{16}{(1+2\bar{r}^2)^2}$	$-\frac{v_e}{R} \frac{8\bar{r}}{1+2\bar{r}^2}$
Chen <i>et al.</i> (2007)	$\frac{\Gamma}{2\pi R} \frac{2\bar{r}}{1+2\bar{r}^2} (1+ah\bar{z})$	$\frac{16v_e}{R^2(1+2\bar{r}^2)^2} \left[\frac{(1+ah\bar{z})}{a} \ln(1+ah\bar{z}) \right]$	$-\frac{v_e}{R} \frac{8\bar{r}}{1+2\bar{r}^2} [1 + \ln(1+ah\bar{z})]$

3.2 SIMILITUDE

3.2.1 INTRODUCTION

As the problem of intake vortex formation cannot be solved with sufficient certainty using an analytical approach, alternative methods of solution must be considered. Thus, as noted by Vischer and Hager (1998), due to the complexity of the mechanics associated with vortex formation, physical modeling is recommended for any scenario in which the formation of vortices could lead to significant loss. This recommendation is frequently made in the relevant literature (Hecker, 1987; Gulliver *et al.*, 1986; Jain *et al.*, 1978). It is however, important to recognize that, similarity conditions for vortex flow are not well understood and therefore, physical models are also not free from inaccuracy. There have been instances where vortices have been formed in the model but not in the prototype and vice versa (Jain, 1981). These examples indicate that the particular similarity criterion used in the model did not properly account for or interpret the forces acting on the fluid.

According to Hecker (1987), as the use of hydraulic model studies to predict the occurrence and intensity vortices will continue, it is necessary to question the reliability of such models as predictors of prototype performance. If it is assumed that there are no errors in model geometry, construction or operation, this question primarily concerns the possible scaling effects associated with the modeling of the vortex and swirling flow phenomena. In some instances, such as the design of an intake for the cooling system of a nuclear reactor, a critical analysis of potential scale effects must be made if a hydraulic model study is being used to predict prototype performance (Durgin and Hecker, 1978). Such an analysis, however, is not straightforward. In this section, the theoretical foundation of hydraulic modeling and the problems associated with modeling vortex flows (e.g. scale effects) are introduced and discussed.

3.2.2 DIMENSIONLESS PARAMETERS

Hydraulic modeling is theoretically founded on the principle that all the forces acting on a fluid can be represented using a number of dimensionless parameters and that equality of these parameters between model and prototype scale will produce a similar flow condition. The typical dimensionless numbers are: the *Froude number*, Fr , the *Reynolds number*, Re , and the *Weber number*, We , which account for gravitational, viscous and surface tension forces, respectively. For vortex flow, an additional dimensionless number, the *circulation number*, N_Γ , is often used to describe the influence of circulation on the flow (Knauss, 1987). These dimensionless parameters are defined as:

FROUDE NUMBER

The Froude number, Fr , is defined as the ratio between the inertial and gravitational forces acting on the flow and is defined as:

$$Fr = \frac{V}{\sqrt{gd}} \quad (\text{intake Froude number}) \quad [3.23]$$

where d = intake diameter, V = cross-sectionally averaged velocity through the intake and g = gravitational acceleration.

REYNOLDS NUMBER

The Reynolds number provides a relation between the inertial and viscous forces. It appears in the literature in two forms, as an *intake Reynolds number*, Re , (Jain *et al.*, 1978) and as a *radial Reynolds number*, Rr , (Anwar and Amphlett, 1980), defined as:

$$Re = \frac{vd}{\mu} \quad (\text{intake Reynolds number}) \quad [3.24]$$

$$Rr = \frac{4}{\pi} \frac{1}{h/d} Re = \frac{Q}{\mu h} \quad (\text{radial Reynolds number}) \quad [3.25]$$

where μ = kinematic viscosity.

WEBER NUMBER

The Weber number relates the inertial forces to the surface tension forces acting on a fluid element. It is defined as:

$$We = V \sqrt{\frac{\rho d}{T}} \quad (\text{intake Weber number}) \quad [3.26]$$

where ρ = density and T = surface tension.

CIRCULATION NUMBER

The circulation number is used to describe the influence of circulation on the flow. It relates the circulation to the inertial forces (Knauss, 1987).

$$N_{\Gamma} = \frac{c}{va} \quad (\text{circulation number}) \quad [3.27]$$

Through several experimental studies (Jain *et al.*, 1978; Daggett and Keulegan, 1974; Anwar *et al.*, 1978; Anwar and Amphlett, 1980) it has been roughly determined that the critical submergence depth is primarily dependent on the intake Froude number and the circulation. Thus, to further simplify matters, according to Jain *et al.* (1978), these parameters can be combined to produce another parameter known as the swirl number, N_S . The swirl number is defined as

$$N_S = N_{\Gamma} Fr = \frac{c}{\sqrt{g} d^{\frac{3}{2}}} \quad (\text{swirl number}) \quad [3.28]$$

3.2.2.1 INFLUENCE OF FROUDE NUMBER

Practically all studies to date, with the exception of Haindl (1959), indicate that prediction of the critical submergence through model studies should be performed according to Froude-scaling (Ranga Raju and Garde, 1987). Therefore, most models are first scaled to this parameter.

In a Froude-scaled model, the inertial and gravitational forces are similarly reduced such that the Froude number is unchanged. Unfortunately however, at the same time, viscous and surface tension forces cannot be adequately reduced, thus simultaneous equality of all parameters is not possible. The extra influence that the viscous and surface tension forces have on the modeling of vortices is called a *scale effect* (Hecker, 1981). Despite many past attempts to quantify the magnitude or account for these scale effects in vortex flow, (Daggett *et al.*, 1974; Anwar *et al.*, 1978; Jain *et al.*, 1978; Anwar and Amphlett, 1980; Jain, 1981) there still remains some controversy over how to properly deal with this unavoidable problem.

In some circumstances, it is believed that Froude-equality alone is sufficient to ensure dynamic similarity. However, as noted by Dhillon *et al.*, (1981), this is only true in the case of the initial formation of a surface depression. In the case of an air-entraining vortex, local velocity gradients can produce significant viscous shear forces and the influence of the Reynolds number may become important.

3.2.2.2 INFLUENCE OF REYNOLDS NUMBER

There are conflicting opinions on the influence that the Reynolds number has on the formation of air entraining vortices. Haindl (1959) found that the formation of a free surface vortex is primarily a function the Reynolds number. Although he argues that Reynolds equality is essential for similitude in vortex formation, most subsequent investigators found that Froude dependence is dominant and Reynolds equality is of a secondary concern (Zielinski and Villemonte, 1968; Daggett *et al.*, 1974; Anwar *et al.*, 1978; Jain *et al.*, 1978; Anwar and Amphlett, 1980; Jain, 1981).

The influence of viscosity may also be dependent on the manner in which the circulation in the flow is produced. As discussed in Section 3.1.3, the primary sources of vorticity are eccentricity in the approaching flow, velocity gradients at boundaries and rotational wakes behind obstructions. The latter two sources are influenced by viscosity and, therefore, may be more Reynolds number dependent than the first source (Durgin and Hecker, 1978).

Daggett *et al.* (1974) showed that the discharge through an intake is influenced by viscous effects when $Re > 2.5 \times 10^4$ and that beyond this value, viscous effects are unimportant. The concept of a limiting Reynolds number beyond which viscous influence on vortex formation is negligible has also been endorsed by Anwar (1978) and Anwar and Amphlett (1980) and also by Jain *et al.* (1978), who argued that the limiting Reynolds number is Froude number dependent.

3.2.2.3 INFLUENCE OF WEBER NUMBER

The influence of surface tension on vortex formation is not well understood and in previous studies, for the most part, has been neglected. There is also an inherent difficulty in evaluating the influence of the Weber number alone. Hecker (1981) pointed out that isolation of the effect of the Weber number would require the plotting of a vortex-related parameter against the Weber number for constant values of circulation and Reynolds number. However, due to the interrelationship between the Weber and Reynolds number, such a plot would be difficult to generate.

As discussed in Section 3.1.7.2, Jain *et al.* (1978) performed experiments with liquids of different surface tensions and determined that vortex formation is independent of Weber number as long as $We > 11.0$. Additionally, Daggett *et al.* (1974) found that surface tension does not influence vortex intensity. Thus, if a model is sufficiently large, it can be safely inferred that surface tension does not significantly influence vortex flow and its consideration can, therefore, be omitted in the modeling process (Dhillon, 1981).

3.2.2.4 INFLUENCE OF CIRCULATION

As circulation is primarily dependent on the geometry surrounding the intake and the approach flow conditions, similarity of circulation can only be achieved through geometric similarity (Jain *et al.*, 1978) and thus is typically not used as a significant modeling parameter.

In summary, it appears that the formation and intensity of intake vortices is predominately a function of the surrounding geometry and Froude number and secondarily of the Reynolds number (Durgin and Hecker, 1978). Ranga Raju and Garde (1987) emphasized that this secondary influence of the Reynolds number is not well understood and the disparity between various modeling techniques is a result of differences in the interpretation of the importance of the Reynolds number relative to that of the Froude number.

3.2.3 MODELING CRITERIA

It is apparent that vortex formation is dependent both on the Froude and Reynolds numbers. However, this dependence is not well defined, and because constancy of both Froude and Reynolds numbers cannot be attained simultaneously in hydraulic modeling, appropriate modeling criteria should be followed in order to minimize scale effects created by this inherent problem. In this section, some notable attempts by past investigators to develop such criterion are examined.

3.2.3.1 REYNOLDS SCALING

Although, for the most part, it is believed that Reynolds number has only a secondary influence on vortex formation, Haindl (1959) found that the formation of vortices in a slowly draining reservoir is primarily dependent on the Reynolds number. Therefore, Haindl argues that geometrical similarity and Reynolds constancy are required to ensure correct model-prototype similarity. However, numerous subsequent studies have shown that Froude similarity is in the dominant criteria (Anwar, 1968; Durgin and Hecker, 1978; Jain *et al.*, 1978; Anwar and Amphlett, 1980).

3.2.3.2 ANWAR'S CRITERION

Anwar (1968) and Anwar and Amphlett (1980) showed that for $Rr > 3 \times 10^4$ viscous forces do not influence vortex formation and that, if this condition is met, vortex behavior is dependent only on circulation and the Froude number. Anwar (1968) suggests that a geometrically similar model, based on Froude constancy with a sufficiently high Reynolds number, will adequately reproduce prototype circulation and vortex behavior if its scale is not less than 1:20. The limiting radial Reynolds number prescribed by Anwar was confirmed by Padmanabhan and Hecker (1984), and a similar criterion was advocated by Prossor (1977) who recommends that $Rr > 2 \times 10^4$ and that the minimum scale should be between 1:10 and 1:30.

Padmanabhan and Hecker (1984) found that no significant scale effects occurred in 1:2 and 1:4 models operated under Froude similarity, thus confirming that intake vortices can be adequately modeled by Froude-scaling at scales larger than that prescribed by Anwar (1968).

3.2.3.3 JAIN *ET AL.* CRITERION

Jain *et al.* (1978) found that the limiting Reynolds number at which viscous forces no longer influence the critical submergence is dependent on the Froude number and that Froude number similarity can be used at any scale to simulate prototype performance if an appropriate correction factor is used to adjust the results. This correction factor is defined in Jain *et al.* (1978) and has a value of unity when the value of the Reynolds numbers is high in comparison to the Froude number, or when

$$\frac{g^{1/2}d^{3/2}}{\mu} > 5 \times 10^4 \quad [3.29]$$

Therefore, according to Jain *et al.* (1978), a Froude-scaled model will reproduce prototype conditions with acceptable accuracy provided that the intake diameter is of sufficient size to ensure a high enough Reynolds number such that viscous forces can be neglected. For water at 20° C, the kinematic viscosity is approximately $\mu = 1.004 \times 10^{-6} \text{ m}^2/\text{s}$, and the minimum intake diameter, according to equation 3.29, is roughly 6.3 cm.

The use of a minimum intake diameter was also suggested by McCorquodale (1968) who, based on his experimental results, states that significant scale effects can be expected in models with diameters equal to or less than 5.1 cm.

By the Jain *et al.* (1978) criterion, if the diameter of the intake is less than the value dictated by equation 3.29, viscous forces are significant enough to produce scale effects in the model and the resulting critical submergence prediction should be increased by a correction factor. This approach however has been questioned by some investigators (Amphlett, 1979; Hebaus, 1979; Blaisdell, 1979; Hecker, 1981). The main argument against this approach, as described by Amphlett (1979), concerns the validity of the viscosity parameter, $g^{1/2}d^{3/2}/\mu$, which is derived through dimensional analysis by combining the Reynolds and Froude numbers. This parameter is thus, a ratio of gravitational to viscous forces and has no inertial term. It is therefore questionable whether such a term can be used to describe the viscous influence on a predominately inertial flow. Furthermore, Hecker (1981) added that other studies have shown that, if a correction factor is used, it would be a function of the particular geometrical properties of the intake and the mechanisms through which the circulation is generated.

3.2.3.4 EQUAL-VELOCITY CRITERION

Some investigators have suggested the use of larger intake velocities than those required by Froude scaling. Based on their experimental results, Denny and Young (1957) suggested that prototype performance can be adequately simulated under similar submergence conditions if equal model-prototype velocities are used. However, a larger than Froudean intake velocity is likely to exaggerate vortex formation through amplification of the axial stretching mechanism and thus, subsequent investigators have found that this approach leads to a conservative design (Dhillon *et al.*, 1981; Ranga Raju and Garde, 1987). Additionally, as noted by Hecker (1981), for some scale ratios, the use of the equal model-prototype velocity approach can seriously undermine the primary Froude-scaling criterion and thus, the approach flow conditions and resulting circulation will not be properly reproduced.

3.2.3.5 VALIDITY OF MODELING CRITERIA

In review of the available literature, it is apparent that an adequate model design is dependent mostly on Froude number equivalence. Therefore, modeling by Reynolds similarity, as suggested by Haindl (1959), cannot be justified. Therefore, the model designer must decide on which of the remaining criteria to base their design. The equal-velocity criterion as well as Anwar's (1968) and the Jain *et al.* (1978) criteria are similar in that they all acknowledge the Froude number to be the dominate parameter but also that the flow is not completely independent of the Reynolds number. The dissimilarities between the aforementioned criteria are a result of the different investigators interpretations of the secondary influence of the Reynolds number. As this secondary influence remains poorly defined, it becomes difficult to determine which criterion is most appropriate.

In an attempt to solve this problem, a study was performed by Dhillon *et al.* (1981) to evaluate the validity of the established modeling criteria. In this study, different models were constructed of a prototype intake which had already been constructed and whose performance characteristics were well known. The models were built in accordance with the three criteria identified above. Dhillon *et al.* (1981) found that the equal-velocity criterion produced strong model vortices contrary to the behavior of the prototype. Thus, confirming the idea that the equal-velocity criterion yields a conservative result. On the other hand, the criterion prescribed by Jain *et al.* (1978) was found to give non-conservative results, such that vortices observed in the prototype were not observed in the model. Lastly, the performance of the model constructed using Anwar's (1968) criterion was found to compare well with the performance of the prototype. Therefore, in light of this study, it appears that correct similitude will be most adequately produced if the criterion presented by Anwar (1968) is followed. Hence, to avoid the influence of viscous forces, modeling should be carried out using Froude-scaling such that a high radial Reynolds number ($Rr > 3 \times 10^4$) is maintained.

3.2.4 DISCUSSION

Hydraulic modeling is not an exact science. For some factors, such as boundary roughness, scaling rules and modeling criteria have not been well defined and are generally not well understood. Also, with respect to flows that involve the entrainment of air, additional difficulties are introduced by the non-scalability of the 'bubble-rise' velocity (Jain and Kennedy, 1983). In vortex flow, rotational energy is dissipated by boundary roughness and air is entrained by the vortex core. Therefore, it is conceivable that inaccuracy could be introduced by the inability to correctly account for the influence of such factors. Although nothing can be done to improve the scalability of the air-water interaction, particular attention should be paid to the boundary roughness used in the model. If too rough a surface is used, excessive circulation may be dissipated and therefore, flow conditions may not be properly reproduced.

Furthermore, some investigators have argued that inaccuracy may arise in a model because the relative effect of vorticity generated in the boundary layer compared to the other sources of vorticity is generally not considered and may not be properly reproduced by the model (McCorquodale 1968; Hecker, 1981; Chang, 1982). Considering this argument and the radial boundary layer flow component of the total outflow (see Section 3.1.8.3), it becomes apparent that boundary roughness should be considered as a significant parameter in model design. Through an evaluation of 22 model-prototype comparisons, Hecker (1981) recommends that considerable attention should be given to the scaling of the approach topography and boundary roughness in order to ensure that the flux of vorticity approaching the intake is properly modeled.

In summary, in view of the prior discussion, it can be stated that surface tension, for the most part, does not affect vortex behavior and thus can be considered negligible if $We > 11.0$. The formation of intake vortices is considered to be primarily governed by the Froude number and secondarily by the Reynolds number, but the significance of each parameter relative to the other is not well defined. To compensate for this ambiguity, Dhillon

et al. (1981) showed that the use of Anwar's (1968) criterion (Section 3.2.3.2) produced the most favourable results.

Regardless of the aforementioned difficulties, due to the complexity of the vortex flow structure and the inability to develop an adequate analytical solution, hydraulic modeling is considered to be the most effective method of design validation (Hecker, 1987; Gulliver *et al.*, 1986; Jain *et al.*, 1978) because the formation of strong air-core vortices can, for the most part, be completely eliminated. The occasional formation of weaker air-core vortices however cannot be completely eliminated with great certainty because accurate prediction of the critical submergence through hydraulic modeling remains problematic due to the previously identified scaling difficulties.

PART II – EXPERIMENTAL STUDY

4. EXPERIMENTAL STUDY

4.1 EXPERIMENTAL SETUP

4.1.1 APPARATUS

In order to investigate the efficiency of drop structures, an experimental study was considered in the current work. A drop structure model (Figure 2.5 and Figure 4.1-Figure 4.4) was constructed of ½ inch (0.0127 m) Plexiglas sheets and installed in the Hydraulics Laboratory at the Department of Civil Engineering, University of Ottawa. The intake structure includes a rectangular basin above the intake with a vertical depth of 0.762 m, a longitudinal depth of 0.915 m and a width of 0.610 m. The inflow is supplied by a pump with a maximum capacity of 0.3 m³/s and delivered to the structure through a 0.305 m (inside diameter) horizontal steel pipe. Twenty-three (23) piezometers distributed across the floor of the structure were installed in order to measure the level of the water above the intake. The piezometers were used for calibration purposes (see Section 4.5.2) and readings were only taken under steady state conditions, therefore, their response time was not considered to be significant. Detailed structural CAD drawings of the experimental apparatus are provided in Appendix A of this report

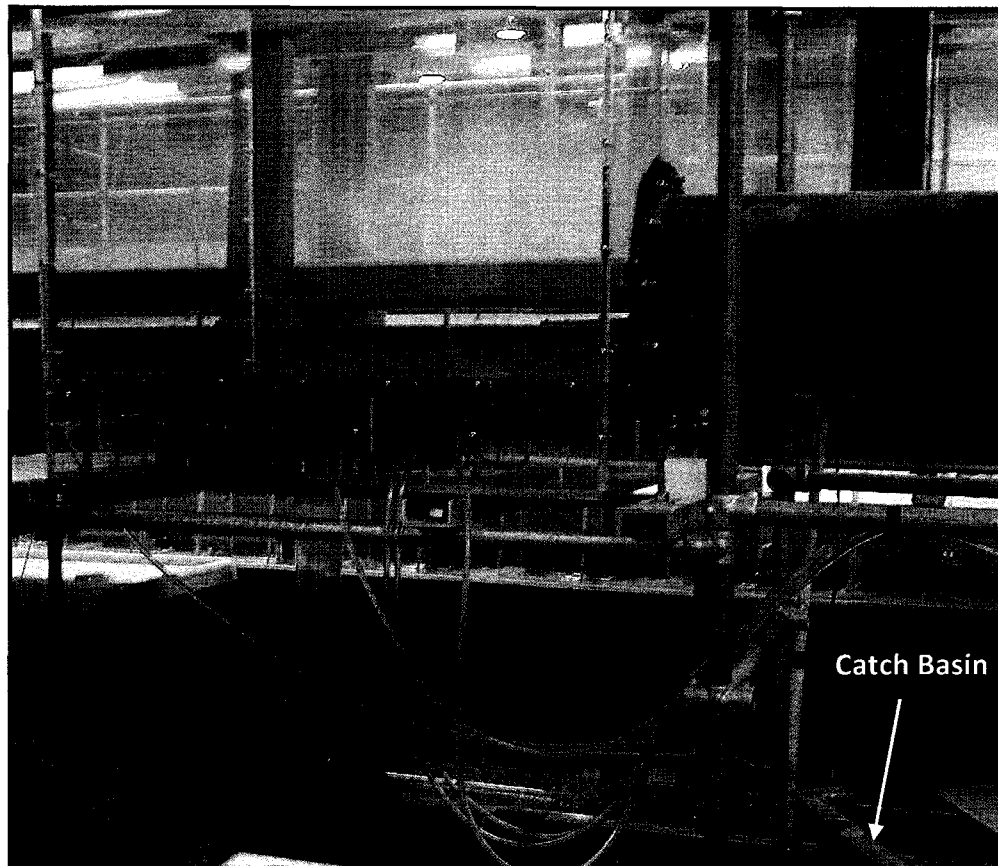


Figure 4.1: Experimental apparatus

A $0.356 \text{ m} \times 0.356 \text{ m}$ recess, 0.152 m deep and centered along the axis of the intake was cut into the floor of the structure. This was done to facilitate the testing of various different intake entrance shapes. In total, the performance of nine (9) geometrically-different intake shapes was investigated (Section 4.2). A plan view of the experimental setup is provided in Figure 4.2.

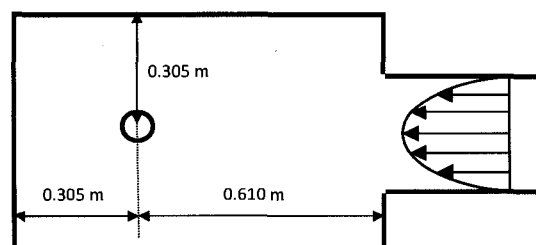


Figure 4.2: Plan view of experimental setup

Inside the structure, the flow experiences a 90° change in direction as it enters the vertical shaft through the intake ($d = 0.0762$ m). The vertical shaft, made of $1/8$ inch (0.003 m) thick Plexiglas, has a constant diameter of 0.0762 m. The total length of the vertical pipe section is 0.584 m, after which the water flows through a short-radius ($\frac{r_b}{d} = 1$), 90° PVC elbow and further through a 1.372 m section of horizontal pipe (with the same diameter as the vertical shaft) before discharging into a catch basin (Figure 4.4) where the flow is measured using a fully contracted 90° V-notch sharp-crested weir (Section 4.5.3).

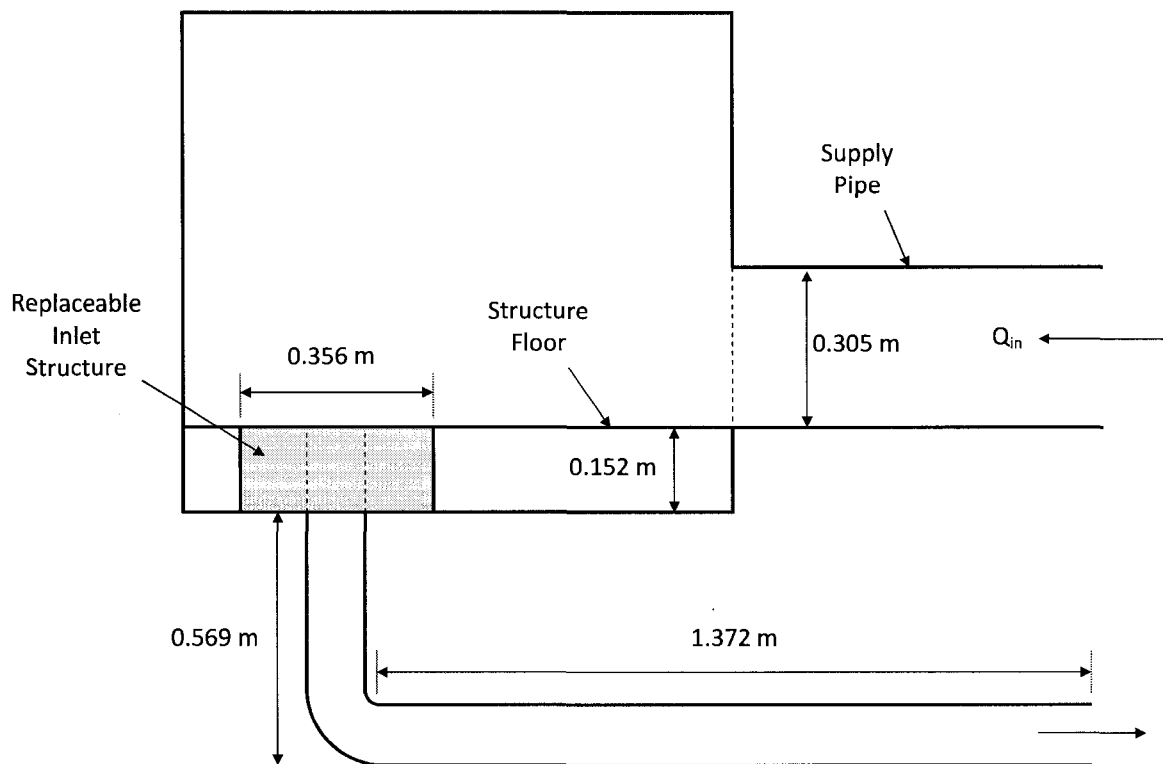


Figure 4.3: Longitudinal cross-section of experimental setup

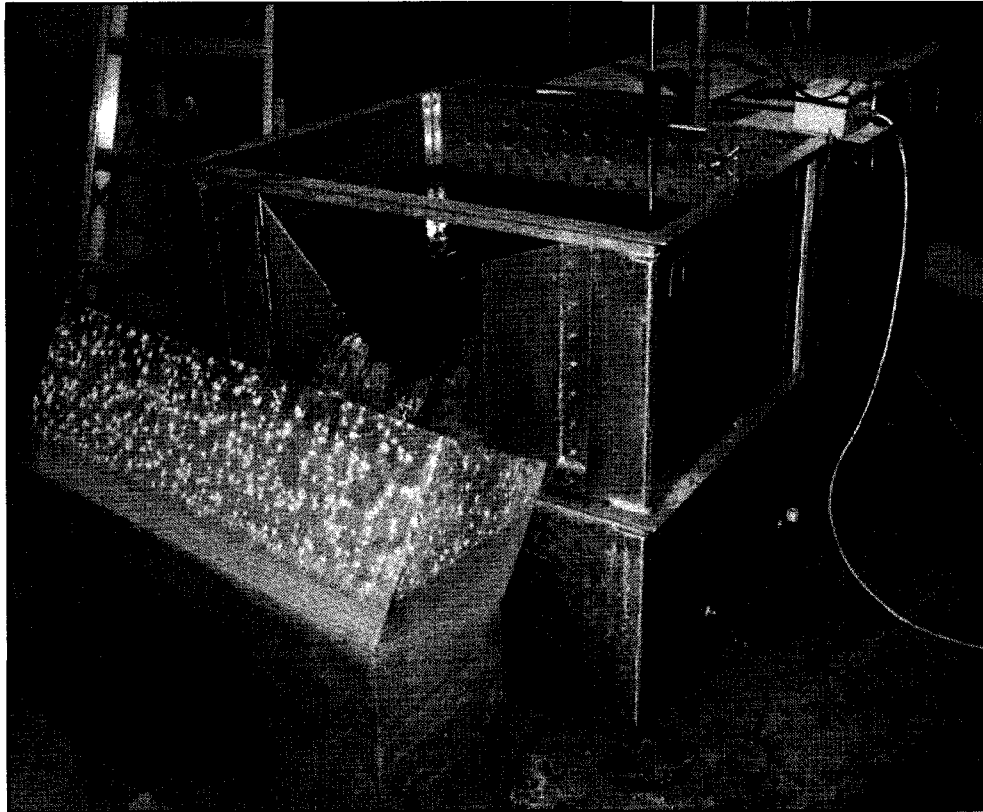


Figure 4.4: Catch basin and V-notch weir

In order to understand the operation of the experimental setup, it is necessary to also briefly describe the characteristics and operation of the experimental system as a whole. Once the pump has been started, a supply valve must be opened to allow the inflow to enter the experimental system. This flow however, does not travel directly to the structure, but first into a primary storage tank that is connected to the structure by the 0.305 m horizontal supply conduit. Unfortunately, this 'two-tank' system produced some unwelcome oscillations during the testing phase when unsteady flows were encountered; these oscillations are explained further in Section 5.2.2.

With respect to the hydraulic modeling of the vortex formation process, the diameter of the intake (0.0762 m) is greater than the minimum diameter (0.063 m) prescribed by the Jain *et al.* (1978) criterion and in the range of flow where vortex formation occurs, the average radial Reynolds number Rr is approximately 3.3×10^4 , thus satisfying Anwar's (1968) criterion of $Rr > 3 \times 10^4$. In this range of flow, the average Weber number We is roughly 77.5 which is much larger than the minimum of 11.0 suggested by Jain *et al.* (1978). Therefore, as per the discussion in Section 3.2.3, the vortex formation process should be properly reproduced in the experimental study and the subsequent results should be applicable to geometrically similar, Froude-scaled prototype structures.

4.2 INTAKE SHAPES TESTED

A range of similar tests were performed on nine geometrically-different intake entrance shapes to investigate the role that shape plays on intake performance. The shapes that were studied included: (i) an 'abrupt-entry' which, as the worst performing entrance geometry from a hydraulic efficiency viewpoint, became the 'reference' or 'base' case for subsequent comparison studies, (ii) three separate 'cone-type' entries with flare angles of 30° , 45° and 60° (to the vertical), (iii) a 'quarter-round' entry ($r = 0.0762$ m), (iv) a symmetrical 45° 'inverted-pyramid' entry, (v) an asymmetrical 'inverted-pyramid' that included both 45° and 60° flare angles, and (vi) two different 'ogee-type' profile entries. The intake shapes were constructed so as to be dimensionally similar, essentially a 0.356 m x 0.356 m x 0.152 m block with initially, a straight 0.0762 m hole at its centre. Each intake was then individually machined to provide the desired shape. An example of one of the intakes used in the experimental program is shown in Figure 4.5.

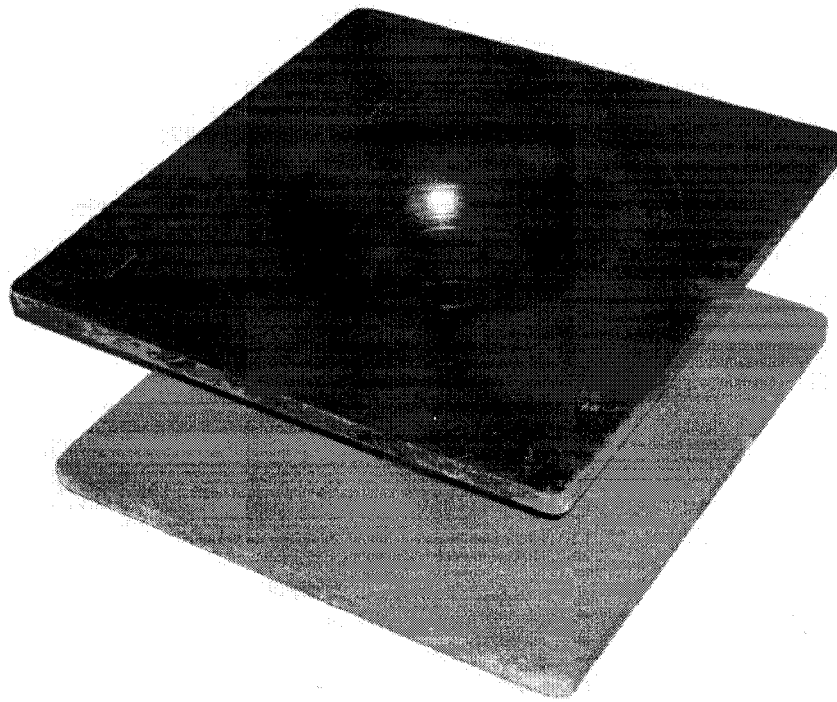


Figure 4.5: Example of intake used in experimental study (Ogee 1 profile)

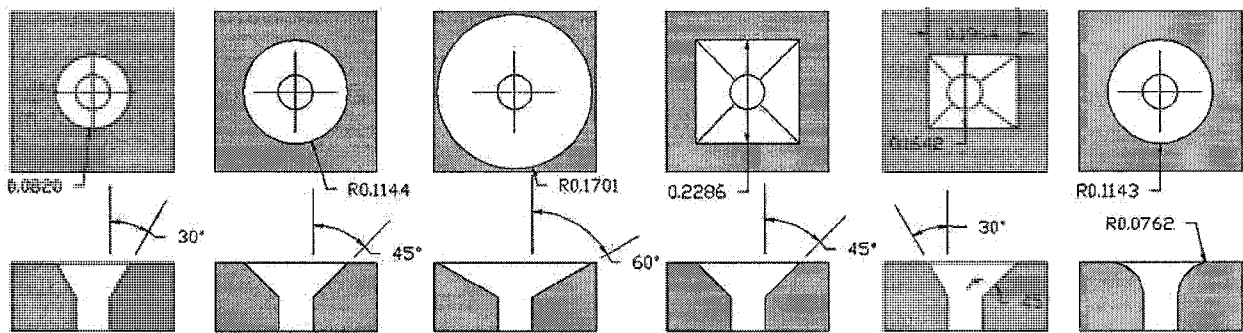


Figure 4.6: Intake shapes tested (From left to right: i) 30° cone-type, ii) 45° cone-type, iii) 60° cone-type, iv) symmetrical 45° 'inverted-pyramid', v) asymmetrical 'inverted-pyramid', vi) 'quarter-round' ($r = 0.076$ m))

Figure 4.6 shows the structure and dimensions of the three 'cone-type', two 'inverted-pyramid' and 'quarter-round' entrance shapes. The two 'ogee-type' profiles were adapted from the USBR's publication *Design of Small Dams* (1987). Profiles 1 and 2 were designed based on the profiles suggested by the USBR for shallow approach flow conditions for relative

depths of $2h/d = 0.3$, and $2h/d = 0.2$, respectively. These profiles are shown in Figure 4.7 and their tabulated (x-y) coordinates can be found in Appendix B.

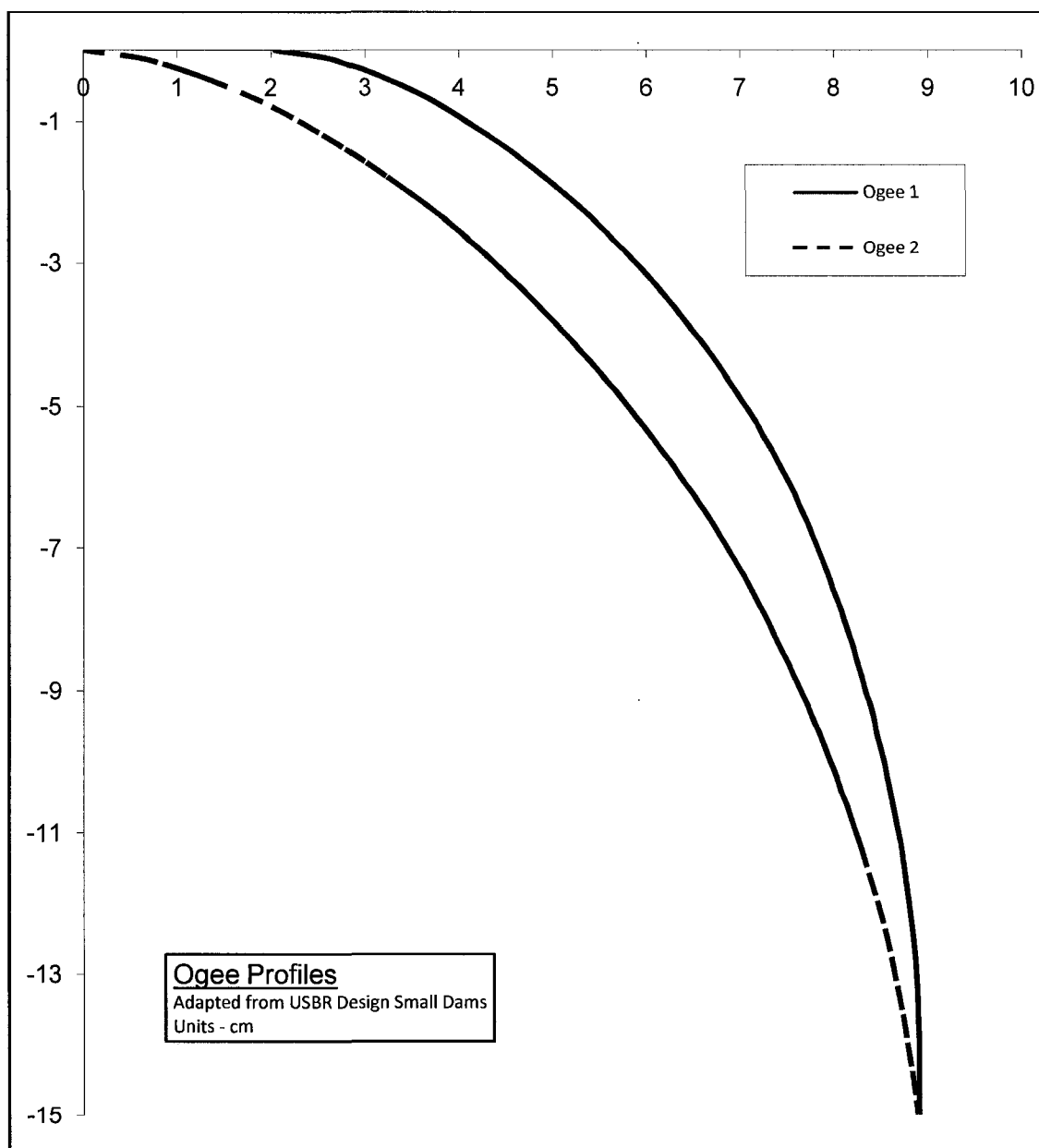


Figure 4.7: Ogee profiles

4.3 GEOMETRICAL ARRANGEMENTS TESTED

Theoretically, if a vortex forms in an ideal fluid, the energy associated with the rotating fluid would never be dissipated and the vortex would persist forever. In reality however, viscous dissipation naturally extracts energy from the rotating fluid body. The amount of energy dissipation that can occur is dependent on the intake's proximity to its nearby boundaries. If no nearby boundaries are present, little energy will be lost from the flow and the vortex will retain most of its strength. Whereas, anything that causes a transfer of energy from the rotating fluid will effectively reduce its strength.

To investigate the influence that the surrounding boundaries have on the hydraulic performance of the intake, the geometrical arrangement of the intake structure was altered and tests were carried out using the abrupt-entry intake for direct comparison to the reference case. The reference case is determined by testing the abrupt-entry (or straight) intake inside the original structure (as described in Section 4.1). The boundaries include the structure floor (remains unaltered throughout all tests), the surrounding vertical walls and the water surface. In the reference case, the wall behind and those on either side are all located at a distance of 0.267 m from the crest of the intake and the water surface is open to the atmosphere.

In the present experimental program, the dimensions of the structure were varied through the use of movable walls (made of 0.0127 m thick Plexiglas) fixed at different locations inside the original structure. The wall behind the intake was moved closer to the intake to distances of $0d$ (0.000 m), $1d$ (0.076 m) and $2d$ (0.152 m) from the downstream crest of the intake (Figure 4.8) and the side walls were moved closer to distances of $1.5d$ (0.114 m) and $2d$ (0.152 m) from the intake crest (Figure 4.9).

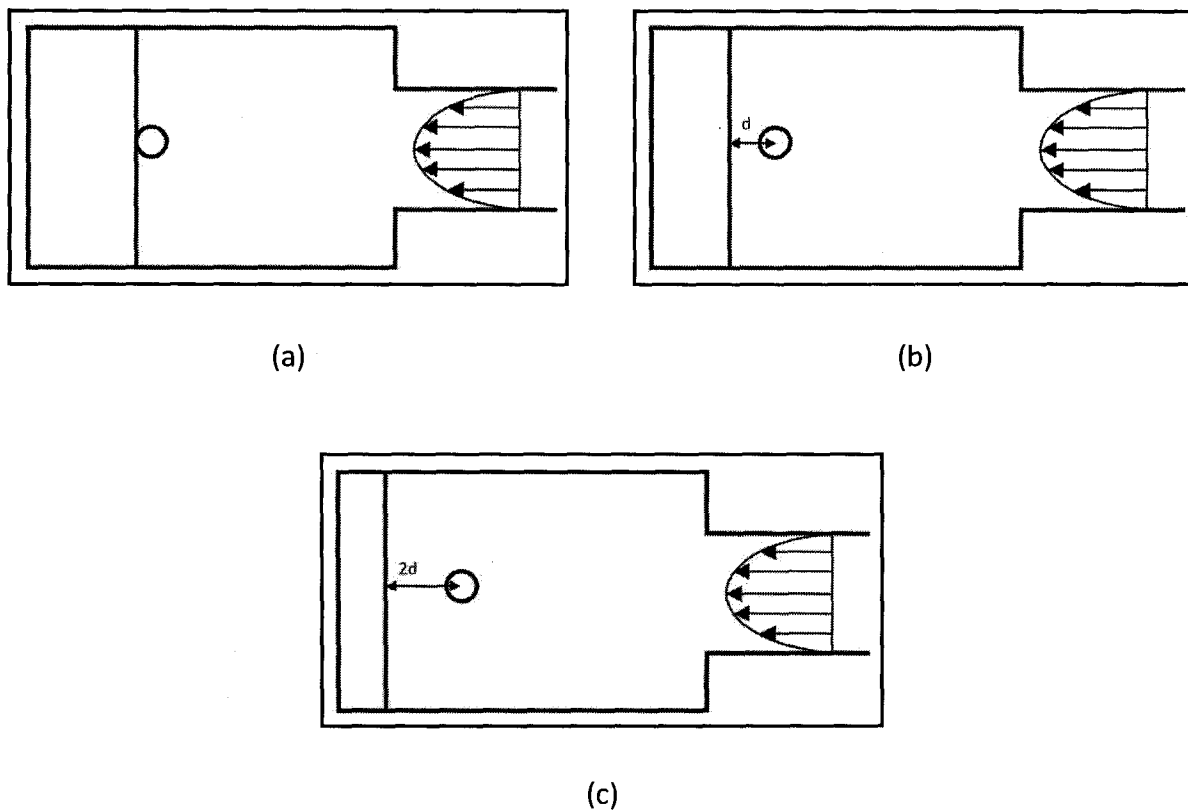


Figure 4.8: Geometrical arrangements using back wall (a) 'Anti-vortex' wall or $x=0$; (b) $x=d$; (c) $x=2d$

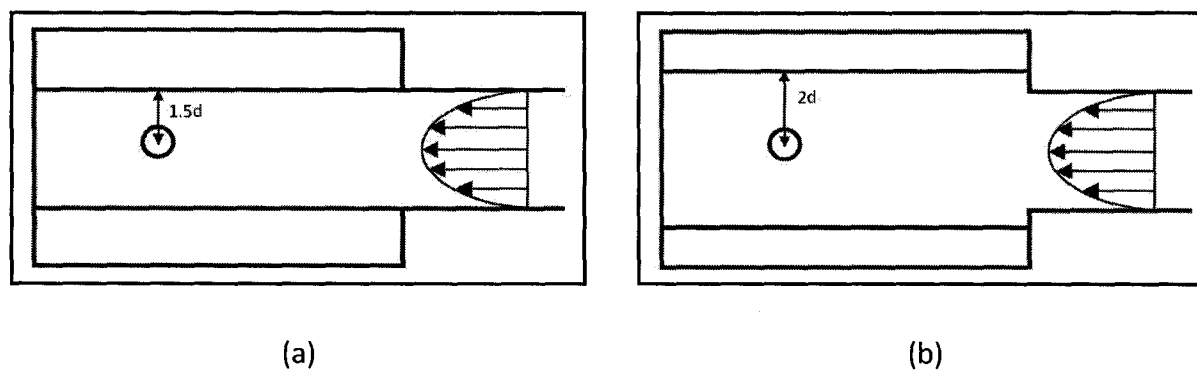


Figure 4.9: Geometrical arrangements using side walls (a) $x=1.5d$; (b) $x=2d$

It was also considered that vortex occurrence may be efficiently discouraged by the use of a longitudinal wall placed in the centre of the structure, directly above the intake. Accordingly, tests were carried out using a 'middle curtain', hung above the intake (Figure 4.10) at distances of $0.5d$ (0.038 m) and $1d$ (0.076 m).

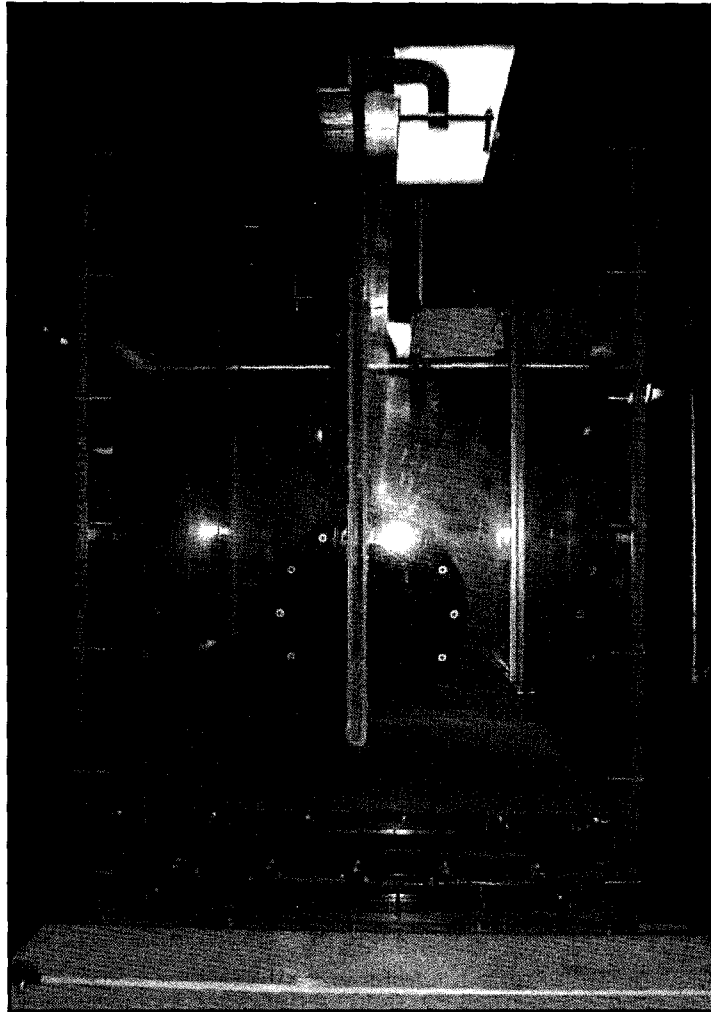


Figure 4.10: Middle 'curtain' setting

The last geometrical arrangement tested in this study involved the use of a floating surface. The surface was created by taking a large piece of Styrofoam, 0.0762 m thick, cut to the same dimensions of the original structure and trimming the edges such that the Styrofoam was free to move up and down with the water surface while keeping the amount of space that is open to the atmosphere at a minimum (Figure 4.11).

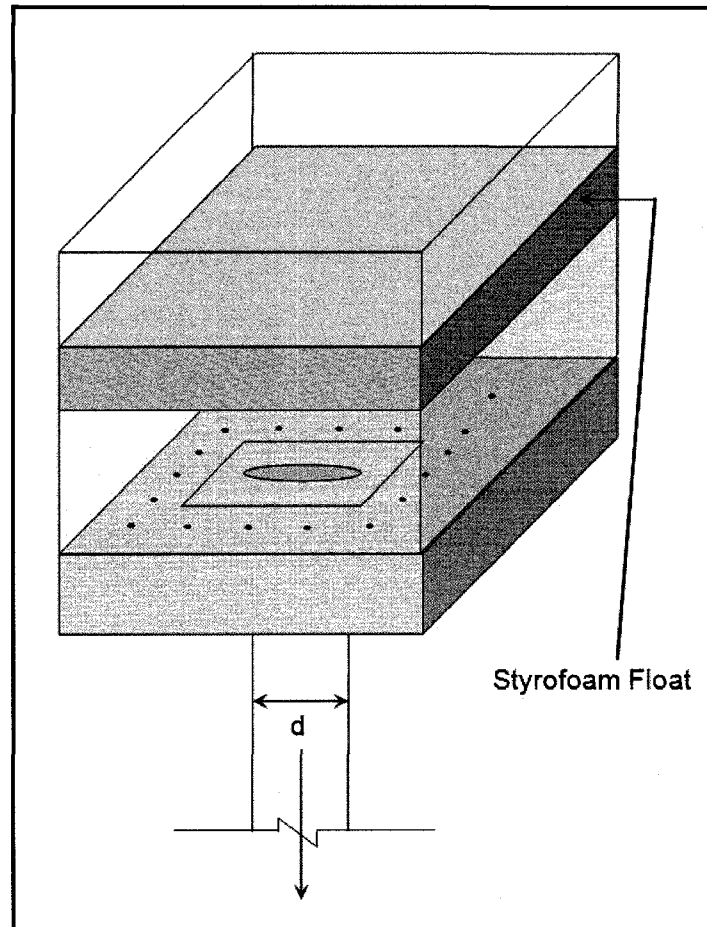


Figure 4.11: Floating surface

4.4 TEST METHODOLOGY

Particularly in the unstable-vortex flow range (Section 5.2.2), due to the fluctuating nature of the flow, as discussed in Section 3.1.5.2, obtaining useful information from these experiments required analysis of the flow behavior over time. Accordingly, the data collection procedure was designed in order to obtain data of both the flow rate through the intake and the depth of water above the intake as functions of time. These measurements were made using capacitance wave gauges (see Section 4.5.1) and are used as a ground for comparing the different intake entrance shapes and geometrical boundary arrangements.

The chosen test procedure employed individual tests, each 8 minutes in length, during which, the inflow rate to the structure was constant and the water level above both the intake and V-notch weir were measured (Section 4.5.1) using a sampling rate of 2 Hz ($N=960$). Each sequence of tests began under steady state, full-pipe flow conditions, from which flow was incrementally decreased.

After each flow rate decrease, it was necessary to wait for the system to re-establish a steady state condition before recording data. Accordingly, a 15 minute delay period was used, after which, changes in the water level above the intake were no longer measurable. Figure 4.12 shows that a 15 minute waiting period is of adequate length for changes in intake submergence of up to 15% (under full-pipe flow conditions).

Therefore, each individual test required a total of 23 minutes (15 minutes of waiting and 8 minutes of measurement). The seemingly short 8 minute testing period was chosen in consideration of the relatively long waiting period and the large number of individual tests required by the study as a whole.

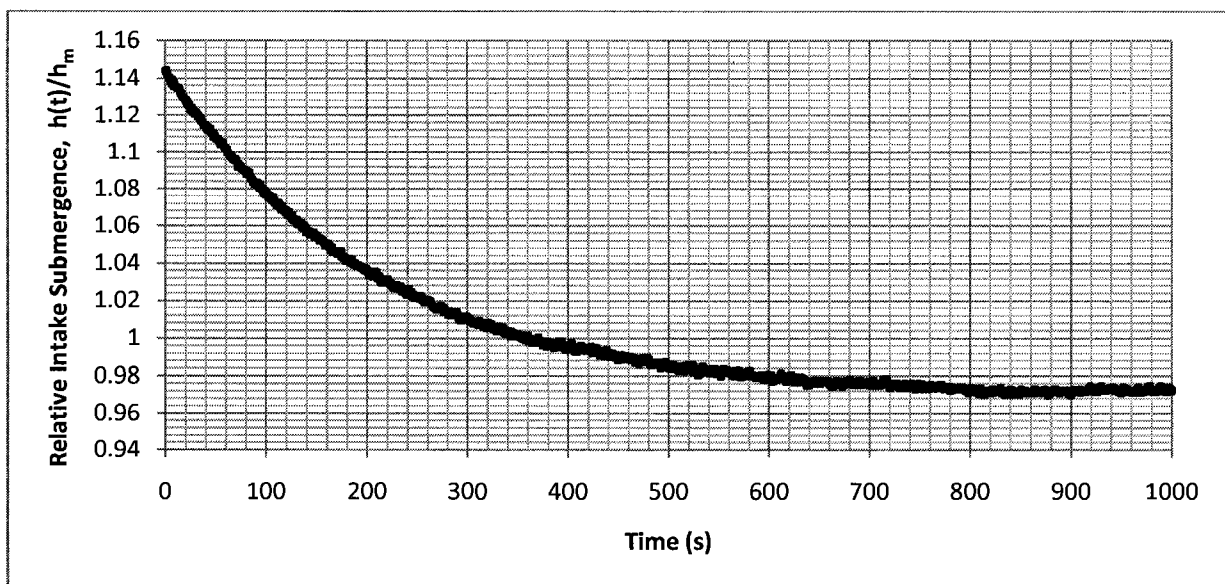


Figure 4.12: Time required for reestablishment of steady state conditions (Plot shows instantaneous submergence $h(t)$ relative to the mean submergence h_m as a function of time beginning immediately after change in inflow)

4.4.1 TEST PROGRAM

The testing program consisted of three main parts: (i) investigation of the reference case (abrupt-entry intake) as a benchmark for comparison of subsequent test results; (ii) testing with intakes of different entrance shapes (e.g. cone-type, quarter-round, ogee, etc.); and (iii) testing of the abrupt-entry intake under various altered boundary conditions.

The first step in the experimental program was to establish a solid benchmark to which the latter tests could be compared. The abrupt-entry intake was used as a reference as it is assumed to be the hydraulically worst performing intake. As the subsequent test results will be compared to this reference case, it was imperative that a thorough investigation be conducted. Therefore, a much larger number of tests were performed on the abrupt-entry intake to provide for an accurate determination of its behavior. To accomplish this, the procedure described above was repeated numerous times to ensure that all flow conditions were thoroughly observed.

In the unstable-vortex flow range, there was a large amount of scatter in the recorded data due to the instability and continuous formation and dissipation of the established vortices. Therefore, it was required that the full extent of this scattering be properly determined. However, to observe the full extent of the variability of the results, an even larger number of tests would be required. To conserve time and to observe the variability of the results from the 8 minute tests under constant inflow conditions, tests of extended length were also conducted within the unstable-vortex flow range, each 120 minutes long. To remain consistent and to observe the extent of the scattering of the 8 minute test results, the results of the 120 minute tests were broken down into fifteen (15) separate 8 minute tests. These extended tests also allowed for observation of the long term behavior of the flow in the unstable-vortex range. These procedures yielded a total of 643 individual 8 minute tests and provided sufficient means to establish a reference case for comparison of the results from subsequent tests.

The second part of the experimental program involved the testing of the various intake entrance shapes. These tests were performed using the 23 minute sequence outlined above. Table 4.1 shows the number of tests performed on each intake.

Table 4.1: Test program for different intake shapes

Intake Shape	No. of Tests Completed
Cone (30 deg.)	38
Cone (45 deg.)	43
Cone (60 deg.)	41
Pyramid (symmetric)	31
Pyramid (asymmetric)	36
Round	30
Ogee 1	31
Ogee 2	34

The final set of experiments was performed under various geometrically-altered boundary conditions. These tests were carried out using the same 23 minute procedure as previously described. Table 4.2 shows the number of tests performed under each geometrical arrangement. Fewer tests were carried out in this phase because the presence of the closer boundaries produced a more stable flow pattern that could be adequately described with a lesser number of data points.

Table 4.2: Test program for different geometrical arrangements

Geometrical arrangement	No. of Tests Completed
0d Back Wall	28
1d Back Wall	25
2d Back Wall	33
1.5d Side Walls	31
2d Side Walls	20
0.5d Middle Curtain	19
1d Middle Curtain	31
Floating Surface	32

The inconsistency in the number of tests used was due to the fact that it was very difficult to control the magnitude of the changes in inflow. The maximum flow that the structure can safely manage is approximately $0.017 \text{ m}^3/\text{s}$, which is only roughly 5% of the pump's capacity ($0.3 \text{ m}^3/\text{s}$). Consequently, the ability to make minor adjustments to the flow was initially very limited as the slightest turn of the supply valve would result in an undesirably large change in flow. To correct this problem, an outlet pipe ($d = 0.0635 \text{ m}$) with an auxiliary valve was installed at the bottom of the primary storage tank. This allowed for the minor adjustments necessary for a more detailed study. Nonetheless, as the response of the different intake shapes and geometrical arrangements could not be predicted, the magnitude of the changes in inflow could not be fully controlled.

4.5 DATA ACQUISITION METHODOLOGY

Large fluctuations of both the flow and submergence were encountered in the unstable-vortex flow range as the inception of an air-core vortex lead to an abrupt decrease in flow rate. For intake submergence, the velocity of the fluctuation was found to be typically of the order of $1\text{-}5 \text{ mm/s}$ and the fluctuations in flow were observed to occur at rates of up to $3\%/s$.

The rate and magnitude of the fluctuation in both submergence and flow were dependent on the inflow conditions. Under full-pipe and stable-vortex flows ($Q > 13.9 \text{ L/s}$ and $Q < 4.0 \text{ L/s}$, respectively, for the reference case), the fluctuations were very small, whereas, the opposite was observed for the intermediate flows in the unstable-vortex range. The consistency of the flow under various inflow conditions can be observed in Figure 4.13 which illustrates the deviation from the mean observed flow as a function of time. Due to the rapidly occurring fluctuations in the unstable-vortex flow region, it became apparent that data would have to be collected by means of an electronic data acquisition system, as manual observations proved to be inadequate. Accordingly, two capacitance wave gauges were used to measure and record the flow and depth of water above the intake. These gauges have an accuracy of roughly $\pm 0.5\%$.

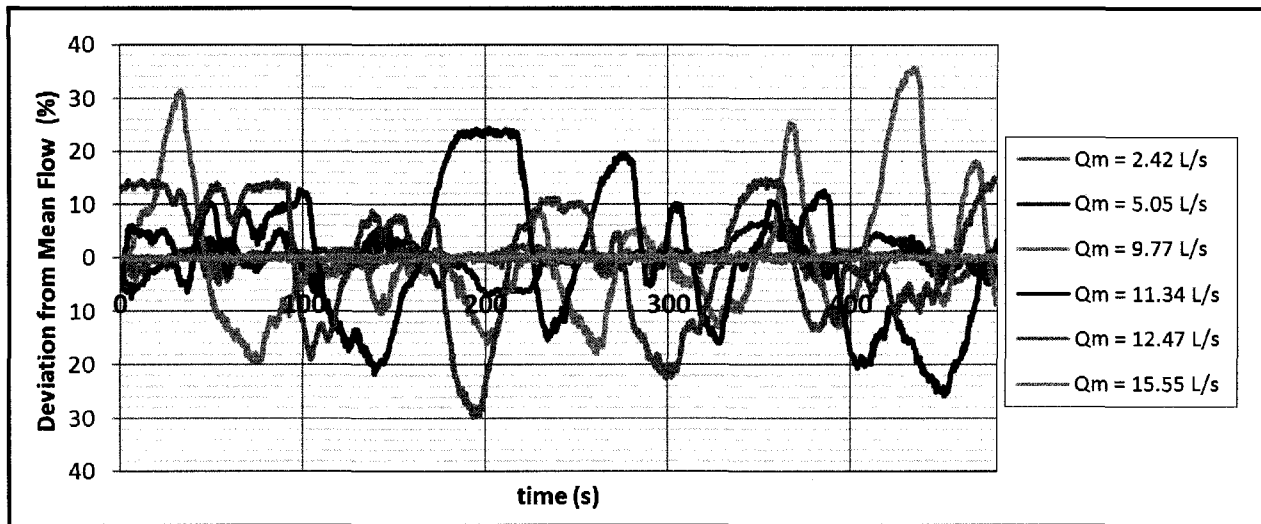


Figure 4.13: Sample results illustrating fluctuations in flow

4.5.1 CAPACITANCE WAVE GAUGES

Capacitance wave gauges are used most commonly to measure fluctuating water surfaces and, as their name suggests, are predominantly used to measure rapidly varying water levels, waves, tides and coastal run-up. Therefore, they provide an ideal means for measuring the unsteady water surface in the present study.

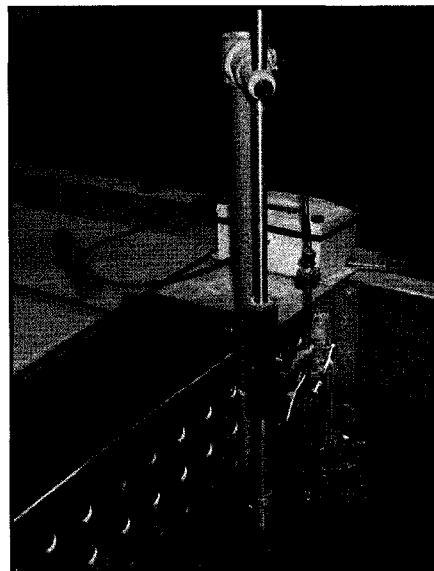


Figure 4.14: Capacitance wave gauge inside catch basin

The basic composition of a wave gauge (as shown in Figure 4.14) is a wire or 'wave probe' held by a thin frame, the length of which is variable depending on its application but is generally in the 0.5-1 m range. In this study, two 0.65 m and 1 m gauges were used. The gauges, when partially submersed in water, measure how much of the wave probe is beneath the water surface. They return this measurement in the form of a voltage. The relationship between the voltage and the depth of water is linear, so the depth of water can be obtained directly from the voltage if the linear relationship is known. However, to obtain an accurate conversion, it is necessary to reference the recorded voltages to a depth that can be reliably measured in some other way (gauge calibration).

4.5.2 CALIBRATION OF GAUGES

The slope of the linear relationship for both gauges was determined using a basin of water with a constant surface level. The measured voltage for each gauge was recorded at 10 Hz for one minute and a temporally averaged mean voltage was obtained. Keeping the water surface level constant, the gauges were then raised a known distance of 0.10 m and the mean voltages were obtained similarly. Repeating this twice more yielded four points from which the slope of the linear relationship could be easily determined.

The next step in calibration was to set the intercepts of the linear voltage-depth relationships. This was rather simple to perform for the gauge measuring flow, as the measurement of interest is the height of water above the invert of the V-notch weir. The gauge was fixed in position inside the catch basin and turned on to enable real-time viewing of the data. The basin was filled to a height above the weir and the inflow was then turned off so that the excess water stored above the invert of the weir was expelled. Once the drop in water surface had ceased, data was recorded at 10 Hz for one minute as in previous step, and a mean voltage was obtained. The mean voltage was then equated to a weir depth of $h_w = 0$ m and the intercept was established. For the gauge used to measure the depth of water above the intake, this procedure was not an option because all of the water would drain out of the structure if the inflow is stopped. Instead, a steady full-pipe flow condition was used in conjunction with an array of piezometers installed on the floor of the structure. Under a

steady full-pipe flow condition, the flow rate and intake submergence do not change with time. Therefore, if sufficient time is allowed for equilibrium to be established, the water surface inside the structure can be assumed to be constant with little error. This assumption was proven to be valid by the results detailed in the following section. Accordingly, to set the intercept, a condition of dynamic equilibrium was established and the intercept was then established by equating the average depth measured by the piezometers to the mean voltage obtained from the one minute sampling period.

As previously noted, the error associated with the wave gauges themselves is roughly $\pm 0.5\%$. In addition to this, another source of error was observed during the experimental program. For relatively static water surface conditions, surface tension effects were observed. When the water surface varied at a very slow rate or not at all, the water surface would 'cling' to the wire until the change in the water surface was large enough to break the 'bond' created at the water surface-wire interface. This type of error would bias the measured mean values in the same direction as the change in water surface. For example, in the present experiments, under nearly steady full-pipe flow conditions, if the water surface inside the structure was increasing/decreasing very slowly, a bond would form between the water surface and the wave probe (wire) such that the submergence of the probe would be slightly lower/higher than the that of the intake. This condition would remain until the difference in submergence was large enough to break the bond. The error is incurred because the probe will continue to record the smaller/larger submergence of the wave probe, rather than the submergence of the intake. An example of this type of error is shown in Figure 4.15. Through temporal averaging, the effect of this type of error can be reduced but the calculated mean values will be slightly biased in the direction of the change in submergence if the direction on the change is constant over the data recording time. In Figure 4.15, it can be seen that the magnitude of this surface tension error is approximately only 1.5 mm and is therefore, considering that the results are averaged over time, of minor significance.

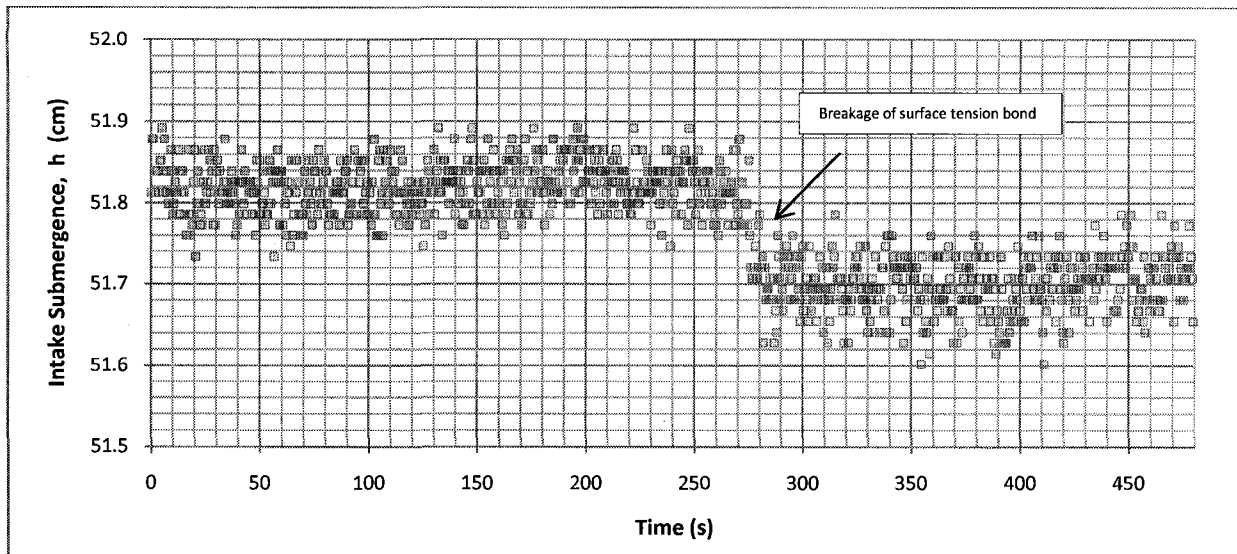


Figure 4.15: Example of error due to surface tension effects

This type of error was observed predominantly inside the structure (above the intake) where a smooth water surface could be established. It was also observed if the reduction in inflow between tests was too large. It seems that the 15 minute waiting period allotted for the re-establishment of steady state conditions was only sufficient if the reduction in inflow was small. This was discovered early in the experimental program and was considered throughout the remaining tests.

The water surface above the V-notch weir (inside the catch basin) was not nearly as consistent as it was inside the structure (above the intake) due to the impact of the jet of water discharging from the structure. Although perforated diffusing walls (Figure 4.4) were used inside the catch basin to dissipate the turbulent energy caused by the jet, a perfectly calm surface, for the most part, could not be established and small oscillations were observed and recorded. The 'rough' nature of the water surface inside the catch basin can be observed in Figure 4.14. These rough surface conditions prevented the formation of the surface tension bonds described above.

The degree of precision of the wave gauges can also be observed in Figure 4.15. Although the water surface is seemingly static, the submergence recorded by the wave gauge varies by roughly ± 0.7 mm. It is unclear whether this fluctuation is due to the minor surface disturbances or due to the imprecision of the gauge itself. Regardless of the source of these fluctuations, they appear to be evenly distributed about the mean and therefore their affect should be minimized through averaging.

4.5.3 V-NOTCH WEIR

In this study, the flow was not measured directly but was rather calculated indirectly by using wave gauge measurements of the depth above the invert of a V-notch sharp-crested weir and the V-notch weir equation (4.1),

$$Q = \frac{8}{15} C_d \sqrt{2g} \tan\left(\frac{\theta_V}{2}\right) h_w^{5/2} \quad [4.1]$$

where Q = flow (m^3/s) and h_w = head above the V-notch weir (m). For precision machined weirs of standard angles, the coefficients of discharge have been previously determined and can be readily found in the literature. For example, a 90° ‘fully-contracted’ weir has a discharge coefficient of approximately $C_d = 0.578$ (Bos, 1989). This particular value has been used in the current study. In equation 4.1, for a 90° weir, $\tan\left[\frac{\theta_V}{2}\right]$ becomes equal to 1; therefore, considering this and $C_d = 0.578$, equation 4.1 can be simplified to yield equation 4.2 which was used in this experimental study to calculate the flow from the recorded $h_w(t)$ data.

$$Q = 1.365 h_w^{5/2} \quad [4.2]$$

It is important to note that flow measurements are subject to a slightly larger amount of error than the submergence depth measurements because, in equation 4.2, the water depth above the invert of the V-notch weir recorded by the wave gauge is raised to a power of $5/2$. Therefore, the error associated with the wave gauge measurement, as previously discussed, is amplified accordingly.

In order to obtain accurate results from the V-notch weir, the weir must be 'fully contracted', or in other words, have an approach channel whose bed and sides are sufficiently far enough away from the edges of the V-notch such that the velocity of the flow approaching the weir is not significantly distorted by friction (Bos, 1989). To ensure that the V-notch weir in the current experiments was fully-contracted, the dimensions of the catch basin used had to be checked against published criteria. Figure 4.16 presents a definition sketch of the structural parameters of a standard V-notch sharp-crested weir. Table 4.3 provides the classification and limits of a fully-contracted weir and the dimensions of the catch basin used in the current experiments can be found in Table 4.4.

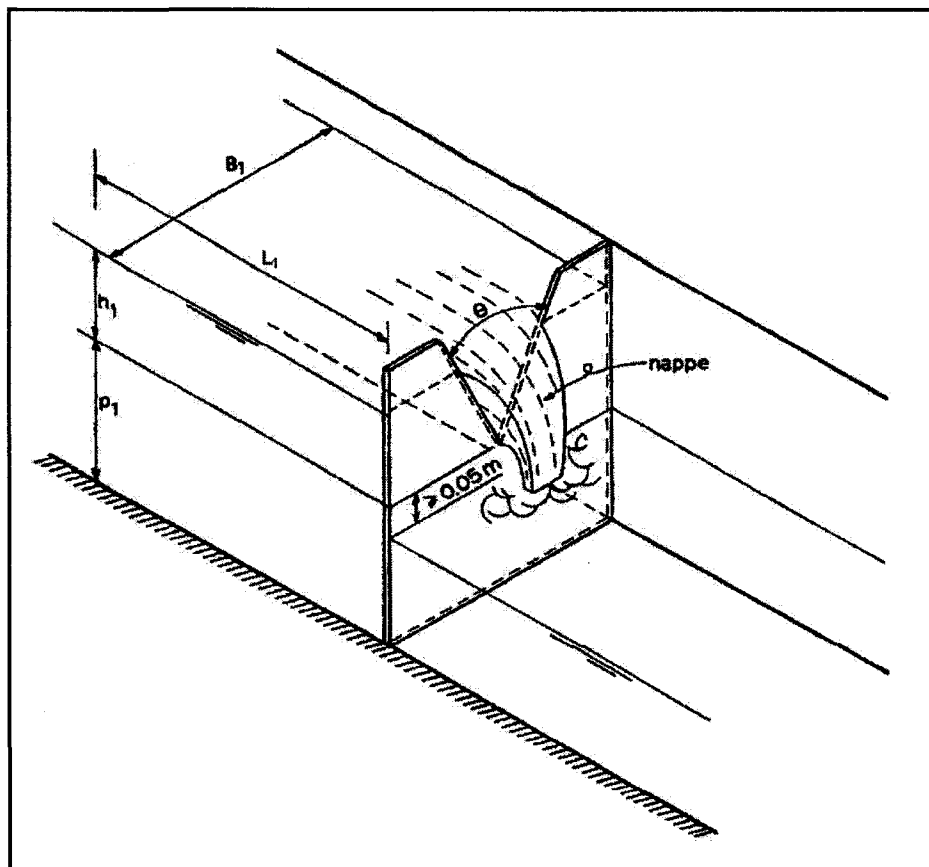


Figure 4.16: V-notch sharp crested weir (Bos, 1989)

Table 4.3: Classification and limits of a fully contracted V-notch sharp-crested weir (Bos, 1989)

h_1/p_1	≤ 0.4
h_1/B_1	≤ 0.2
h_1/L_1	≤ 0.33
h_1	$> 0.05 \text{ m and } \leq 0.38 \text{ m}$
p_1	$\geq 0.45 \text{ m}$
B_1	$\geq 0.90 \text{ m}$

Table 4.4: Structural dimensions of catch basin used in experimental study

p_1	0.554 m
B_1	0.912 m
L_1	0.611 m

By comparison of Table 4.3 and Table 4.4, it can be seen that both the depth below the invert of the weir, p_1 , and the width of the basin, B_1 , conform to the required limiting values and therefore, the basin is of sufficient size to function as a fully contracted weir for weir depths (h_1 or h_w), up to a certain maximum value which must be determined from the first three relative constraints given in Table 4.3. The maximum weir depths were determined from the (h_1/p_1) , (h_1/B_1) , and (h_1/L_1) limitations and were found to be 0.221 m, 0.182 m and 0.201 m, respectively. Therefore, the catch basin is width-limited to a maximum weir depth of 18.2 cm. There is also a prescribed lower limit of 0.05 m on the weir depth, hence, the V-notch weir can only be accurately used to measure the flow when the weir depth is within the range of 5 cm to 18.2 cm; these depths correspond to flows of 0.76 L/s and 19.29 L/s.

The maximum flow rate that could be achieved by the structure, however, was found to be lower than the 19.29 L/s dictated by the weir limitations. The peak flow rate was, on the other hand, found to be limited by the strength of the structure itself. When the submergence of the intake was approximately 65 cm ($h/d \cong 8.5$), the vertical walls of the structure began to noticeably deform under the large hydrostatic pressure. Therefore, to prevent yielding, the intake submergence was limited to the aforementioned value. The flow rate established under such submergence conditions is dependent on the entrance shape of the intake (Section 5.3), the most efficient of which produced a flow of approximately 17.2 L/s

(or $h_w \cong 17.4$ cm) which is below the maximum value of 19.29 L/s (or $h_w \cong 18.2$ cm) dictated by weir limitation. Therefore, testing was carried out such that the flow rate was always greater than 0.76 L/s (as dictated by $h_w > 5$ cm) and the submergence of the intake was less than 65 cm (as dictated by the strength of the structure). Under these limits, the V-notch weir is considered to be fully contracted and therefore should yield accurate results.

It should also be noted that a lag time exists between the submergence and flow measurements. Under full-pipe flow conditions, the magnitude of the lag time was found to be approximately 0.6 s. Due to the relatively small magnitude of this lag time, it was considered to be of minor significance.

4.5.4 MEASUREMENT OF CIRCULATION/VORTEX STRENGTH

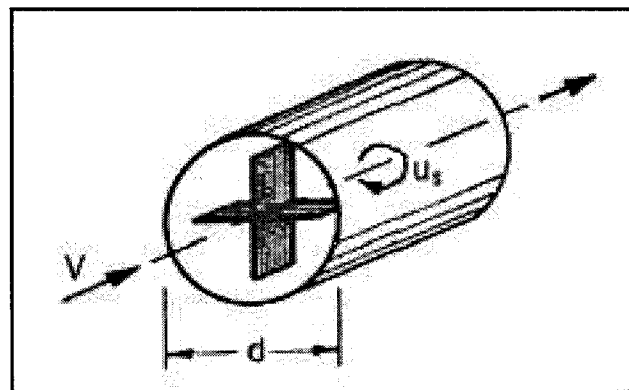


Figure 4.17: Swirl Meter (Knauss, 1987)

Through the use of a swirl meter (or vortometer) a measurement of the magnitude of swirl in the outflow pipe can be obtained. A swirl meter is a propeller-like device that can be mounted in the centre of the outflow pipe. The difference between the blades of a propeller and the blades of a swirl meter is that the latter are flat and parallel to the flow and therefore, should respond only to the tangential component of the flow rather than the axial component. The swirl meter records the number of revolutions per unit time, n . Equation 4.3 is used to translate the number of revolutions per time into values of tangential velocity, u_s , and the swirl angle, α , is determined through the application of equation 4.4.

$$u_s = \pi d n \quad [4.3]$$

$$\alpha = \tan^{-1} \left[\frac{u_s}{v} \right] \quad [4.4]$$

An estimate of the circulation can be obtained indirectly from the measured tangential velocity u_s values obtained from the swirl meter by equation 3.3.

In the present study, however, a swirl meter was not used. The decision not to do so came about as a result of three reasons. First, (i) the instrument would not have functioned properly if the axis of the vortex is along the same line as the axis of the swirl meter. If this condition was not satisfied, the core of a vortex could have travelled past the swirl meter with little to no rotation of the blades (Quick, 1970). Secondly, (ii) due to the high axial velocity component of the flow passing by the blades, lift forces could have been generated by turbulence in the axial flow or by imperfections/misalignment of the blades. These lift forces could have produced auto-rotation of the instrument, and thus, could have reduced the accuracy of the device (Quick, 1970; Durgin and Hecker, 1978). For these reasons, the accuracy of the device was drawn into question. The final, and most significant, reason that a swirl meter was not used is that (iii) the presence of the device would have reduced the cross-sectional area of the vertical shaft and disrupted the overall flow through the intake. As the present study is concerned with the overall hydraulic efficiency of the intake, any such device would produce unwarranted influences that would impede the main objective of the study.

Therefore, in this study, due to the aforementioned difficulties and the desire to preserve an undisrupted flow through the intake, circulation was not measured directly. Instead, the influence of the established vortices on the flow was indirectly investigated by considering the stability of the observed vortices (a function of circulation strength) and the deviation of the flow from the observed full-pipe flow (Section 5.3.2). Although neither of these methods allows for an accurate estimation of circulation or vortex strength, they do provide a means for comparison of the different entrance shapes to the reference case (abrupt-entry intake) and thus, can show whether the shape of the intake results in any significant differences that could be attributed to a change in vortex behavior.

5. RESULTS AND ANALYSIS

5.1 INTRODUCTION

In this section, the experimental results are presented and discussed. In Section 5.2, the different types of observed flows are identified and described. This section also presents the results from the reference case (abrupt-entry intake within the unaltered structure described in Section 4.1.1) and discusses the overall nature of the flow observed during the experimental program. Section 5.3 presents the results obtained through the testing of the various different intake entrance shapes identified in Section 4.2 and Section 5.4 presents the results obtained through the testing of the different geometrical arrangements identified in Section 4.3.

5.2 FLOW REGIMES

Throughout the experimental program, three distinct types of flow were observed. These flow regimes are (i) full-pipe flow, (ii) unstable-vortex flow, and (iii) stable-vortex flow and are illustrated by the abrupt-entry intake results shown in Figure 5.1. In this figure, the mean relative intake submergence (calculated for each 8 minute test) is plotted against the mean intake Froude number and the maximum and minimum observed submergence values are represented by vertical error bars. At higher relative flows, steady full-pipe flow persisted such that the standard deviation of the flow ($N=960$), was found to be less than 0.10 L/s. At intermediate flows, unstable-vortex flow was observed. This type of flow, as described in the literature (Section 3.1.5.2), is marked by large rapidly-occurring fluctuations in both submergence depth and flow rate that result from the continuous vortex formation/dissipation process. Lastly, at low flows, a stable-vortex was observed. The stable vortices formed were spatially wider, had larger air-cores than unstable vortices and were steady in terms of location (directly above the intake), submergence depth and flow rate.

The occurrence of these distinct types of flow could be partly responsible for the difficulty in developing a generalized engineering solution. When designing an intake, it is

important to recognize that different processes govern the dynamics of the different flow regimes and thus, each type of flow should be considered individually.

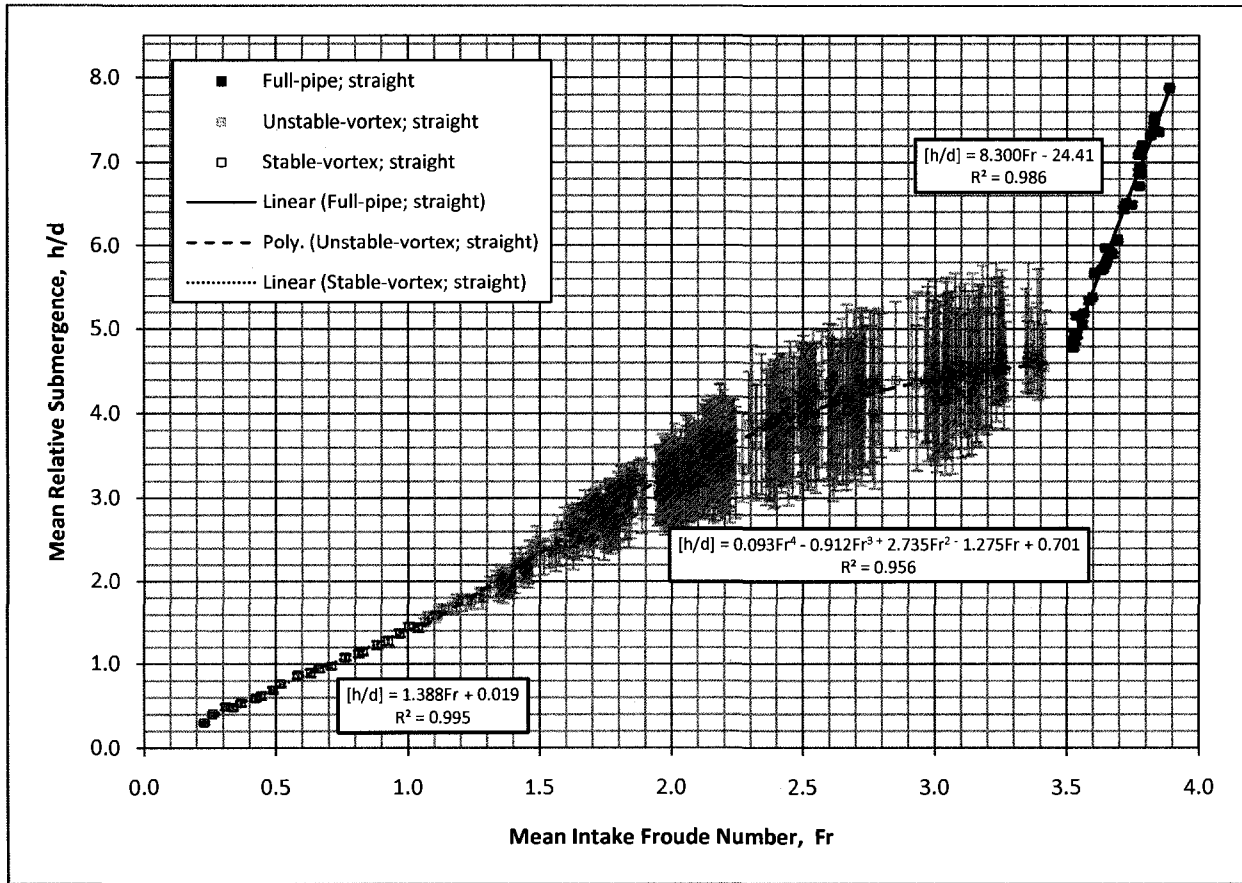


Figure 5.1: Relative submergence vs. intake Froude number for abrupt-entry intake (Error bars indicate maximum and minimum observed values)

Figure 5.2 and Figure 5.3 show, respectively, the variation of the standard deviation of the flow and submergence and provide another depiction of the different flow regimes. From these figures, it can be seen that, for the abrupt-entry intake, the fluctuations in flow are largest at a Froude numbers of approximately , where the maximum standard deviations of flow and submergence were found to be 1.63 L/s and 4.35 cm, respectively. These flows correspond to a relative submergence depth of or roughly 8.5% below the observed critical submergence of

It can also be seen that, although the full-pipe and stable-vortex flow regimes both appear to be steady, the standard deviation of full-pipe flow is slightly larger than that of stable-vortex flow. It is believed that this is due to greater surface roughness above the V-notch weir caused by the higher velocity and larger quantity of water impacting the water surface in the catch basin under full-pipe flow compared to stable-vortex flow.

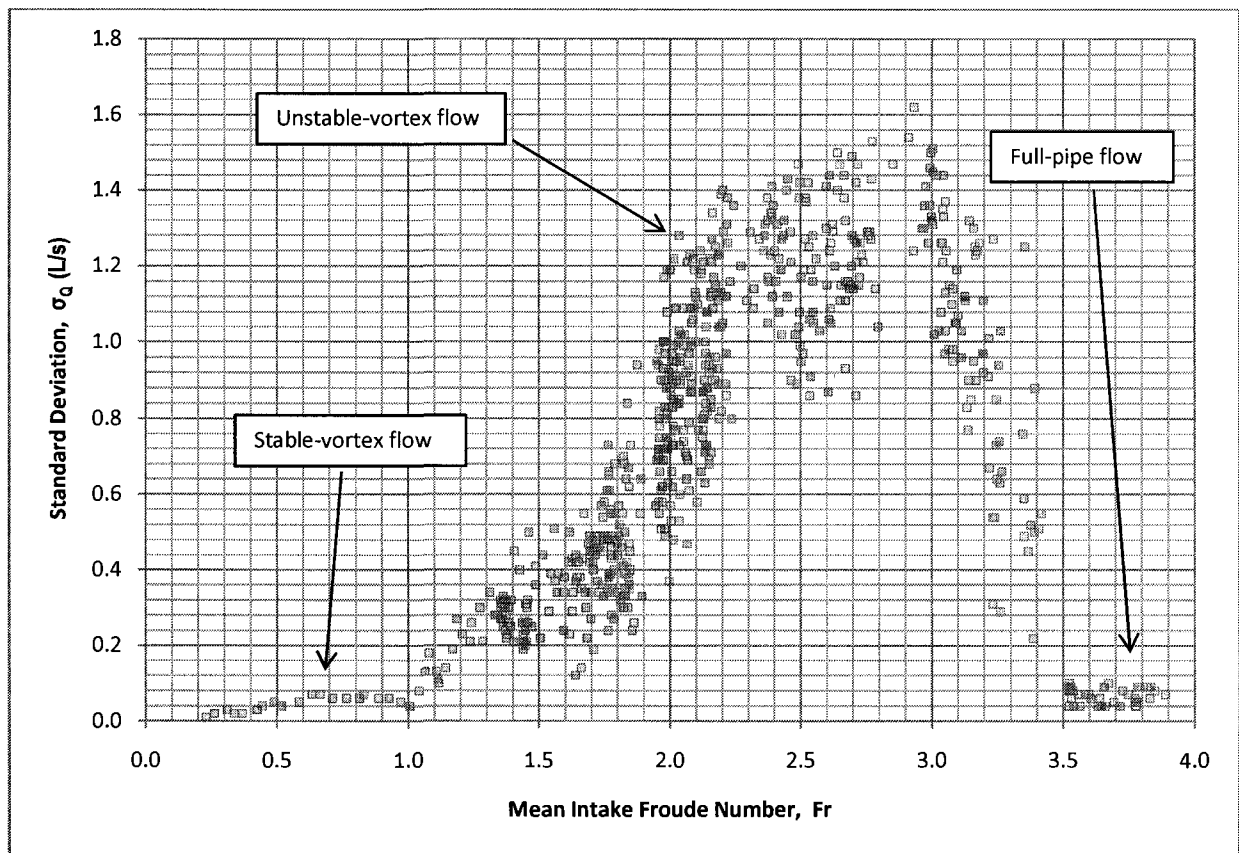


Figure 5.2: Standard deviation of flow vs. intake Froude number for the abrupt-entry intake

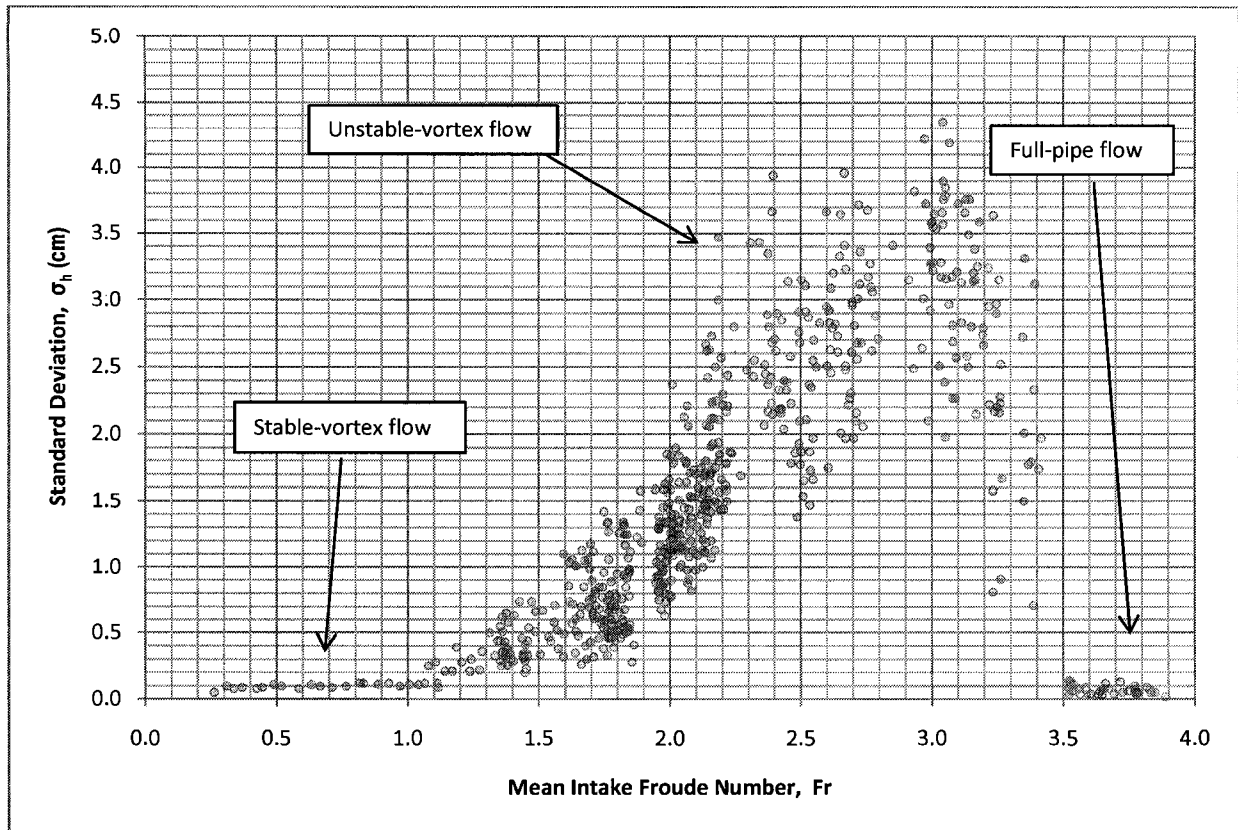


Figure 5.3: Standard deviation of submergence vs. intake Froude number for the abrupt-entry intake

5.2.1 FULL-PIPE FLOW

In the reference case, full-pipe flow was found to prevail at $Fr > 3.52$. The lowest recorded mean relative submergence at which no vortices occurred was found to be $h/d = 4.79$. Hence, this value is considered to be the critical submergence for the reference case. Under full-pipe flow conditions, if the intake Froude number is plotted against the relative submergence, a linear relationship is generated (as shown in Figure 5.1). Within this range of flow, the standard deviation of flow and submergence were found to be less than 0.10 L/s and 0.14 cm, respectively, and therefore the flow is considered to be steady.

At relative submergence depths much greater than the critical value ($h/d = 4.79$), a calm water surface is generated with little evidence of circulation in the flow. As the inflow is reduced and the relative submergence approaches the critical value, surface dimples begin to be observed; indicating the presence of circulation in the flow, but its magnitude is not great

enough to induce an air entraining vortex. However, as the inflow is continuously reduced and the critical submergence is surpassed, air entraining vortices are generated and the nature of the flow condition changes from full-pipe flow to unstable-vortex flow.

5.2.2 UNSTABLE-VORTEX FLOW

As air entrainment causes a significant reduction in flow through the intake, there is a relatively large gap in the measured Froude numbers between the full-pipe and unstable-vortex flow regimes. Consequently, although full-pipe flow conditions ceased to prevail at $Fr < 3.52$, unstable-vortex conditions were observed to occur at $Fr < 3.42$. Therefore, the inception of unstable-vortex flow is accompanied by a rather abrupt reduction of roughly 0.4 L/s in the average flow through the structure. It is also accompanied by a large increase in the standard deviation of both flow and submergence. Immediately outside the full-pipe flow regime ($3.35 \leq Fr \leq 3.42$) the average standard deviation in flow and submergence were found to be 0.61 L/s and 2.09 cm, respectively. These values correspond to increases of 510% and 1392% in standard deviation from that observed under full-pipe flow conditions. In the reference case, unstable-vortex flow continues to persist to a lower limit of approximately $Fr \cong 1.0$ and $h/d \cong 1.50$, where the standard deviation of submergence and flow are both slightly greater than 0.10.

The nature of the flow is similar to that described in Section 3.1.5.2. Both the presence and intensity of the established vortices are not constant. Vortices are continuously formed and dissipated without showing any sign of stabilization, thus large fluctuations in both flow and submergence are generated. At high flows (within the unstable-vortex range), vortices form relatively infrequently and exist only for relatively short periods of time. They have very thin air-cores and their shape and position are both inconsistent. As the flow and submergence are decreased, the frequency and duration of their occurrence, as well as the width of their air-cores, increase. Their position relative to the intake also becomes more stable such that at the lowest flows, the vortex is approaching a stationary position above the intake. Figure 5.4 provides examples of the different types of unstable vortices observed during the experimental program.

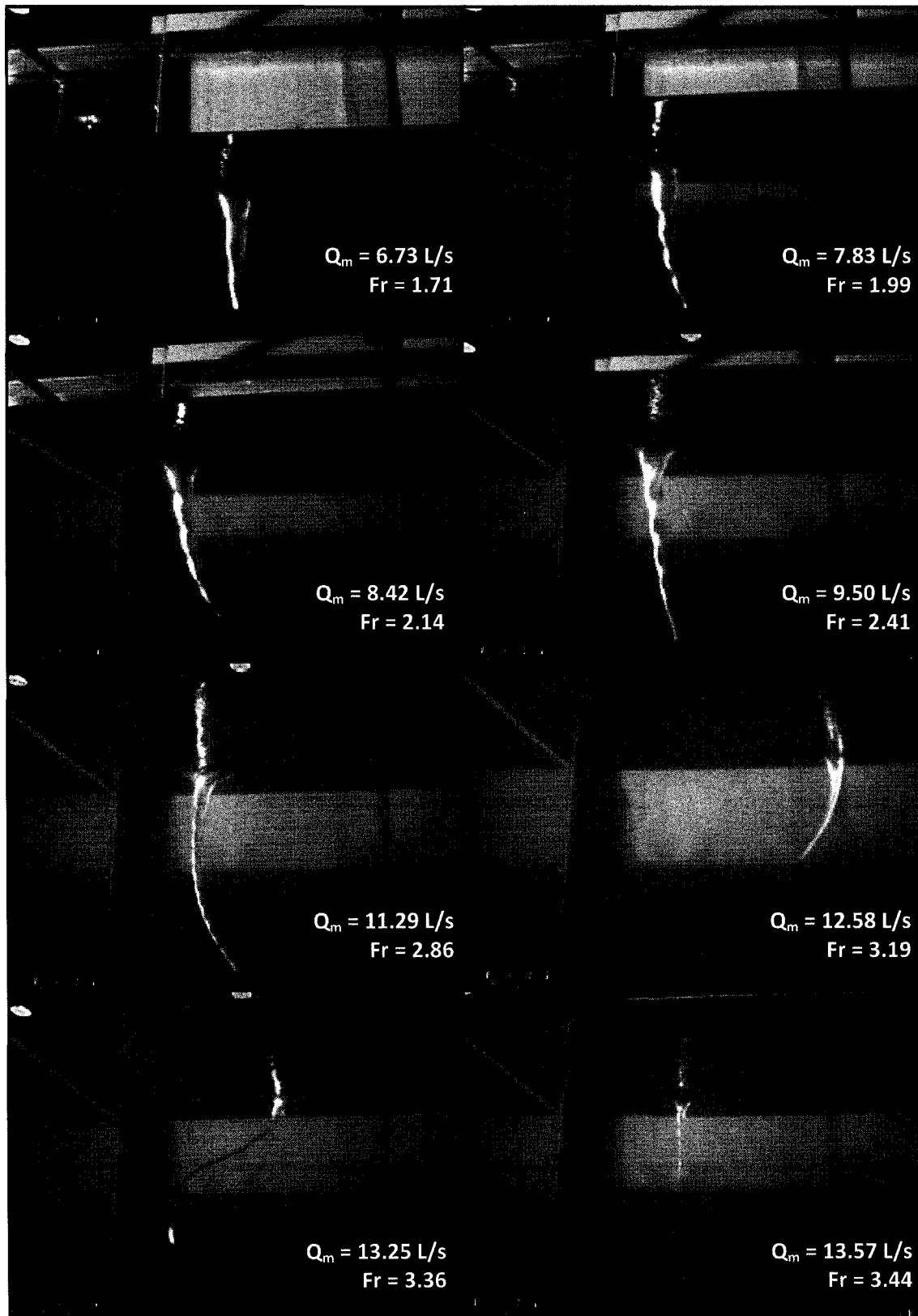


Figure 5.4: Examples of unstable vortices observed during testing with the abrupt-entry intake

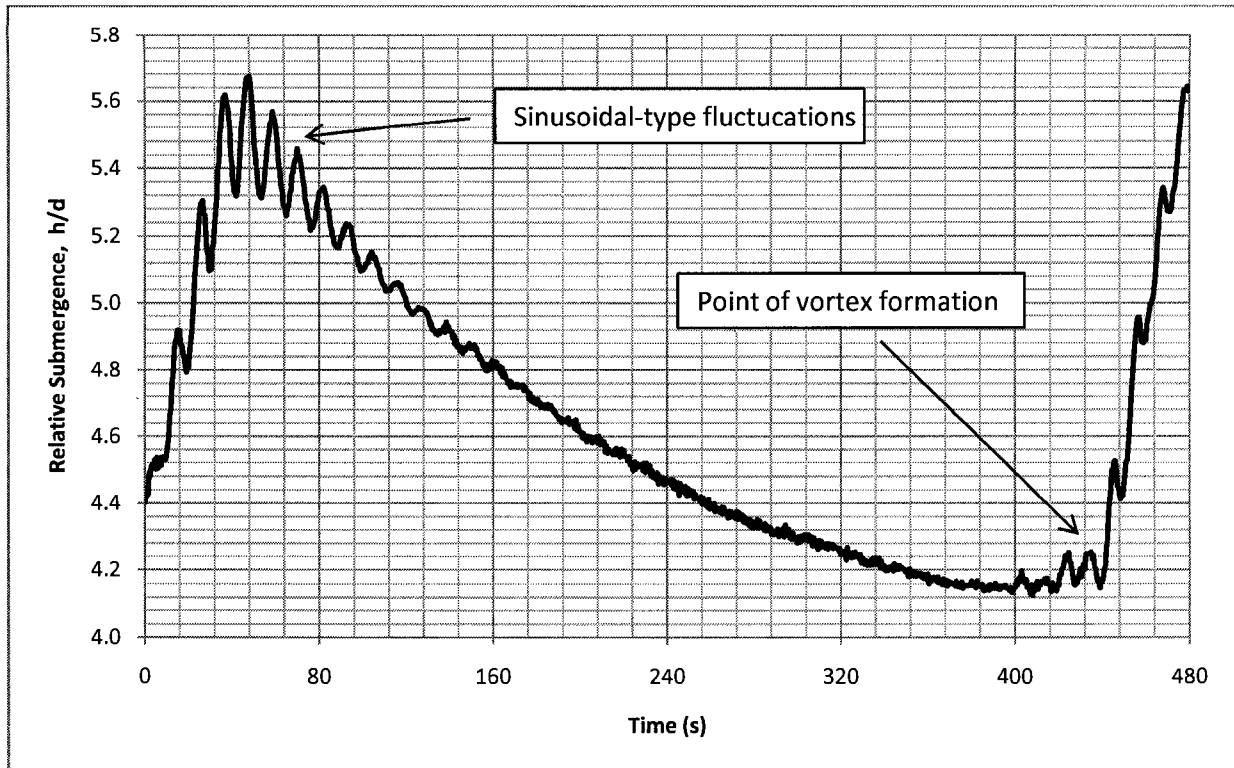


Figure 5.5: Sample results of submergence under unstable-vortex flow ($Q_m = 13.22$ L/s, $[h/d]_m = 4.65$)

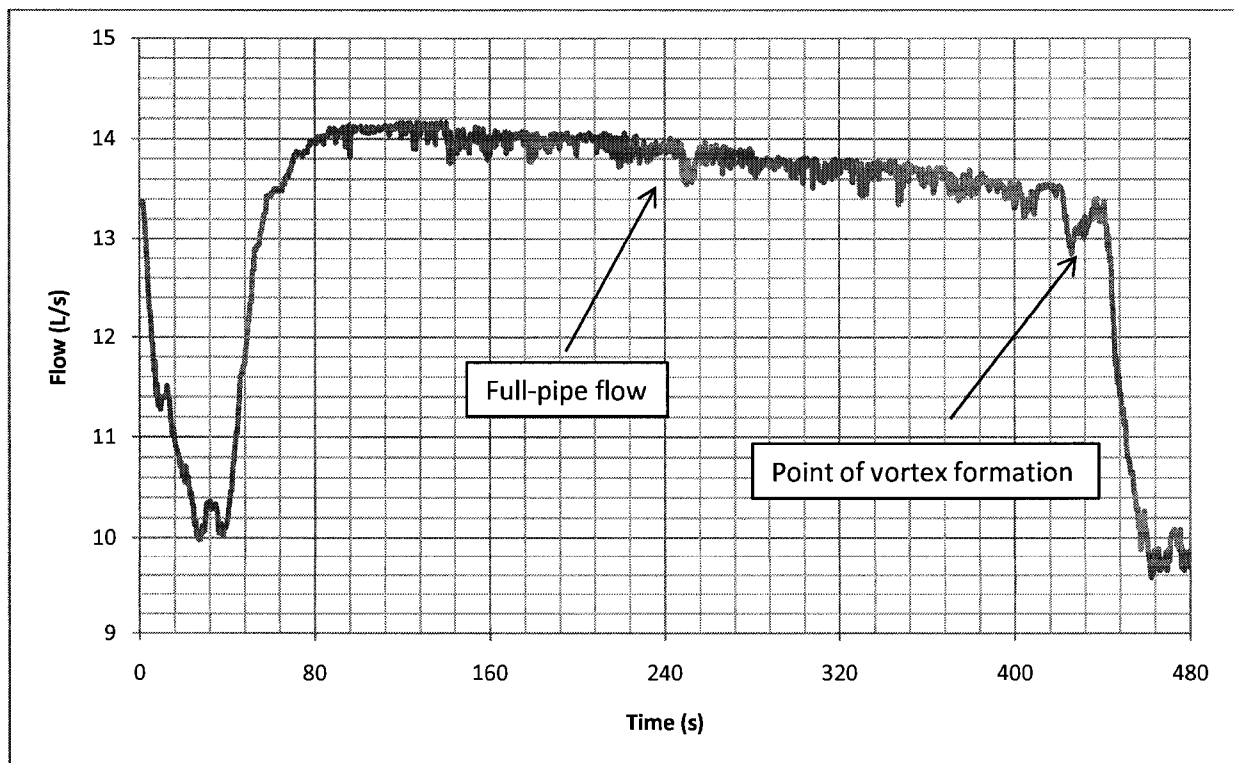


Figure 5.6: Sample results of flow under unstable-vortex flow ($Q_m = 13.22$ L/s, $[h/d]_m = 4.65$)

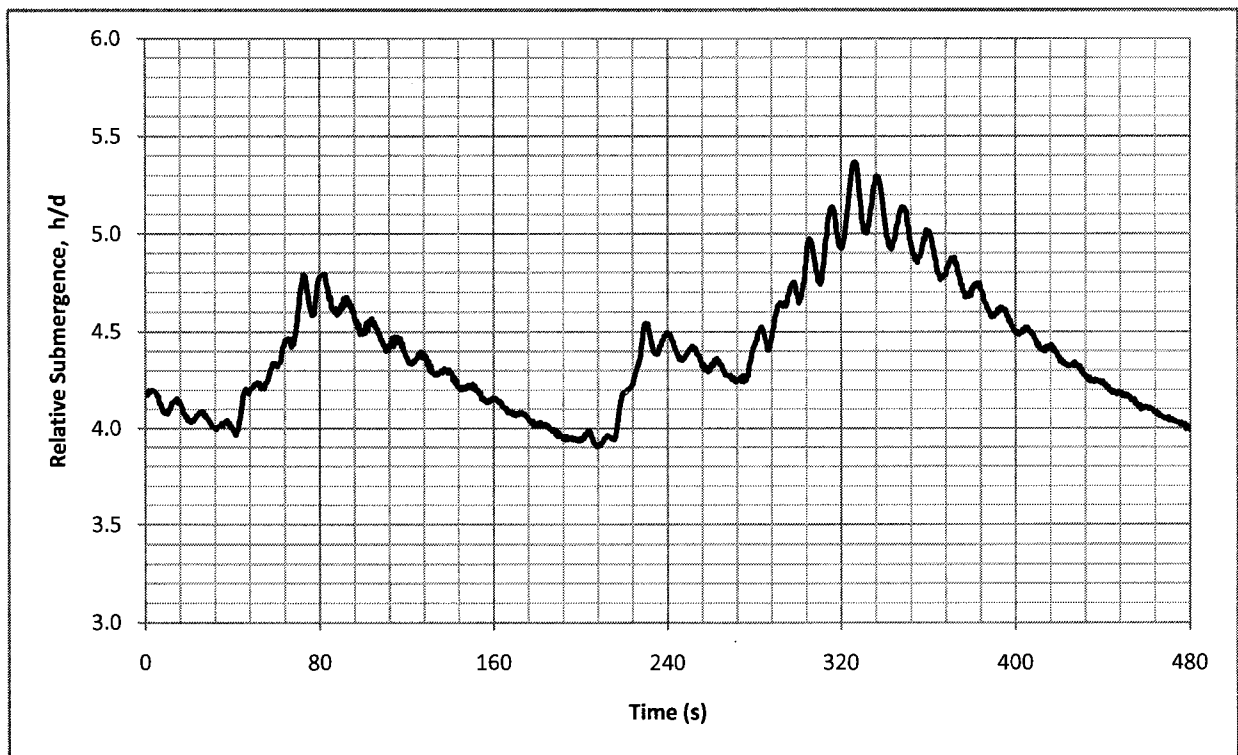


Figure 5.7: Sample results of submergence under unstable-vortex flow ($Q_m = 12.86$ L/s, $[h/d]_m = 4.40$)

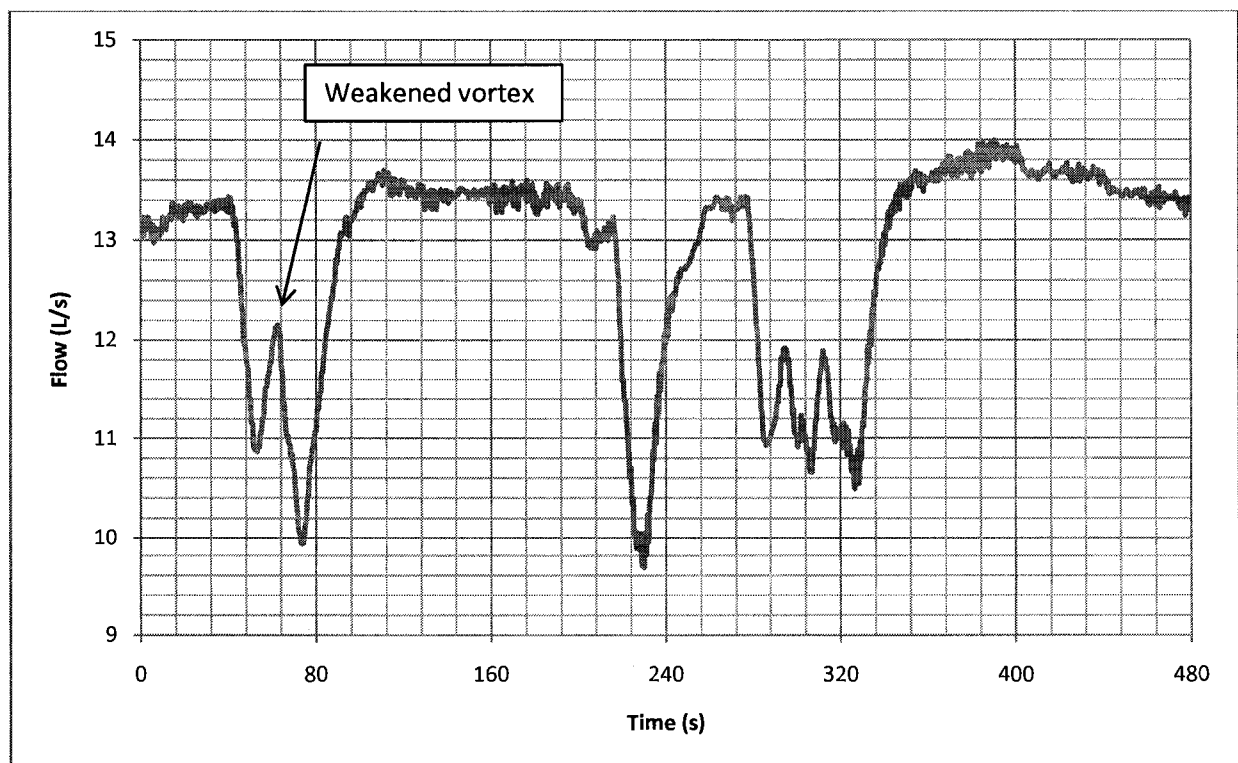


Figure 5.8: Sample results of flow under unstable-vortex flow ($Q_m = 12.86$ L/s, $[h/d]_m = 4.40$)

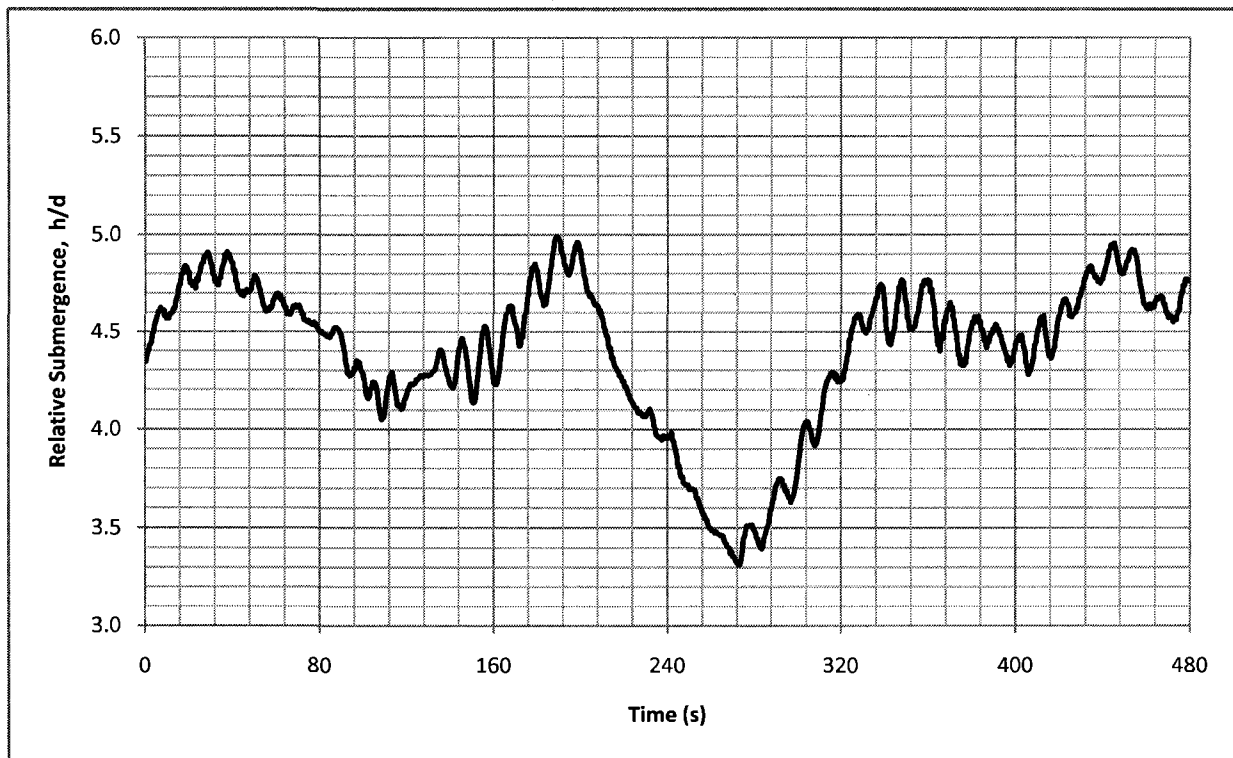


Figure 5.9: Sample results of submergence under unstable-vortex flow ($Q_m = 10.24$ L/s, $[h/d]_m = 4.40$)

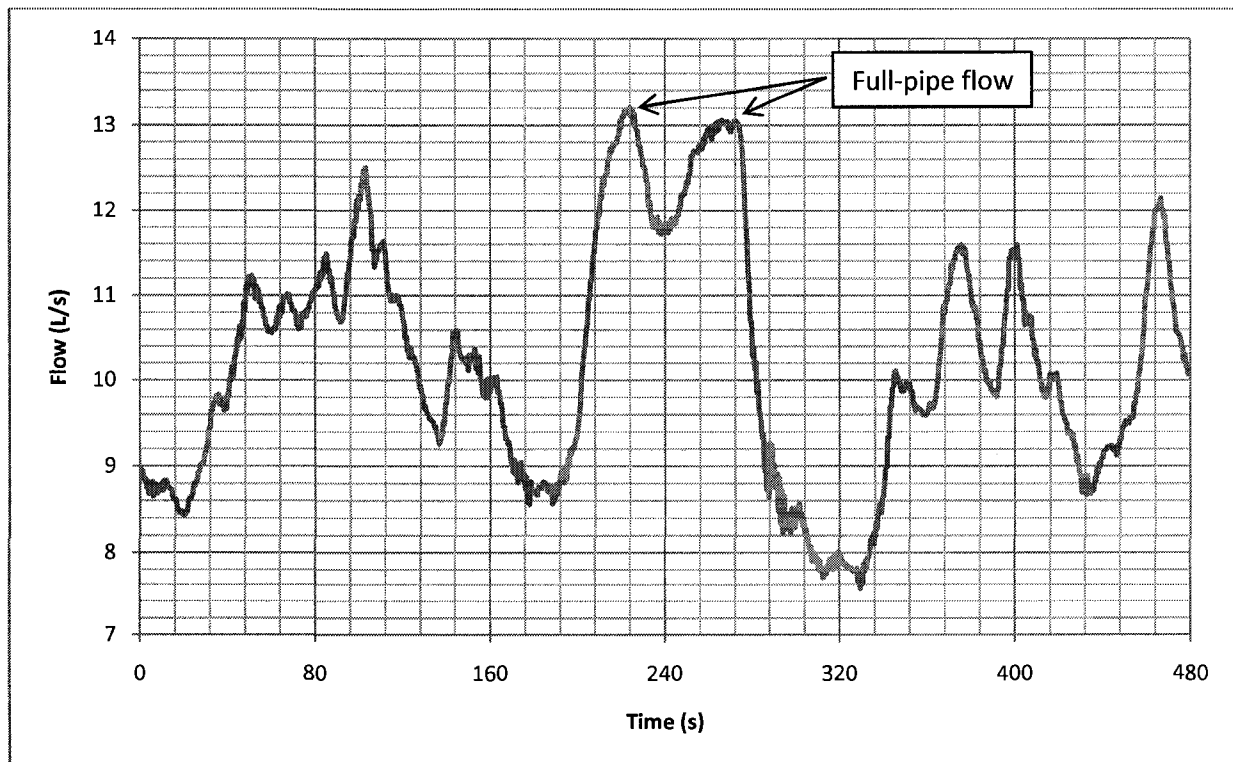


Figure 5.10: Sample results of flow under unstable-vortex flow ($Q_m = 10.24$ L/s, $[h/d]_m = 4.40$)

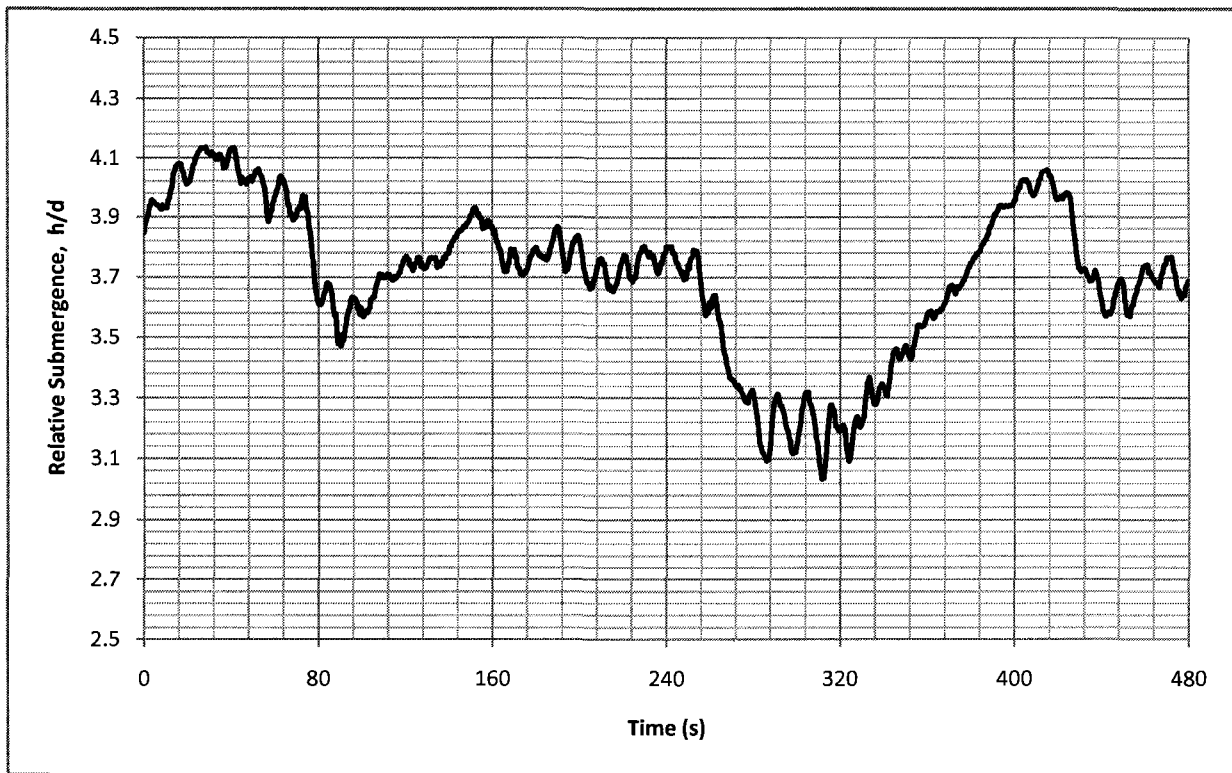


Figure 5.11: Sample results of submergence under unstable-vortex flow ($Q_m = 8.53$ L/s, $[h/d]_m = 3.70$)

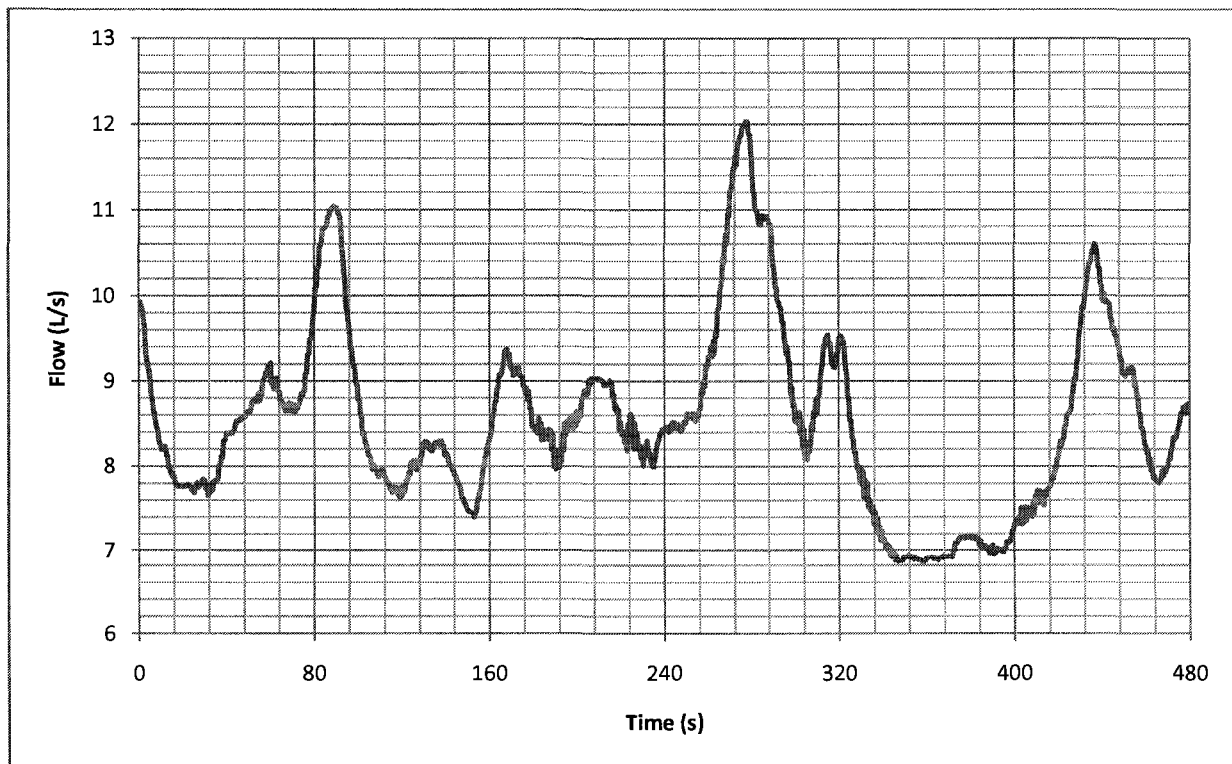


Figure 5.12: Sample results of flow under unstable-vortex flow ($Q_m = 8.53$ L/s, $[h/d]_m = 3.70$)

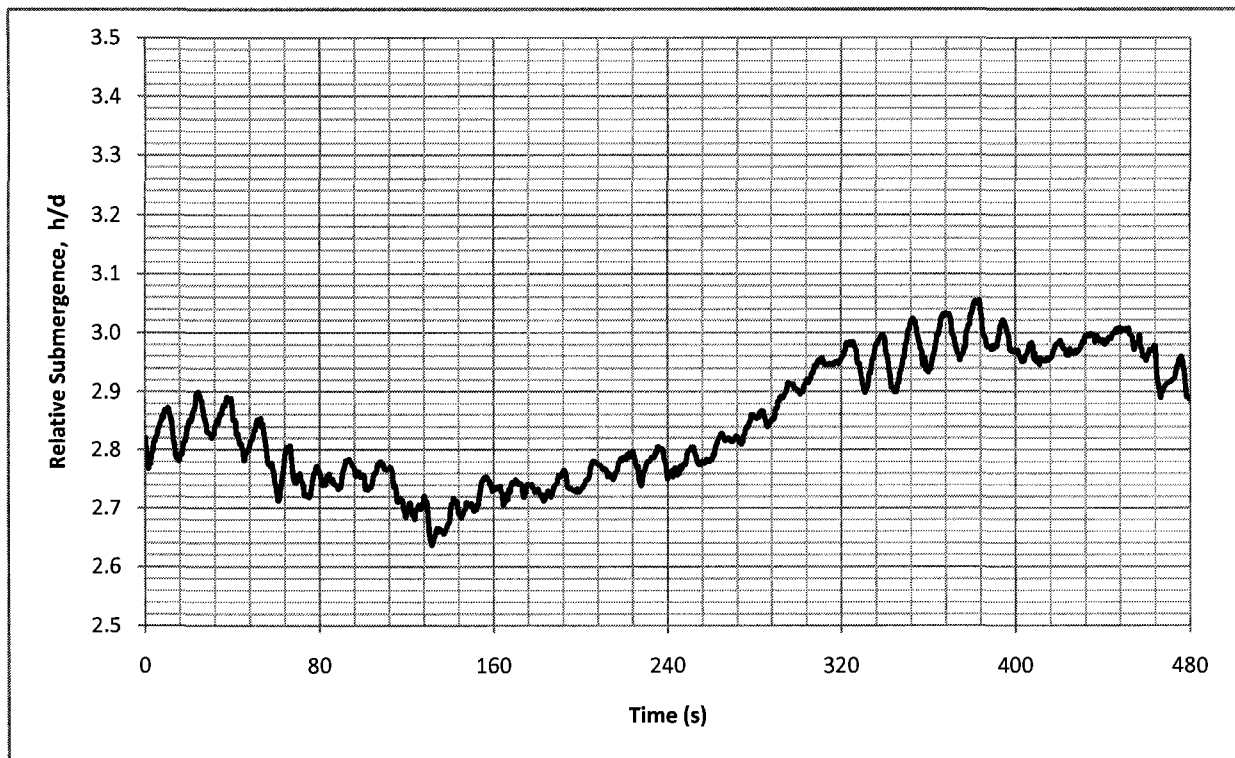


Figure 5.13: Sample results of submergence under unstable-vortex flow ($Q_m = 6.30$ L/s, $[h/d]_m = 2.85$)

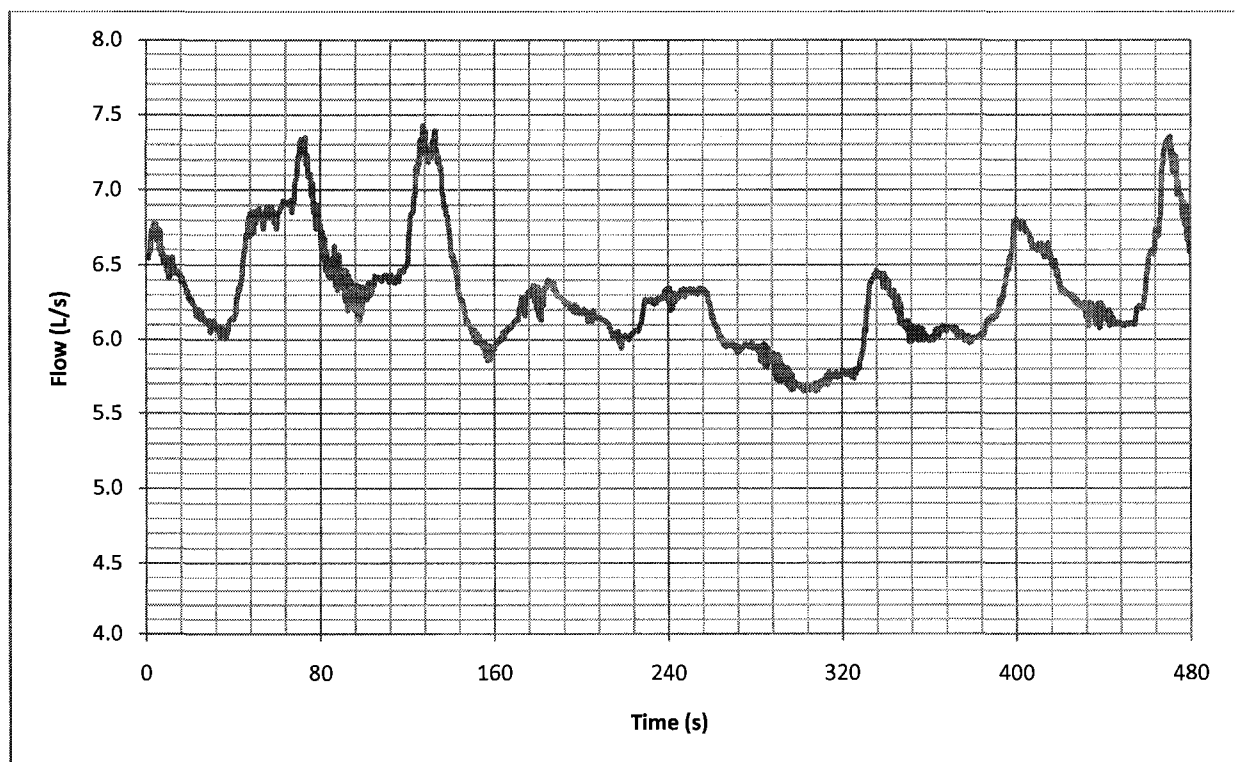


Figure 5.14: Sample results of flow under unstable-vortex flow ($Q_m = 6.30$ L/s, $[h/d]_m = 2.85$)

Figure 5.5 through Figure 5.14 provide examples of the different types of results obtained as well as a means to describe the dynamics of the flow and submergence in this unsteady range of flows. All of the sample results provided in this study were obtained using the abrupt-entry intake. Each pair of figures presents the 8 minute time series of both submergence and flow. Figure 5.5 and Figure 5.6 show the relative submergence (h/d) and flow, respectively, as a function of time when the average relative submergence and flow are 4.65 and 13.22 L/s. Figure 5.7 and Figure 5.8 show the same but at $(h/d)_m = 4.40$ and $Q_m = 12.86$ L/s; Figure 5.9 and Figure 5.10 at $(h/d)_m = 4.40$ and $Q_m = 10.24$ L/s; Figure 5.11 and Figure 5.12 at $(h/d)_m = 3.70$ and $Q_m = 8.53$ L/s; and Figure 5.13 and Figure 5.14 at $(h/d)_m = 2.85$ and $Q_m = 6.30$ L/s. Thus, each pair of figures presents the results at a lower inflow condition than the previous pair.

Figure 5.5 and Figure 5.6 represent a case that is slightly below critical. In these figures, the influence that the formation of a vortex has on flow characteristics can be viewed very clearly. These time series initially begin with the presence of a vortex which dissipates at approximately $t = 40$ seconds. Here it can be observed that the presence of a vortex results in a large decrease in the flow through the intake (roughly 30%). As the inflow supplied to the structure is constant, the decrease in outflow causes water to be stored inside the structure thereby resulting in an increase in the relative submergence of the intake. When the vortex has dissipated, the flow returns to the full-pipe condition. However, the intake submergence has been amplified by the vortex and is too high for the given inflow; therefore, the submergence begins to decrease as the system attempts to reach a stable condition. Nonetheless, as the stable full-pipe submergence at the given inflow rate is less than the critical value, the vortex reforms. This occurs at approximately $t = 440$ seconds.

The sinusoidal behavior of the intake submergence is due to the response of the 'two-tank' system used in these experiments. As discussed in Section 4.1, the inflow to the experimental drop structure is supplied by an upstream head tank which, under steady state conditions, maintains a constant water level. The abrupt change in intake submergence, caused by the vortex occurrence, results in a difference in water surface elevation between the intake structure and the head tank. The sinusoidal-type oscillations in submergence are due to the system trying to eliminate this difference and return to a steady state condition. This is one reason why the results were temporally averaged as instantaneous measurements of submergence are distorted by this effect. It should also be noted that the aforementioned lag time between the submergence and flow measurements may also slightly influence the instantaneous measurements.

In Figure 5.7 and Figure 5.8, it can be seen that the frequency at which the vortices form is increased and the length of time that full-pipe flow is prevalent is accordingly decreased. It can also be seen that the intensity of the established vortices (indicated by the magnitude of the deviation from full-pipe flow) is not constant. The established vortices can become significantly weaker (or disappear completely) for a brief period of time and then quickly re-intensify (or reappear). Under their weakened condition, the vortices entrain less air and therefore result in a smaller decrease in flow. This is evidence of the unsteady nature of the vortices within this flow region.

Figure 5.9 and Figure 5.10 further show that the length of time, during which the intake is flowing full, continues to decrease as the inflow is decreased. They also show the erratic fluctuations in flow when the vortices are present; again providing evidence of unsteady flow.

Lastly, Figure 5.11 through Figure 5.14 show that, at relatively lower inflow rates (within the unstable-vortex range), vortex presence is observed almost constantly; however, their intensity is not consistent (indicated by continuous fluctuations in flow). The degree of these fluctuations tends to decrease with inflow. This reduction can also be observed in Figure 5.2, which shows that, below the peak at $2.9 \leq Fr \leq 3.1$, the standard deviation of the

flow continues to decrease until the stable-vortex flow region is reached at approximately $Fr \cong 1.0$.

Due to the relatively short duration of these tests, it is difficult to confidently state that the flow observed in the unstable-vortex region will continue to remain unsteady. Therefore, tests of extended duration should be used to validate this conclusion. The 120 minute tests described in Section 4.4 provide a means to observe the longer-term behavior of the flow in this region. Figure 5.15 through Figure 5.18 present some of the results from these lengthened tests. In these figures, for easier comparison, the flow has been normalized by dividing the instantaneous flow $Q(t)$ by the mean recorded flow Q_m . The sequencing of the figures is such that each successive one presents the results from a test with a smaller inflow rate.

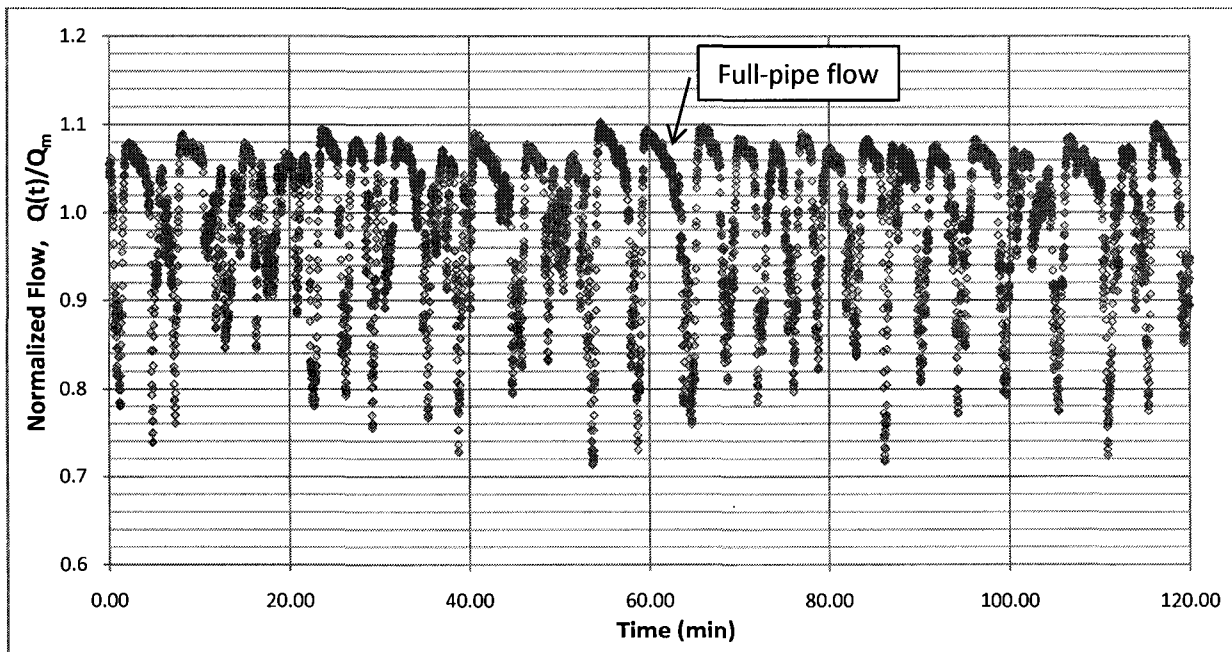


Figure 5.15: Sample of flow results from an extended 120 min. test ($Q_m = 12.18$ L/s, $[h/d]_m = 4.51$)

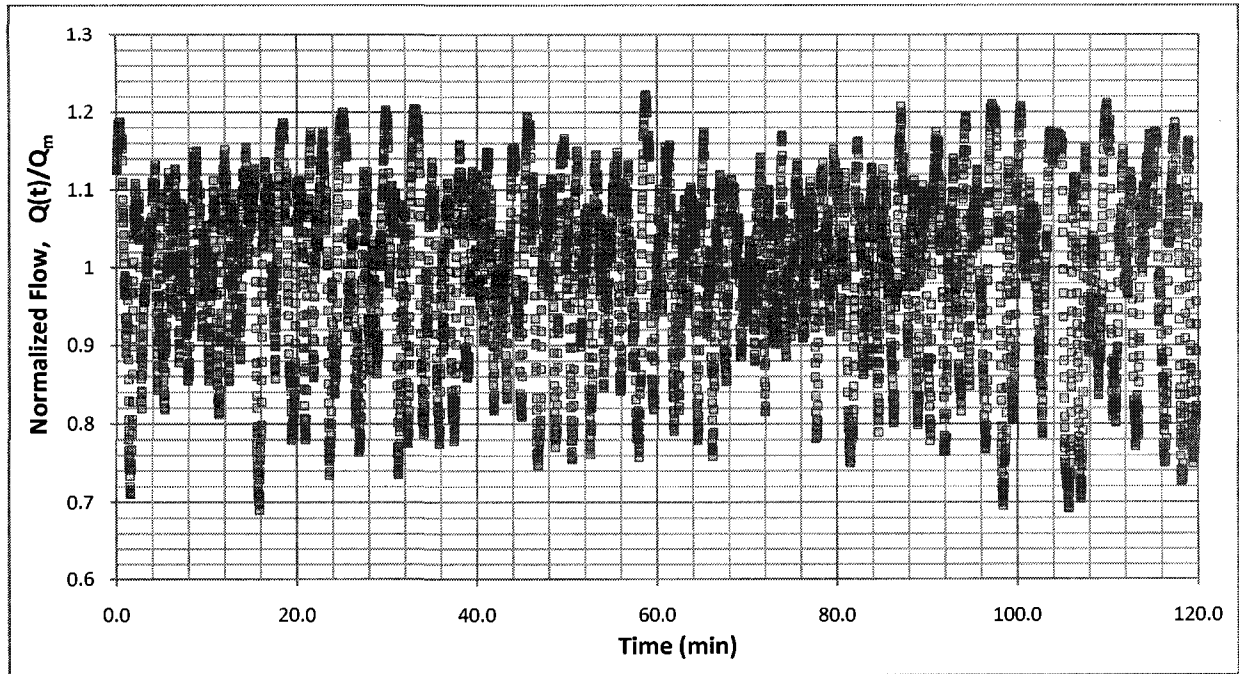


Figure 5.16: Sample of flow results from an extended 120 min. test ($Q_m = 10.58$ L/s, $[h/d]_m = 4.25$)

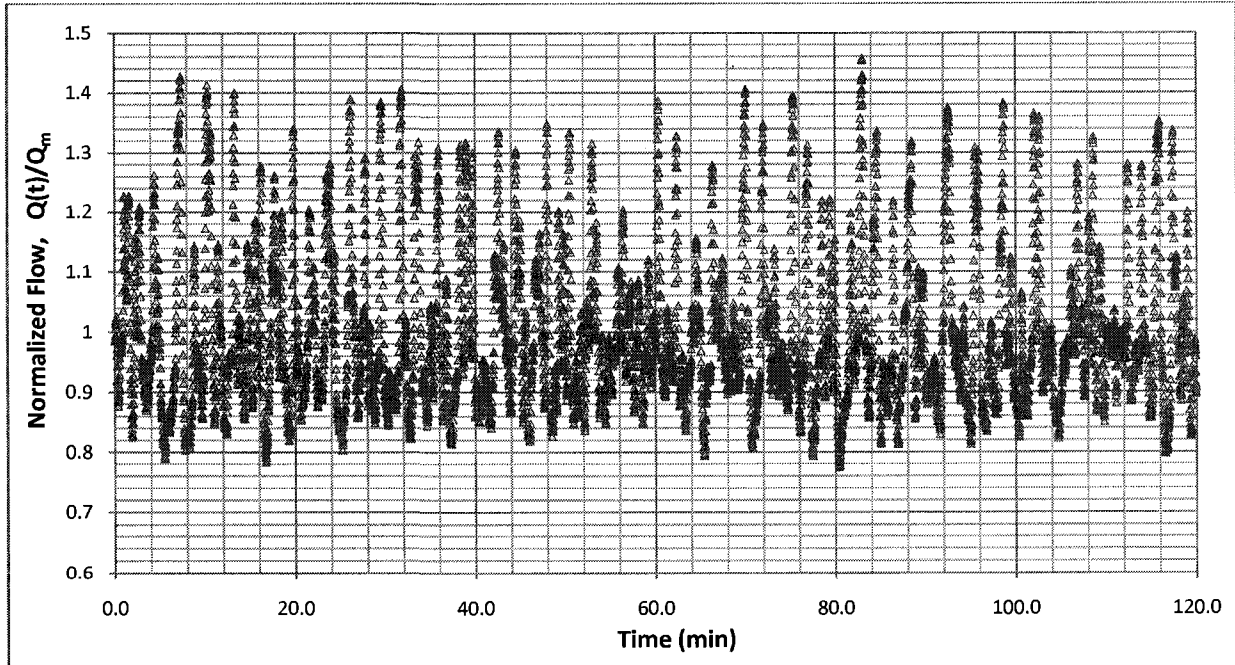


Figure 5.17: Sample of flow results from an extended 120 min. test ($Q_m = 8.24$ L/s, $[h/d]_m = 3.54$)

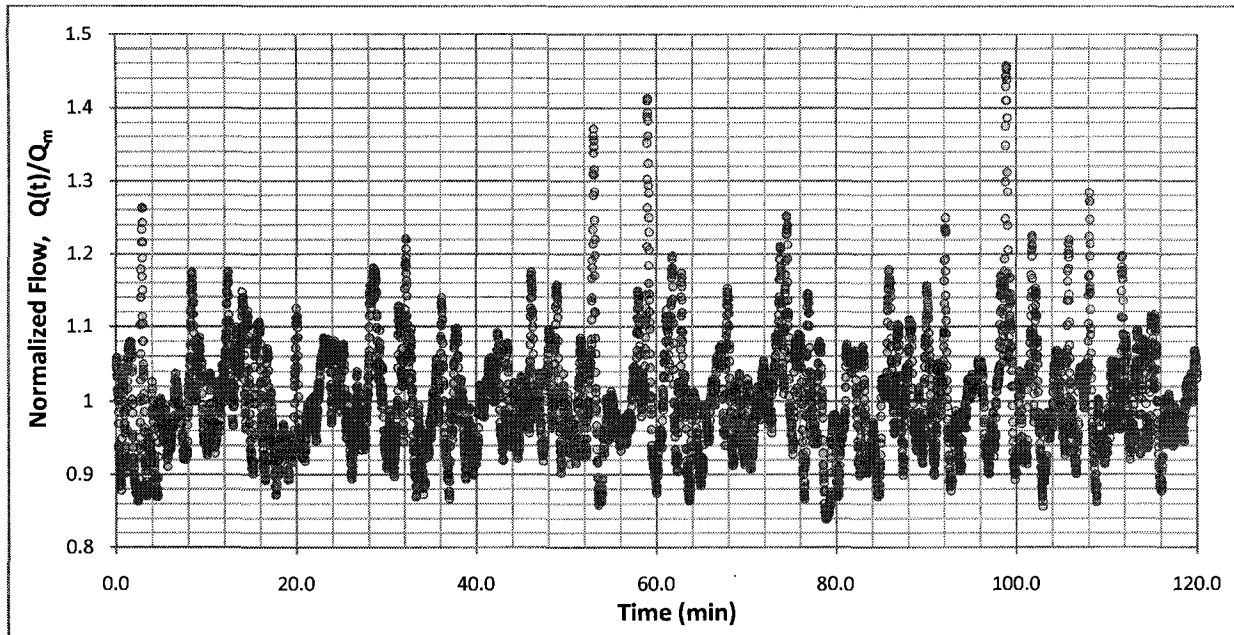


Figure 5.18: Sample of flow results from an extended 120 min. test ($Q_m = 6.87$ L/s, $[h/d]_m = 2.88$)

Similar to Figure 5.6, Figure 5.15 shows that at conditions near critical, full-pipe flow (indicated by the tightly bound, downward sloping clusters of data points) prevails for much of the duration of the test. The full-pipe flow is, however, continuously interrupted by the formation of vortices. The frequency of these vortices does not appear to be either increasing or decreasing; therefore it is reasonable to assume that this behavior will continue without approaching a steady condition. Figure 5.16 shows that, at a lower inflow, vortices are formed much more frequently and, accordingly, that the length of time in which the intake is flowing full is decreased. Figure 5.17 shows that full-pipe flow (indicated by the nearly vertical lines of data points) is continuing to occur less frequently and for only very short periods of time. Lastly, Figure 5.18 shows the same trend; full-pipe flow occurs extremely infrequently and exists only for a very brief period of time.

In Figure 5.15 through Figure 5.18, it is apparent that the flow is not approaching a stable condition of any kind. Therefore, it can be concluded with reasonable confidence that the intake flow within the unstable-vortex region is indeed unsteady and will not reach a stable condition, regardless of the length of time allowed.

By inspection of Figure 5.15: Sample of flow results from an extended 120 min. test ($Q_m = 12.18$ L/s, $[h/d]_m = 4.51$), it appears that the vortices are occurring at a relatively constant frequency. Although not performed in this study, in the future, spectral analysis of results obtained from tests of such long duration may be performed to evaluate the periodicity of vortex formation. This would allow for a more thorough investigation into the time dependency of vortex occurrence. Unfortunately however, in the current experiments, the 120 minute tests were only performed for the reference case; therefore, such an analysis could not be used to compare the results obtained using the different intake entrance shapes.

5.2.3 STABLE-VORTEX FLOW

As the inflow is continually reduced, the unstable nature of the established vortices ceases to exist. In the reference case, once the intake Froude number becomes less than approximately $Fr = 1.0$, both the presence and intensity of the intake vortex become constant. In other words, a vortex of consistent size and intensity is observed all of the time. As shown in Figure 5.1, in the stable-vortex region, if the intake Froude number is plotted against the relative submergence, a linear relationship is observed.

A low-head stable vortex, as described in Section 3.1.5.2, has a larger air-core than the unstable vortices observed under greater submergence conditions and its position remains fixed directly above the intake. As the intensity of the vortex remains constant, the flow conditions at the intake remain unchanged; therefore, the submergence and flow through the intake are also constant. This can be observed in Figure 5.2 and Figure 5.3, where, for the reference case, the standard deviation of both flow and submergence are less than 0.10. Figure 5.19 provides some examples of the stable vortices observed during the experiments. In this figure, it can be seen that the vortices have a well defined shape and that the water surface above the intake is relatively calm and stable.

Figure 5.20 through Figure 5.23 provide some examples of the results obtained in the stable-vortex flow range. It can be seen in these figures that, aside from some minor fluctuation, the measurements of submergence and flow are both relatively stable. The

reason for the fluctuations is not clear. However, as they appear to be evenly distributed about the mean value, their influence should be eliminated by averaging the results over time.

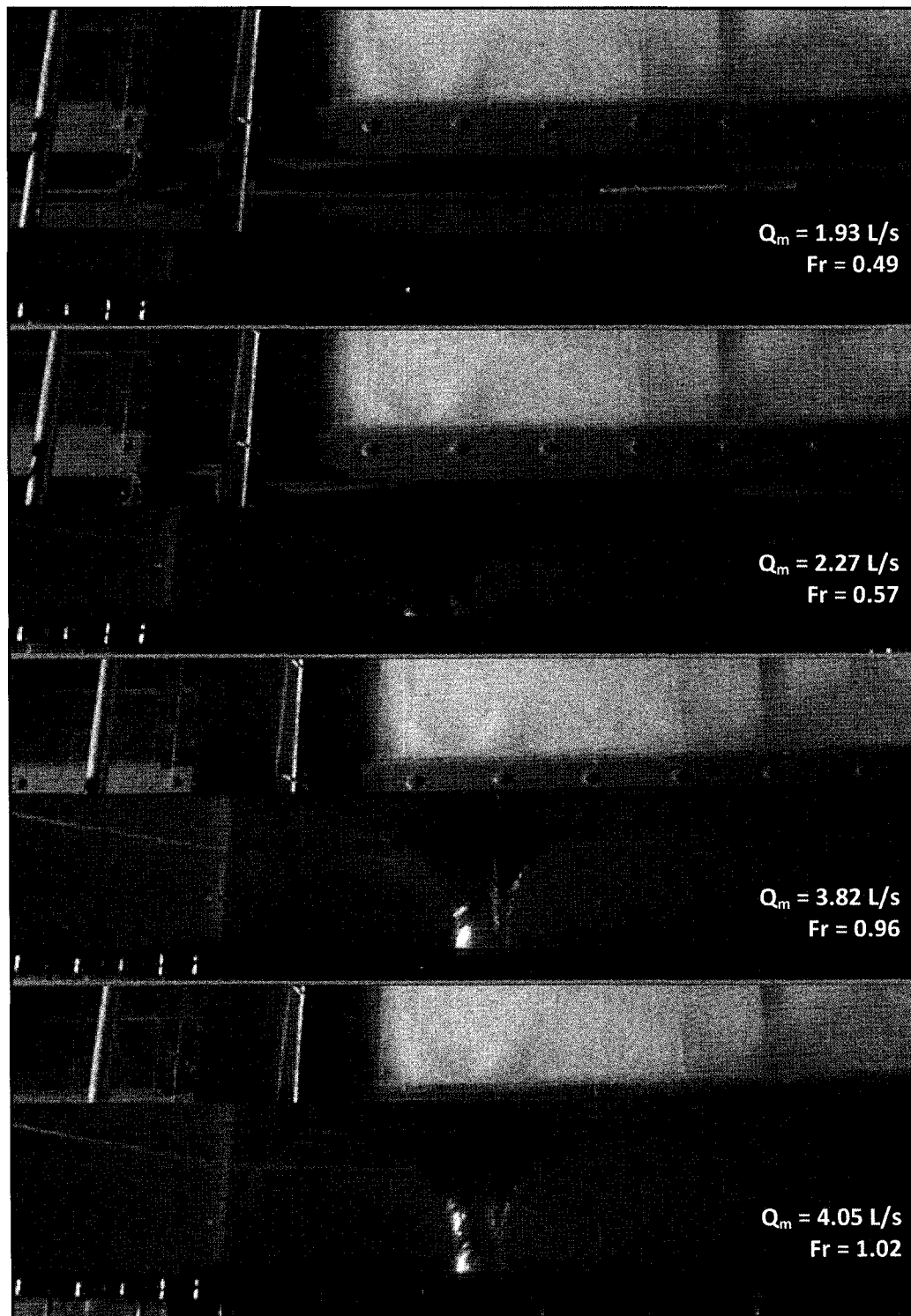


Figure 5.19: Examples of stable vortices observed during testing with the abrupt-entry intake

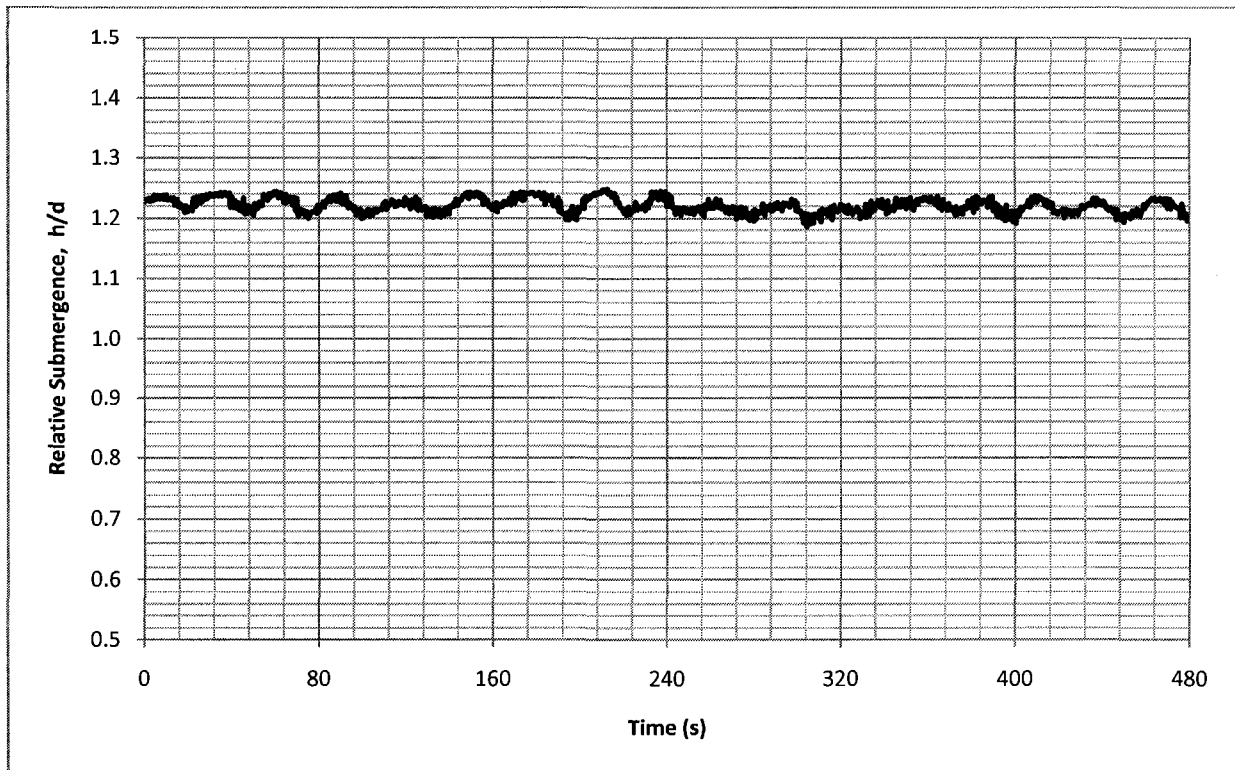


Figure 5.20: Sample results of submergence under stable-vortex flow ($Q_m = 3.11$ L/s, $[h/d]_m = 1.34$)

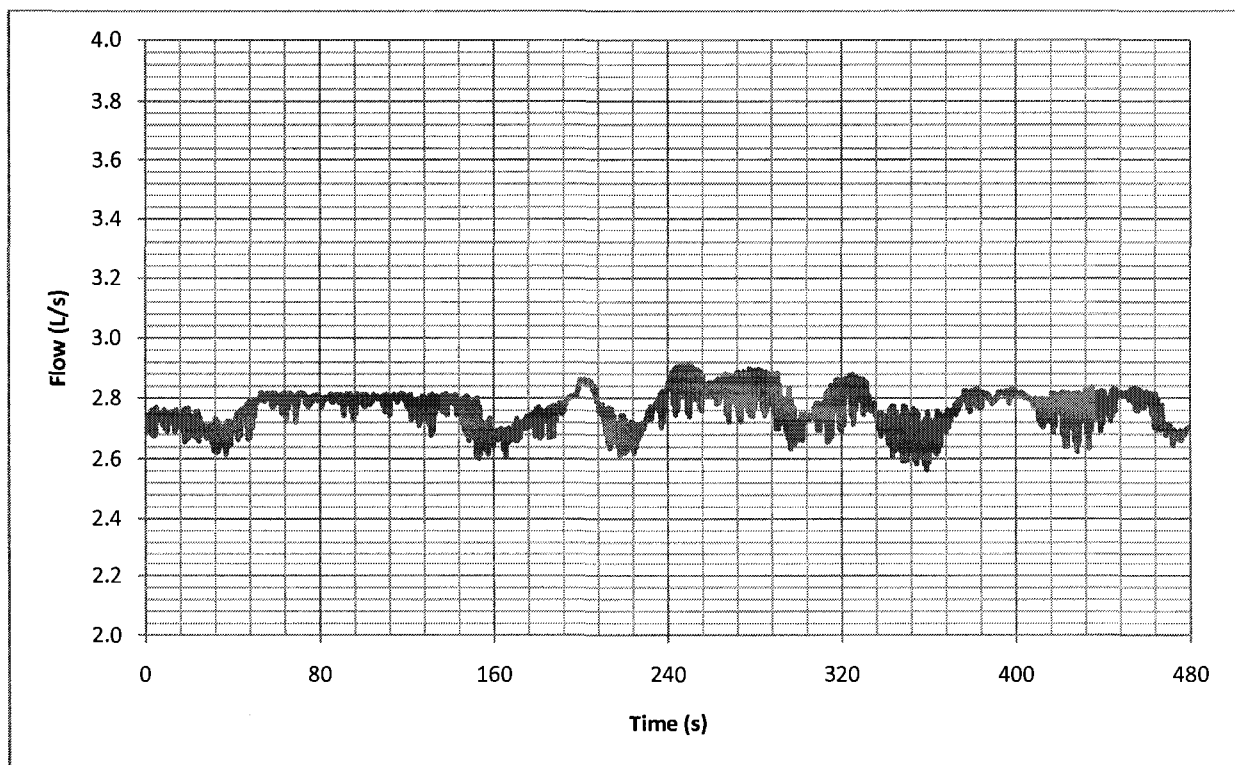


Figure 5.21: Sample results of flow under stable-vortex flow ($Q_m = 3.11$ L/s, $[h/d]_m = 1.34$)

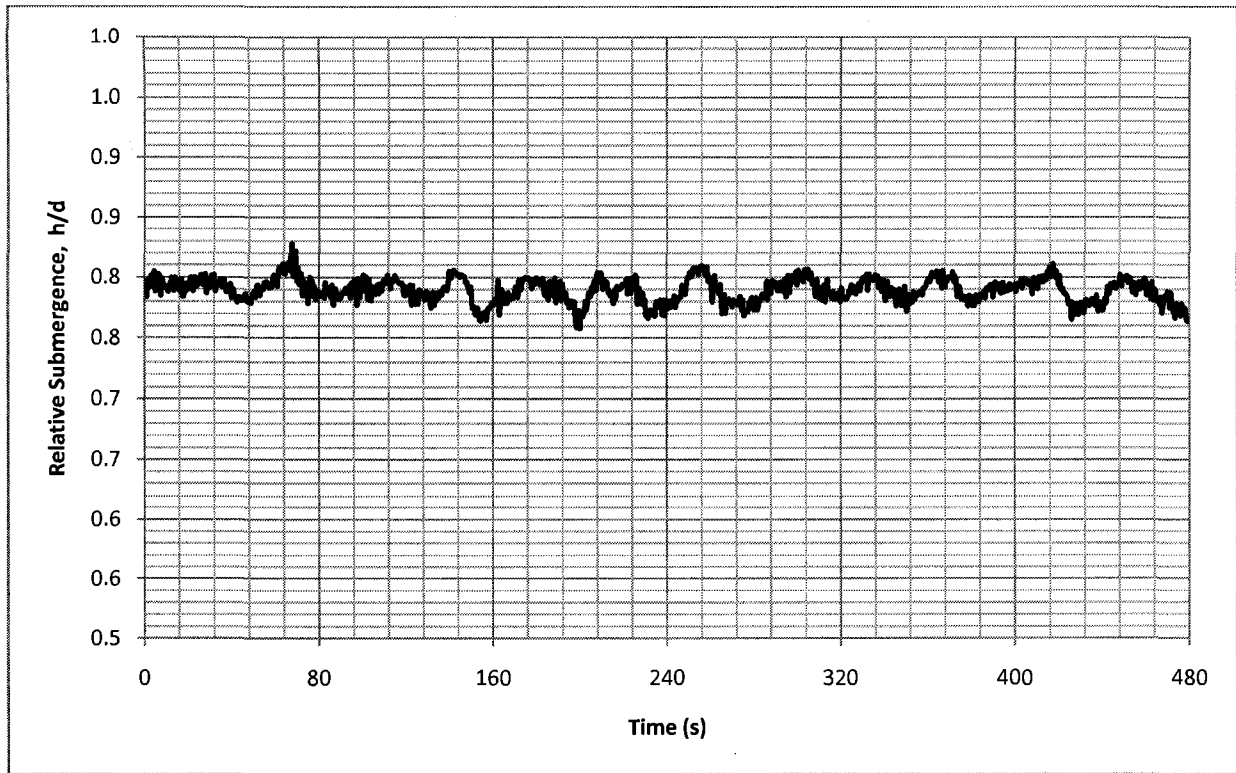


Figure 5.22: Sample results of submergence under stable-vortex flow ($Q_m = 1.45$ L/s, $[h/d]_m = 0.79$)

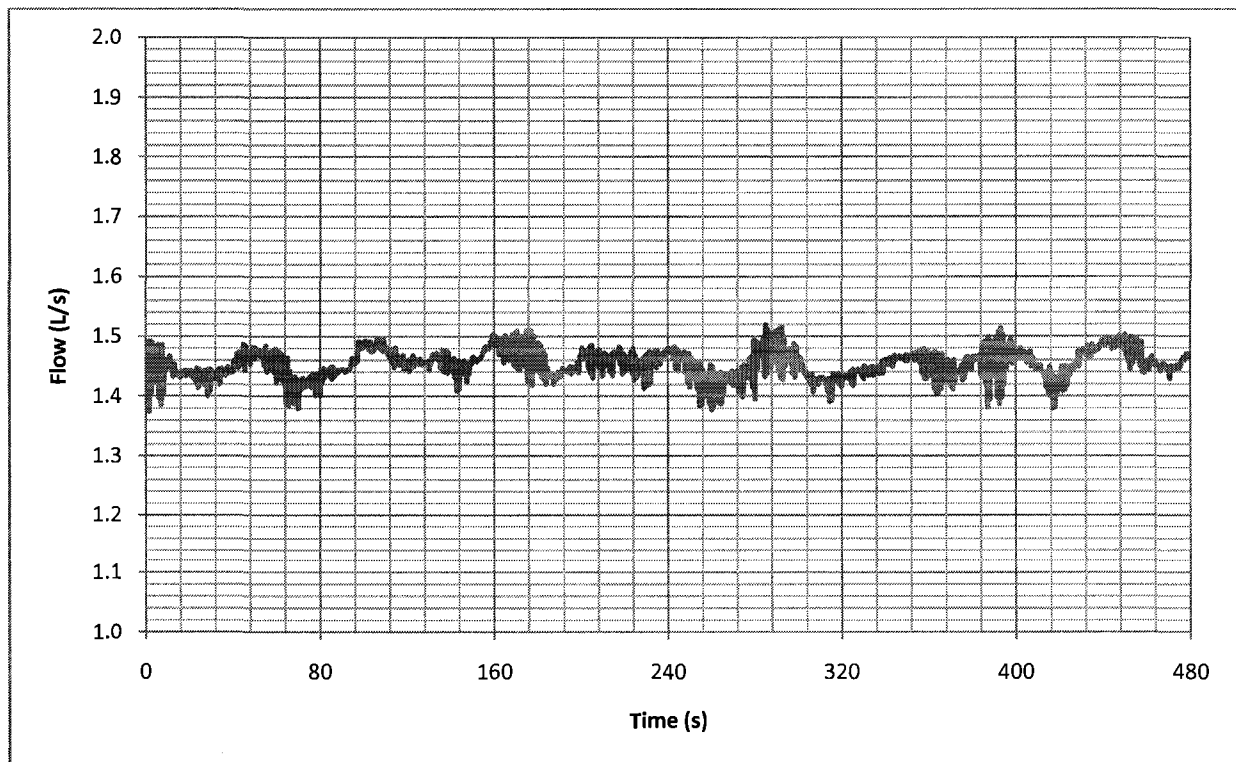


Figure 5.23: Sample results of flow under stable-vortex flow ($Q_m = 1.45$ L/s, $[h/d]_m = 0.79$)

5.3 INFLUENCE OF INTAKE ENTRANCE SHAPE

Figure 5.24 through Figure 5.31 present the results obtained from the tests performed using the various different intake entrance shapes. These tests were carried out using the 8 minute testing procedure outlined in Section 4.4. The results from the reference case have been included in each figure for direct comparison. From these figures it can be observed that all of the intake shapes tested allowed for a greater flow under all flow conditions, when compared to the reference case. Therefore, the assumption that the abrupt-entry intake is the worst performing intake is indeed correct. A comparison between all of the intakes tested under each individual type of flow is provided in Sections 5.3.1 through 5.3.3.

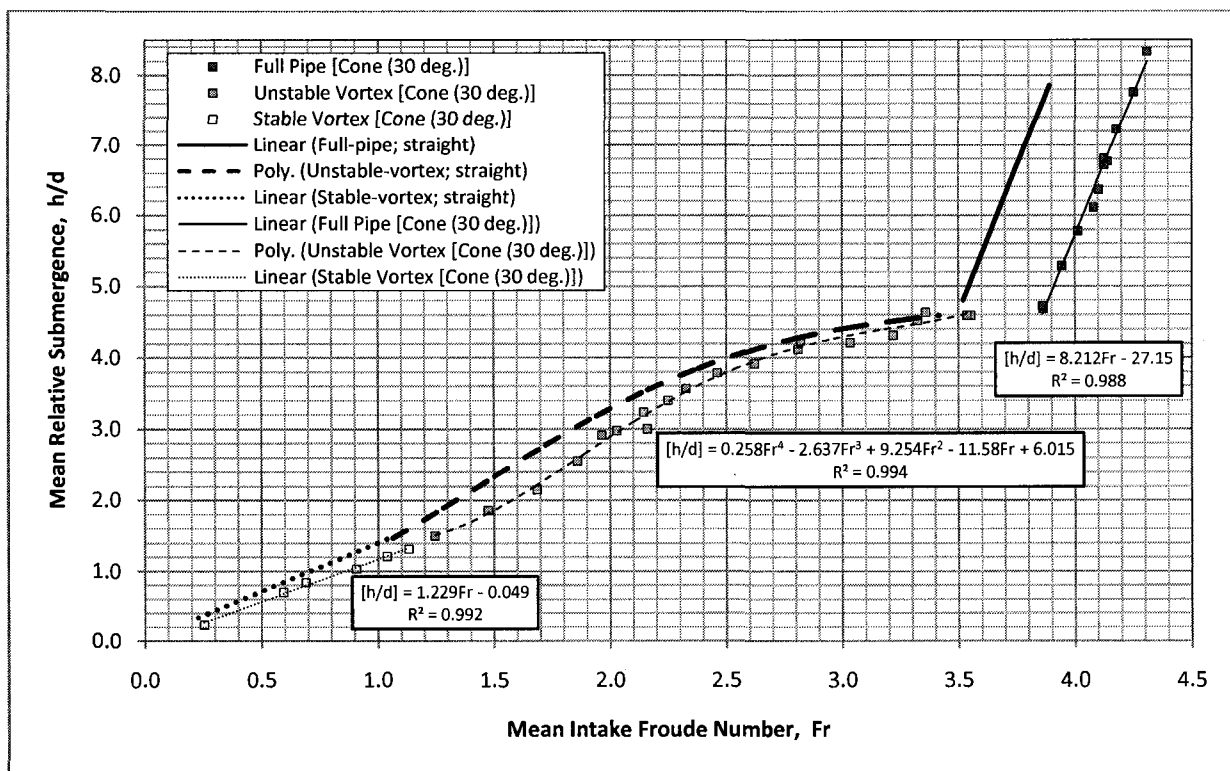


Figure 5.24: Relative submergence vs. intake Froude number for 30° cone intake

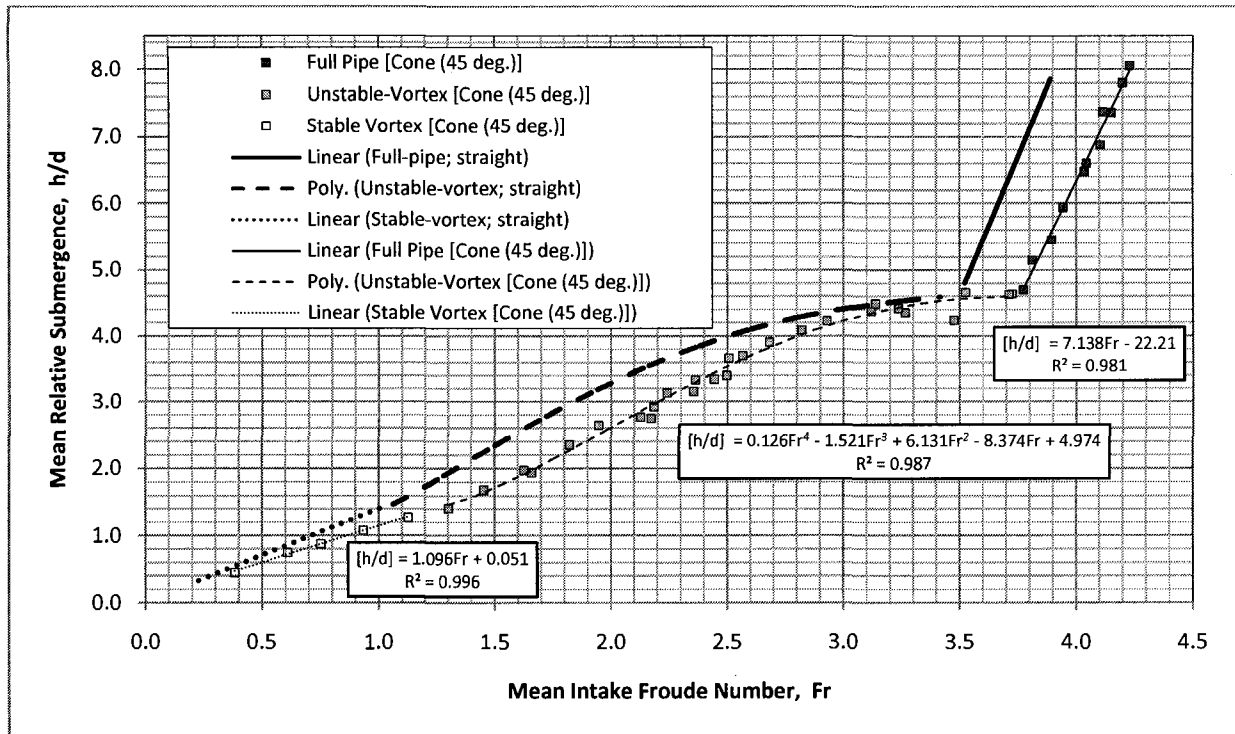


Figure 5.25: Relative submergence vs. intake Froude number for 45° cone intake

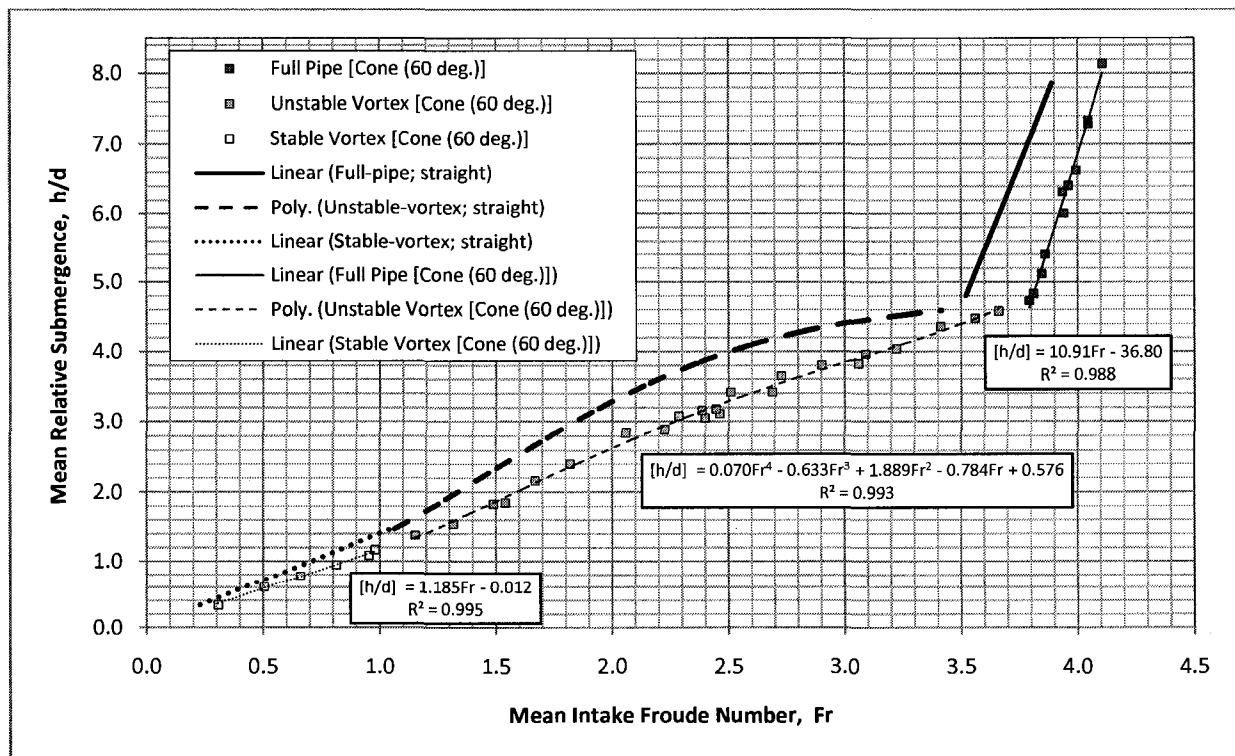


Figure 5.26: Relative submergence vs. intake Froude number for 60° cone intake

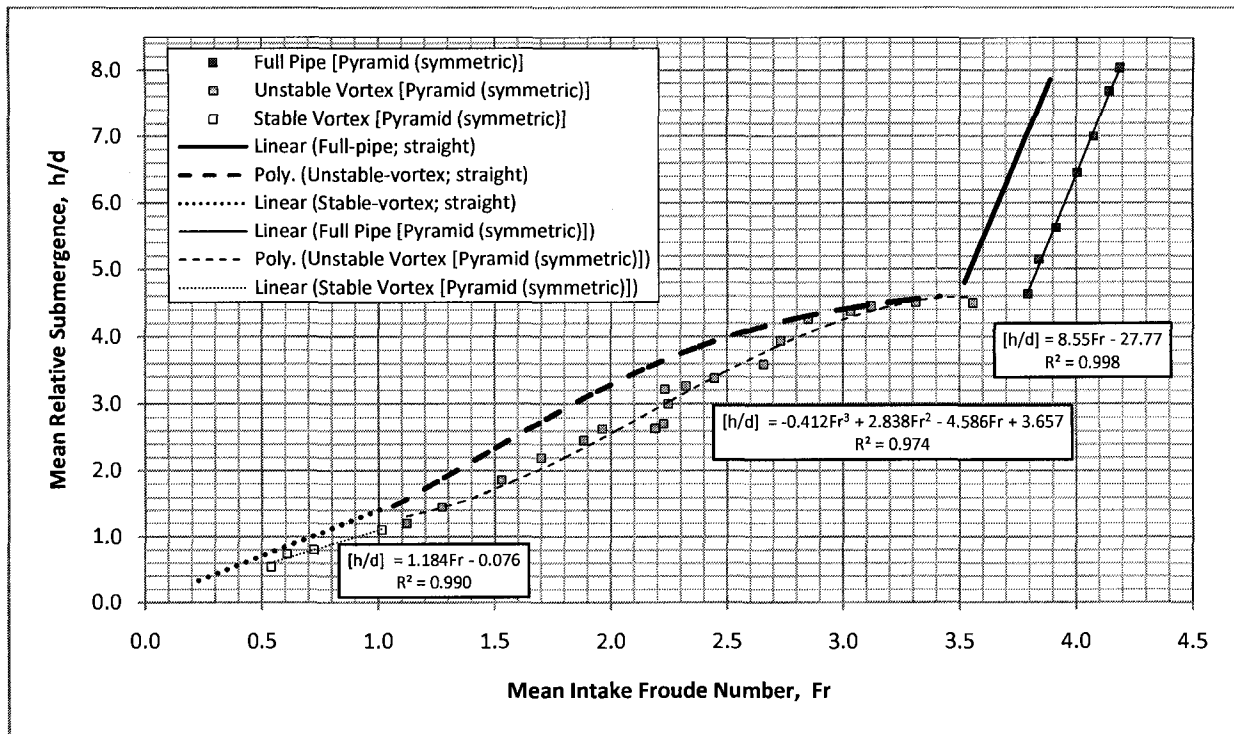


Figure 5.27: Relative submergence vs. intake Froude number for symmetrical pyramid intake

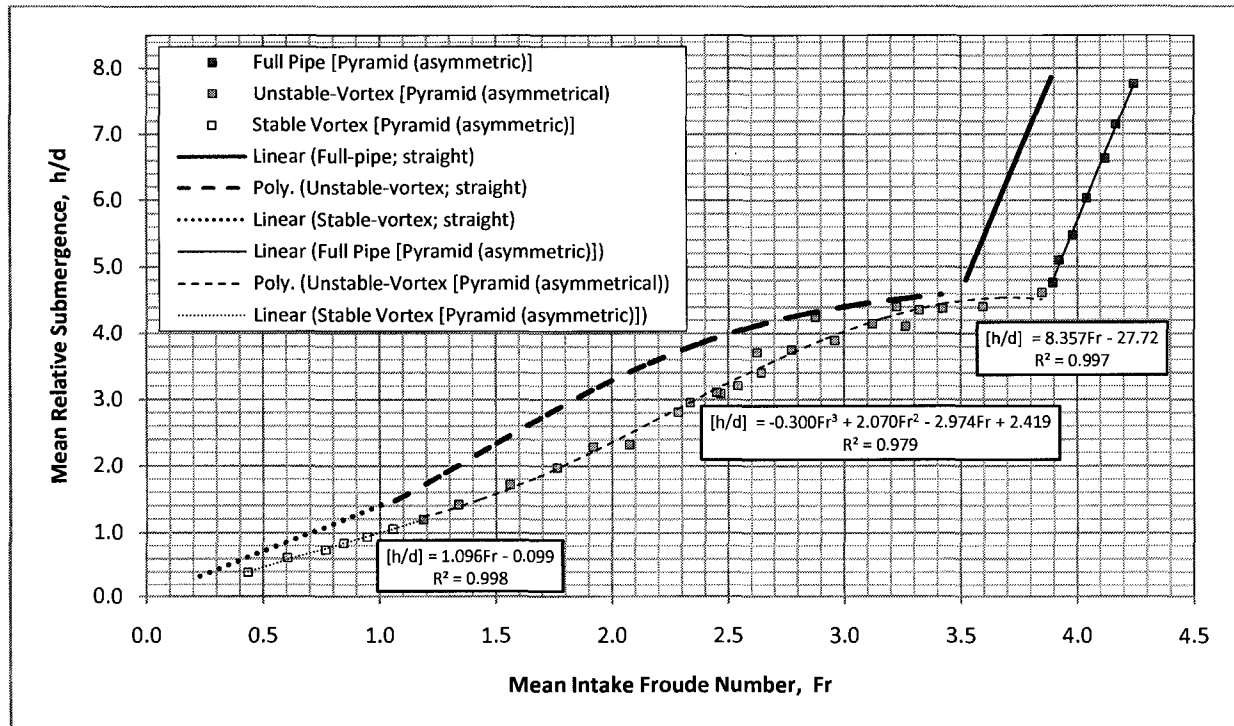


Figure 5.28: Relative submergence vs. intake Froude number for asymmetrical pyramid intake

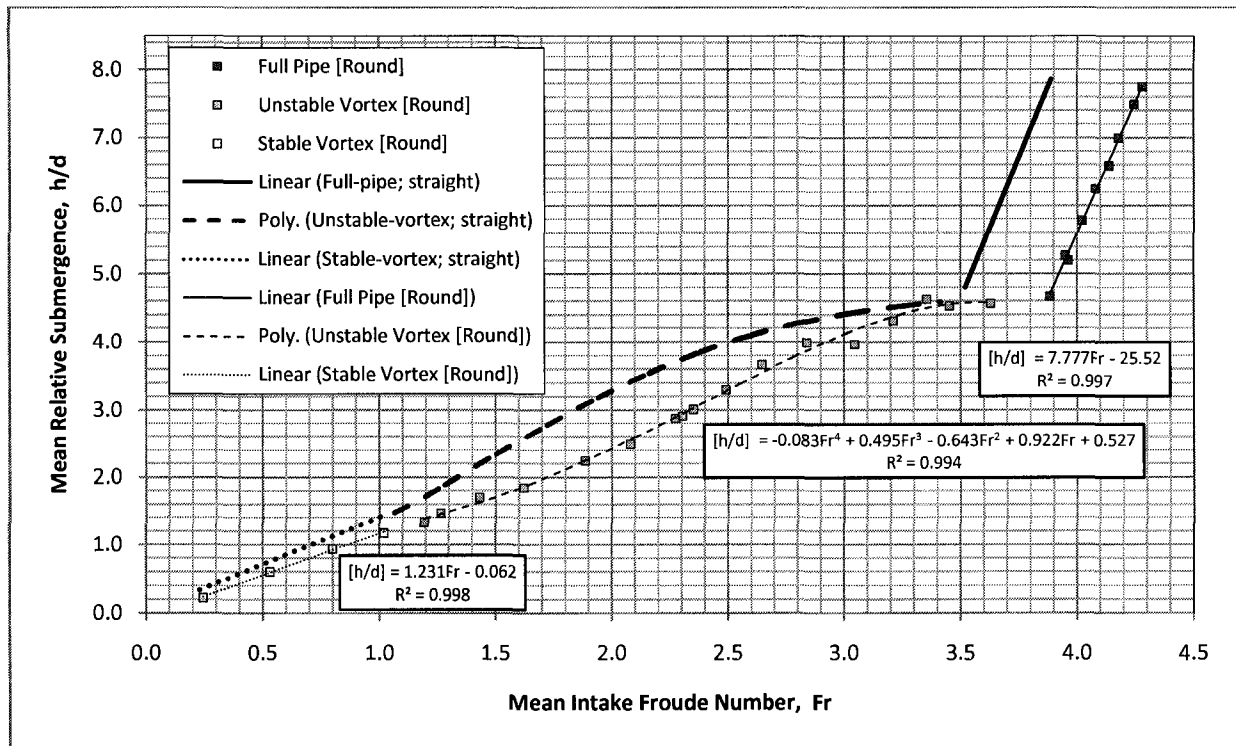


Figure 5.29: Relative submergence vs. intake Froude number for round intake

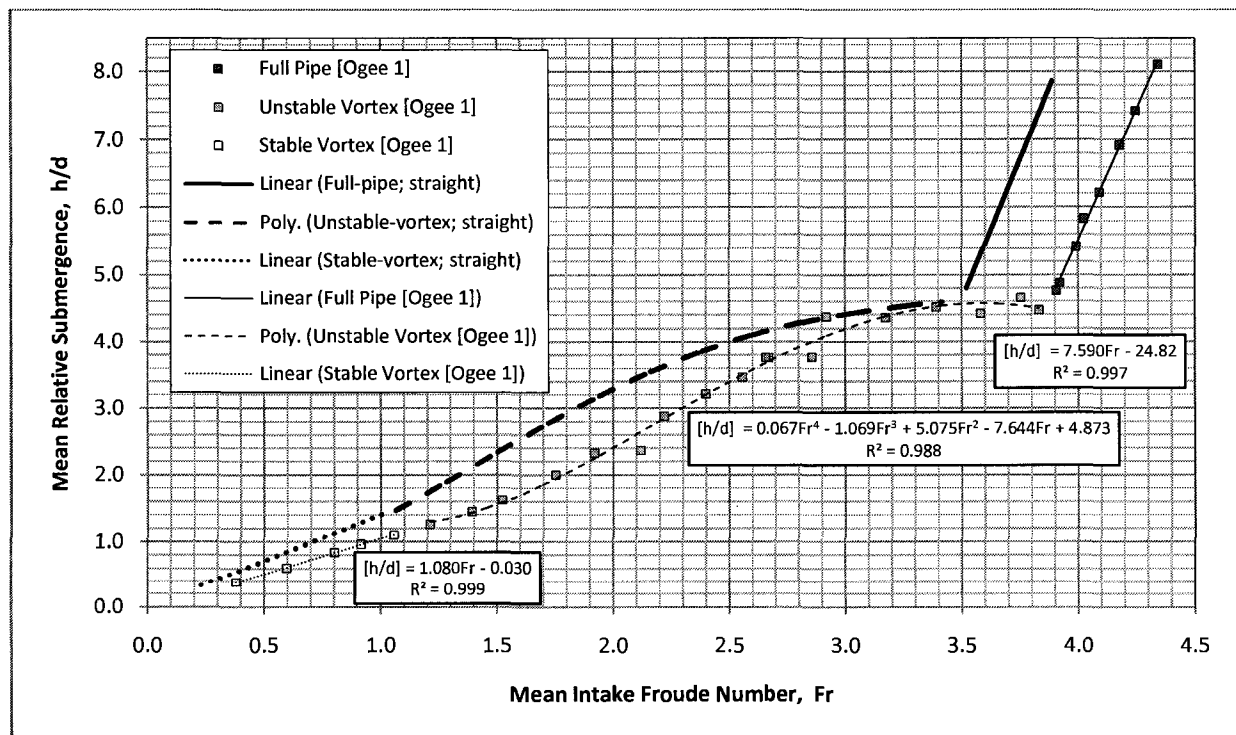


Figure 5.30: Relative submergence vs. intake Froude number for ogee 1 intake

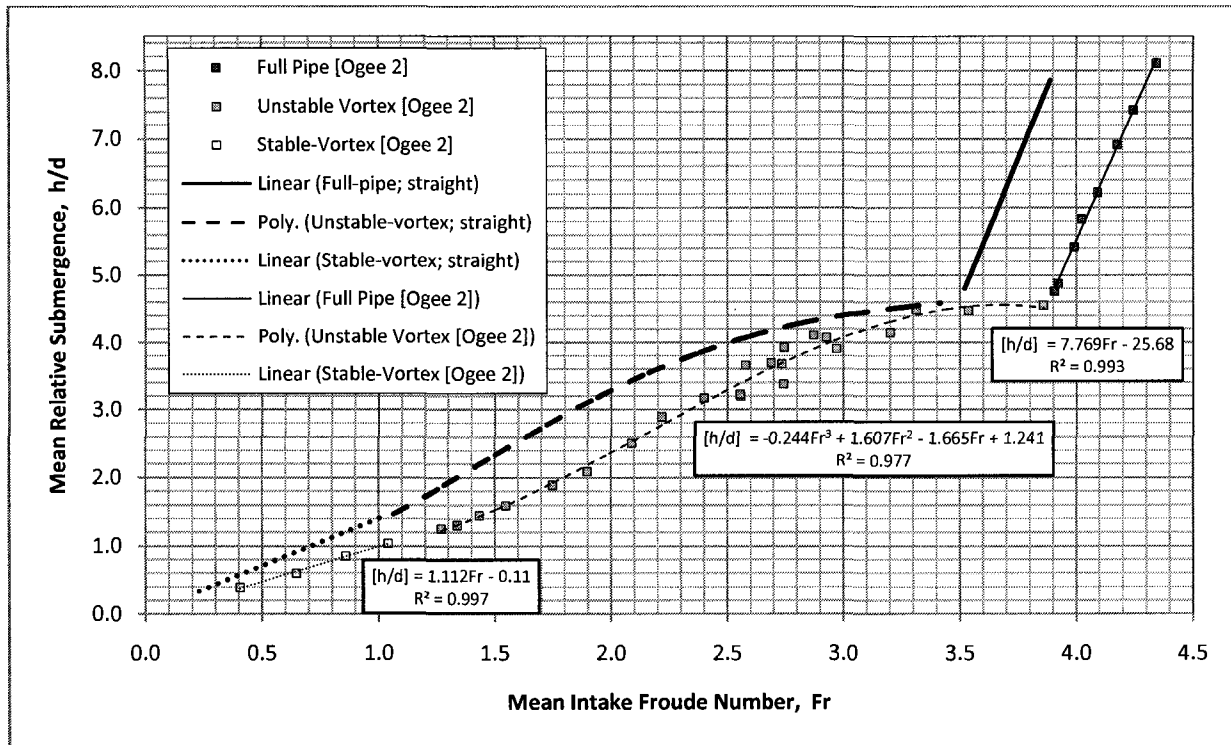


Figure 5.31: Relative submergence vs. intake Froude number for ogee 2 intake

5.3.1 FULL-PIPE FLOW

Figure 5.32 shows the full-pipe flow results from all of the intakes tested, as well as the reference case. In this figure, it can be seen that the shape of the intake does indeed influence the discharge capacity of the intake. The resulting data points, similarly, all produce linear relationships with nearly the same slope as the reference case. The only exception is the 60° cone intake which produced a slightly steeper slope such that it appears to be approaching the results from reference case as the submergence is increased. The reason for this is not exactly clear, however, a possible explanation may lie in this particular intake's relative likeness to the abrupt-entry intake. By inspection of Figure 4.6, it can be seen that, considering all of the intakes tested, the 60° cone intake is the 'flattest' and is most similar to the abrupt-entry intake in this regard. It may be possible that, under large submergence conditions, the influence of this relatively flat angle may be masked by the large depth of water. Following this theory, performance of the 60° cone intake should asymptotically

approach the performance of the abrupt-entry intake under very large submergence conditions.

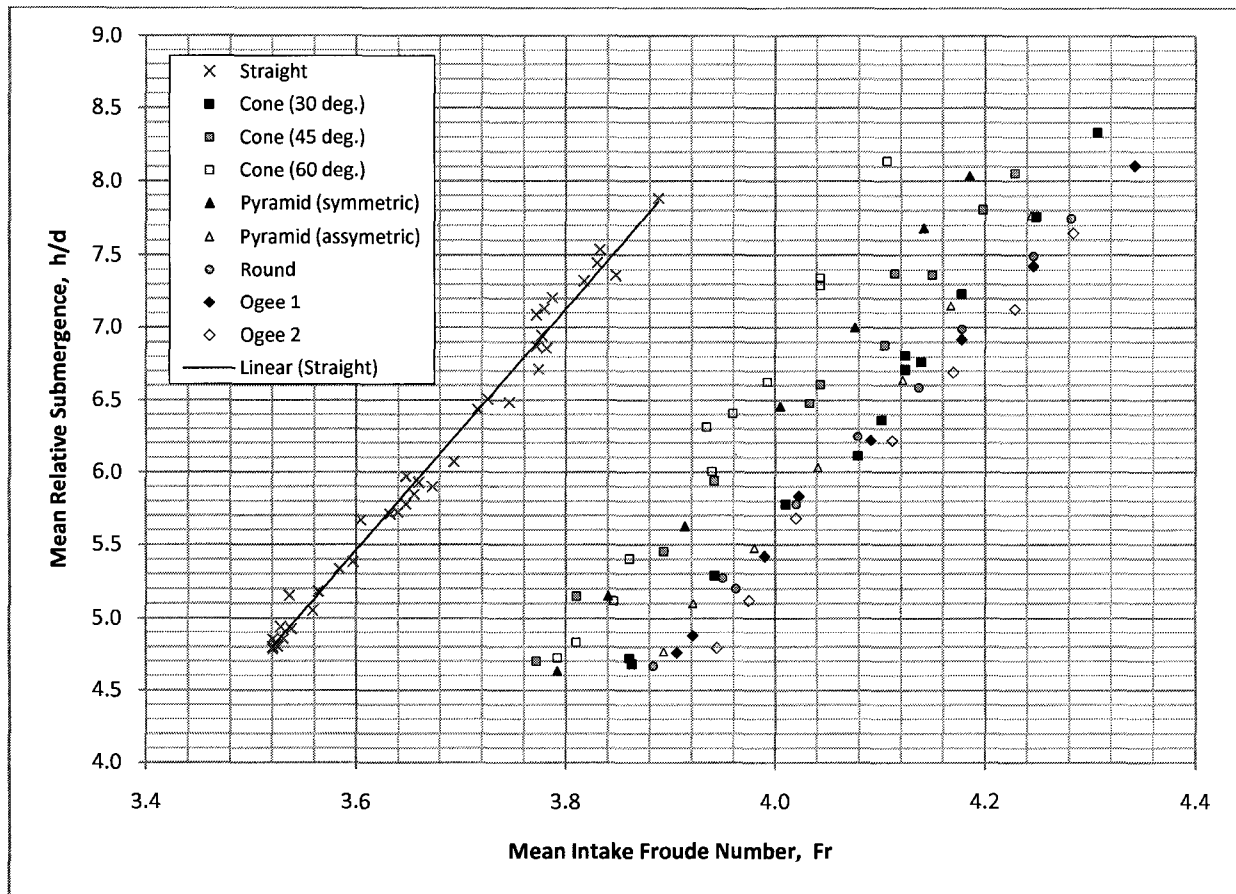


Figure 5.32: Relative submergence vs. intake Froude number for all intakes under full-pipe flow

As no vortices are observed in this range of flow, the likely reason for the increase in flow observed by all of the intakes is a reduction in head loss created by the gradual contraction of the entrance (shared by all of the intakes tested), compared to the abrupt-entry intake.

Table 5.1 presents the results in a quantitative manner and allows for a better comparison of the different intake shapes. From this table it can be seen that, depending on the intake shape and the submergence, the increase in flow (relative to the reference case) in the full-pipe region was observed to be between 5.1% and 11.5%. The most efficient intake

was found to be the Ogee 2 intake while the Ogee 1, Round and 30° cone intakes showed comparable efficiencies. The worst performing intake was found to be the 60° cone intake followed by the 45° cone and symmetric pyramid intakes.

Table 5.1: Intake shape results under full-pipe flow

[h/d]	Difference in flow rate compared to the reference case (%)								
	8.0	7.6	7.2	6.8	6.4	6.0	5.6	5.2	4.8
Cone (30 deg.)	9.6	9.7	9.8	9.9	10.1	10.2	10.3	10.4	10.6
Cone (45 deg.)	8.4	8.3	8.2	8.1	8.0	7.9	7.8	7.7	7.5
Cone (60 deg.)	5.1	5.5	5.9	6.3	6.7	7.1	7.5	7.9	8.4
Pyramid (sym.)	7.1	7.2	7.4	7.5	7.7	7.8	8.0	8.1	8.3
Pyramid (asym.)	9.4	9.6	9.7	9.8	10.0	10.1	10.3	10.4	10.6
Round	10.4	10.4	10.5	10.5	10.6	10.6	10.7	10.7	10.8
Ogee 1	10.7	10.7	10.8	10.8	10.8	10.8	10.9	10.9	10.9
Ogee 2	11.0	11.1	11.1	11.2	11.2	11.3	11.4	11.4	11.5

It can also be seen in Figure 5.32 that, with all of the intake shapes tested, the full-pipe flow region ended at nearly the same submergence. Table 5.2 shows the critical submergence depths observed using the various different intake shapes. In this case, the critical submergence is defined as the minimum observed submergence depth at which no vortices occurred. From this table, it can be seen that all of the intake shapes have critical submergence depths very close the reference case, with the largest observed difference being only 3.3%. This result suggests that vortex formation is governed primarily by the intake submergence and that the shape of the intake has, at most, a minor influence.

Table 5.2: Observed critical submergence depths from intake shape results

Intake Shape	Observed $[h/d]_{cr}$	Fr	Difference in $[h/d]_{cr}$ from straight intake (%)
Straight	4.79	3.50	-
Cone (30 deg.)	4.68	3.86	-1.5
Cone (45 deg.)	4.70	3.77	-1.9
Cone (60 deg.)	4.77	3.81	-0.4
Pyramid (symmetric)	4.63	3.79	-3.3
Pyramid (asymmetric)	4.77	3.89	-0.4
Round	4.67	3.88	-2.5
Ogee 1	4.76	3.91	-0.6
Ogee 2	4.79	3.94	0.0

5.3.2 UNSTABLE-VORTEX FLOW

Figure 5.33 and Table 5.3 show the unstable-vortex flow results from the different intake shapes. In Figure 5.33, it can be seen that the results obtained from the different intakes follow the same general trend as the reference case and, similar to the results obtained under full-pipe conditions, all of the intake shapes tested produced a larger flow than the reference case for all submergence conditions. The efficiency of the intakes in this range of flow was found to vary depending on the submergence, with no intake shape proving to be most efficient under all submergence conditions. This is likely due to the scattering of the results caused by the variability of the flow in this range. The improvement in efficiency (relative to the reference case) of nearly all of the intakes was found to increase as the submergence decreased. Considering the entire range of submergence conditions, the most efficient intakes were found to be the Ogee 2, the asymmetrical pyramid, and the 60° cone intakes. The worst performing intake was found to be the 30° cone intake.

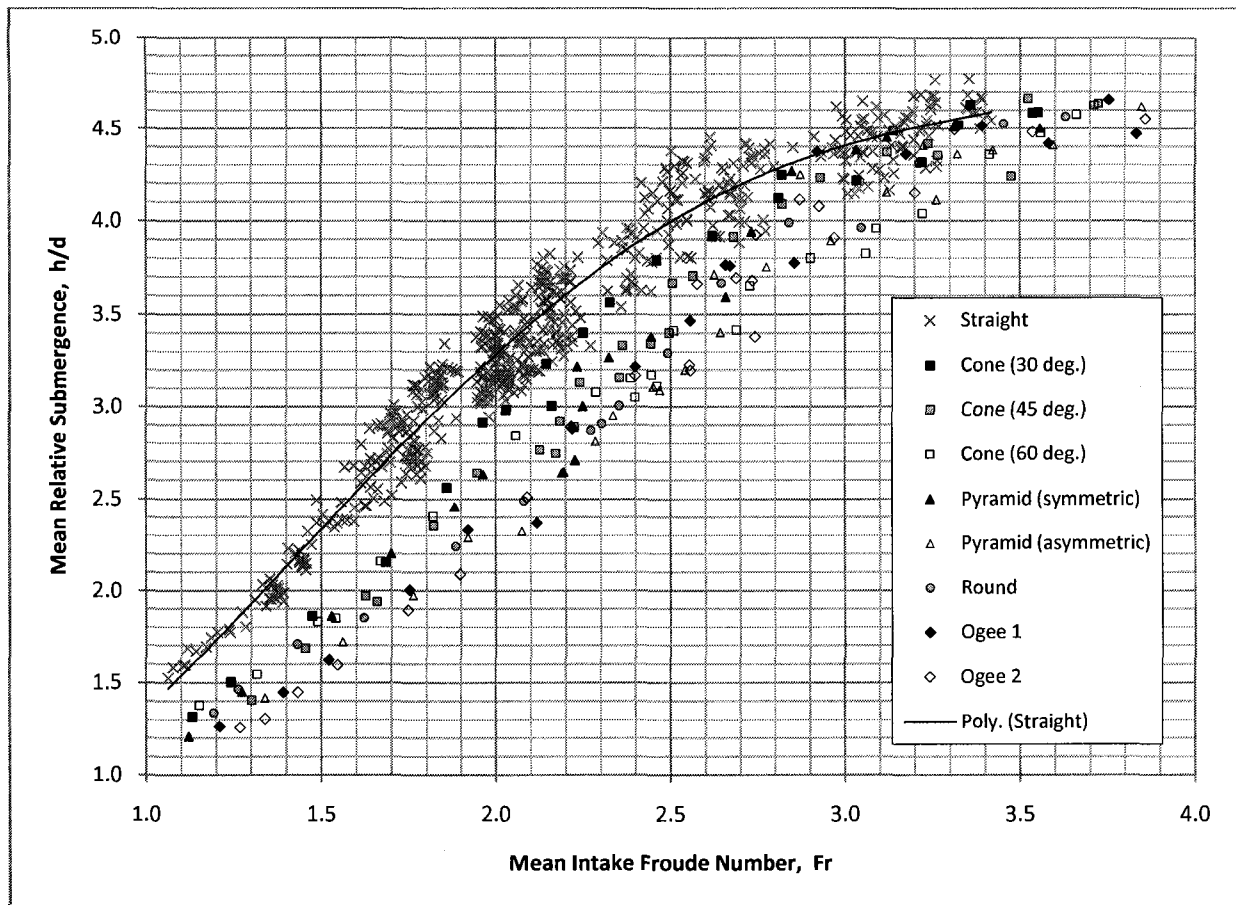


Figure 5.33: Relative submergence vs. intake Froude number for all intakes under unstable-vortex flow

Table 5.3: Intake shape results under unstable-vortex flow

[h/d]	Difference in flow rate compared to the reference case (%)							
	4.4	4.0	3.6	3.2	2.8	2.4	2.0	1.6
Cone (30 deg.)	7.5	6.4	7.7	10.3	12.1	15.0	17.2	17.5
Cone (45 deg.)	9.5	12.8	15.5	18.5	20.7	24.2	25.4	24.6
Cone (60 deg.)	11.3	21.6	25.9	24.6	21.8	20.9	17.9	16.7
Pyramid (sym.)	5.4	12.4	17.3	21.0	23.6	26.1	25.4	22.8
Pyramid (asym.)	13.2	19.2	23.6	27.2	29.9	32.7	33.6	31.6
Round	9.8	17.2	21.8	25.6	28.2	30.1	28.4	22.8
Ogee 1	7.5	13.6	18.2	22.6	25.9	30.7	32.8	34.2
Ogee 2	11.5	18.0	22.3	26.2	28.7	32.0	33.6	36.0

Many of these results do not compare well with the results obtained under full-pipe flow conditions. For example, with respect to the cone-type intakes, under full-pipe flow, the 30° intake performed better than the 60° intake, whereas under unstable-vortex flow, the opposite was observed. To analyze the influence that the intake entrance shape has on vortex flow, the effect it has on the behavior of the established vortices must be investigated. This, however, is not an easy task because, to preserve an unobstructed flow through the intake, no direct measurement of circulation or vortex strength was made; therefore, indirect measures based on total flow must be used. In this analysis, the stability of the observed vortices, as well as the percentage of time that the flow is a certain amount below (e.g. 10% lower) the established full-pipe flow (as determined in Section 5.3.1), are used to indirectly evaluate vortex influence.

In the first part of this analysis, the time dependency of the established vortices is investigated. As vortex stability is a function of circulation strength, any significant change in the circulation induced by the entrance shape should alter the stability of the observed vortices. Assuming that there are no drastic changes in the induced flow pattern, a change in vortex stability should produce a noticeable change in the degree of fluctuation of the observed flow. In Figure 5.34, the standard deviation of the flow through the different entrance shapes is plotted against the mean intake Froude number. In this figure, it can be seen that the magnitude of the deviation observed with the various different intakes shapes is comparable to that observed with the abrupt-entry intake. However, the comparable results do not occur at similar Froude numbers.

In the second part of this analysis, the results from each individual test were analyzed. Considering both the full-pipe flow results (Section 5.3.1) and the observed submergence $h(t)$, the percentage of time that the flow was 5%, 10%, 20% and 30% below the established full-pipe flow was calculated. The results from this analysis for the reference case are presented in Figure 5.35. In Figure 5.36 through Figure 5.39, the calculated results for the different intake shapes are presented and compared to the reference case.

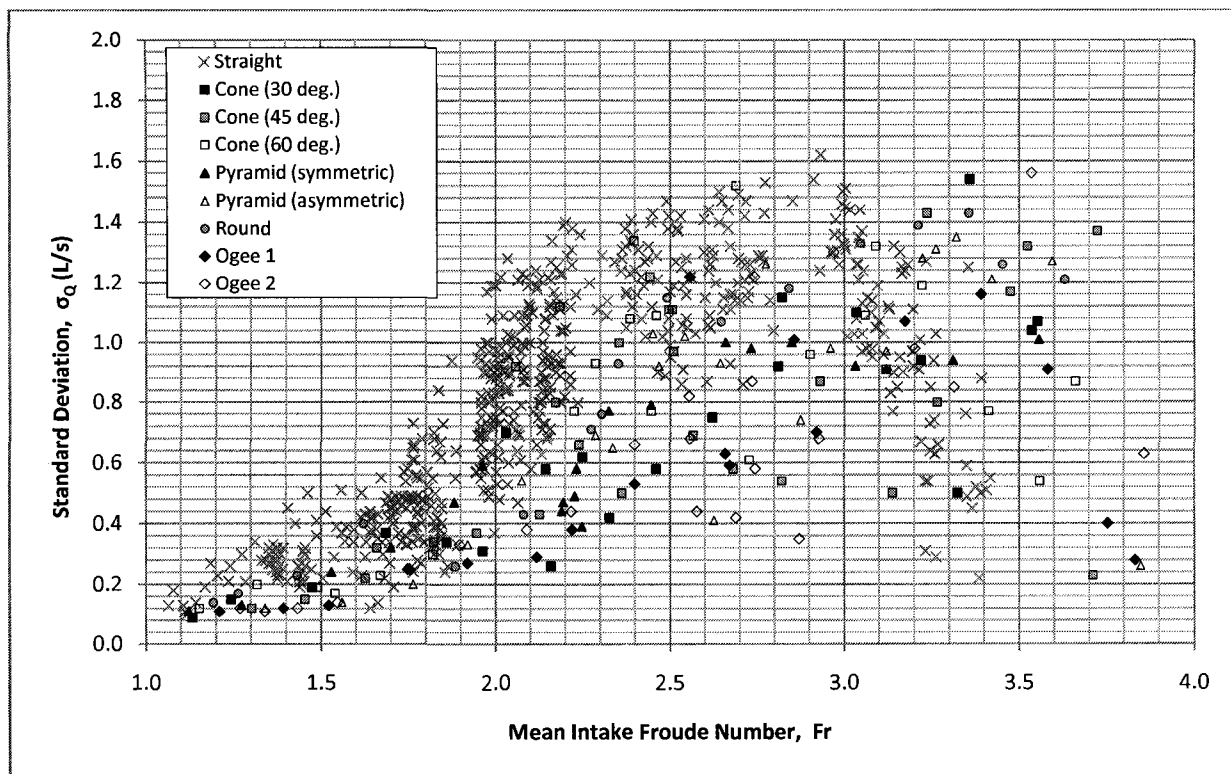


Figure 5.34: Standard deviation of flow vs. intake Froude number for all intake shapes

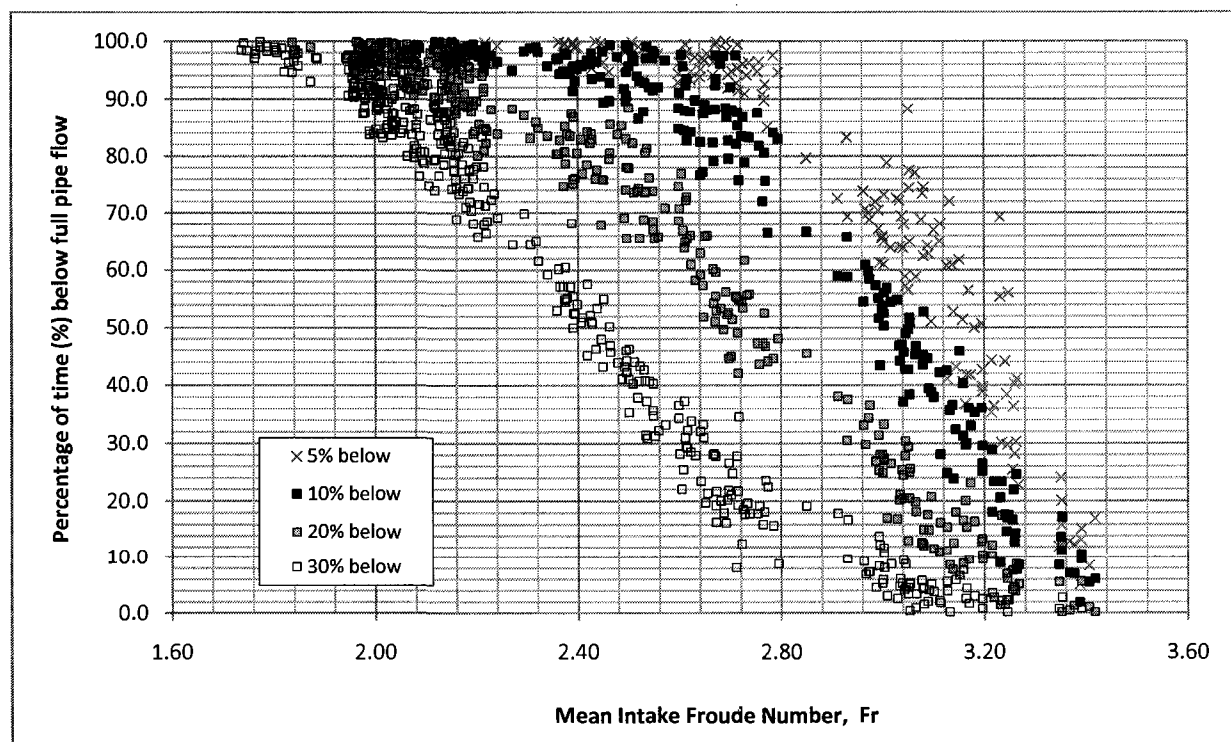


Figure 5.35: Vortex intensity analysis for abrupt-entry intake

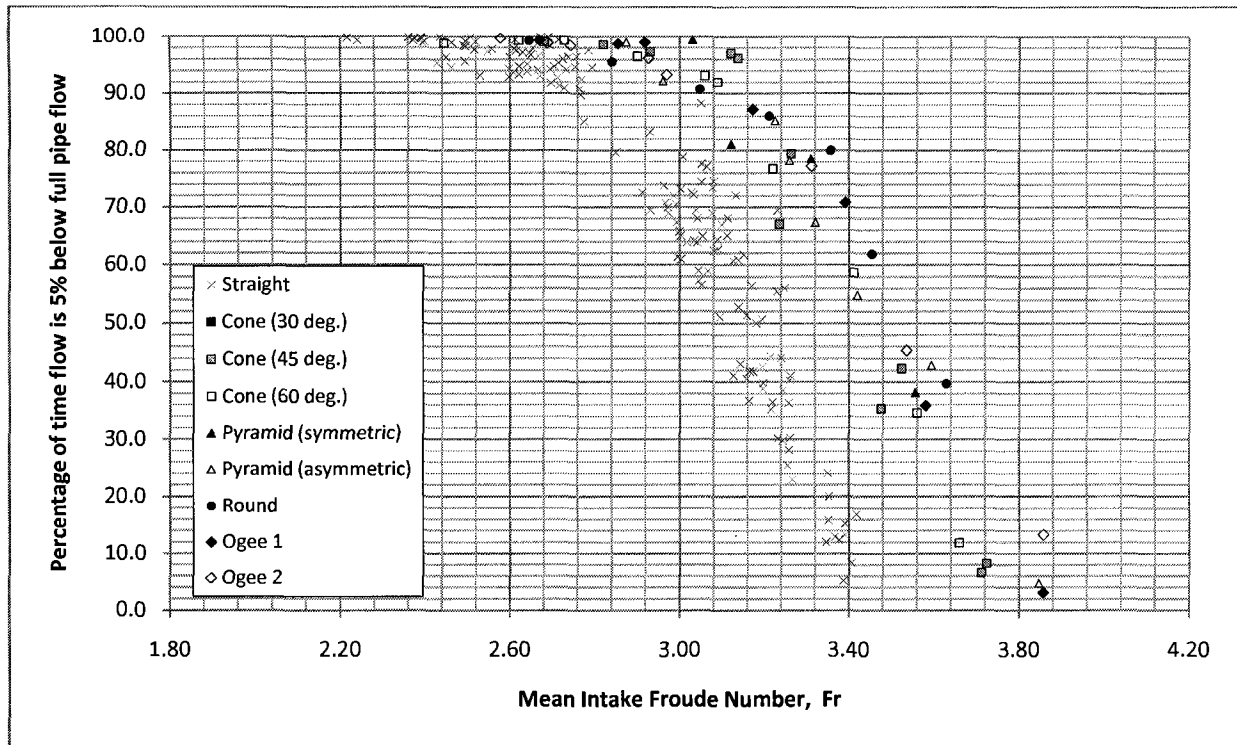


Figure 5.36: Percentage of time flow is 5% below full-pipe flow vs. intake Froude number

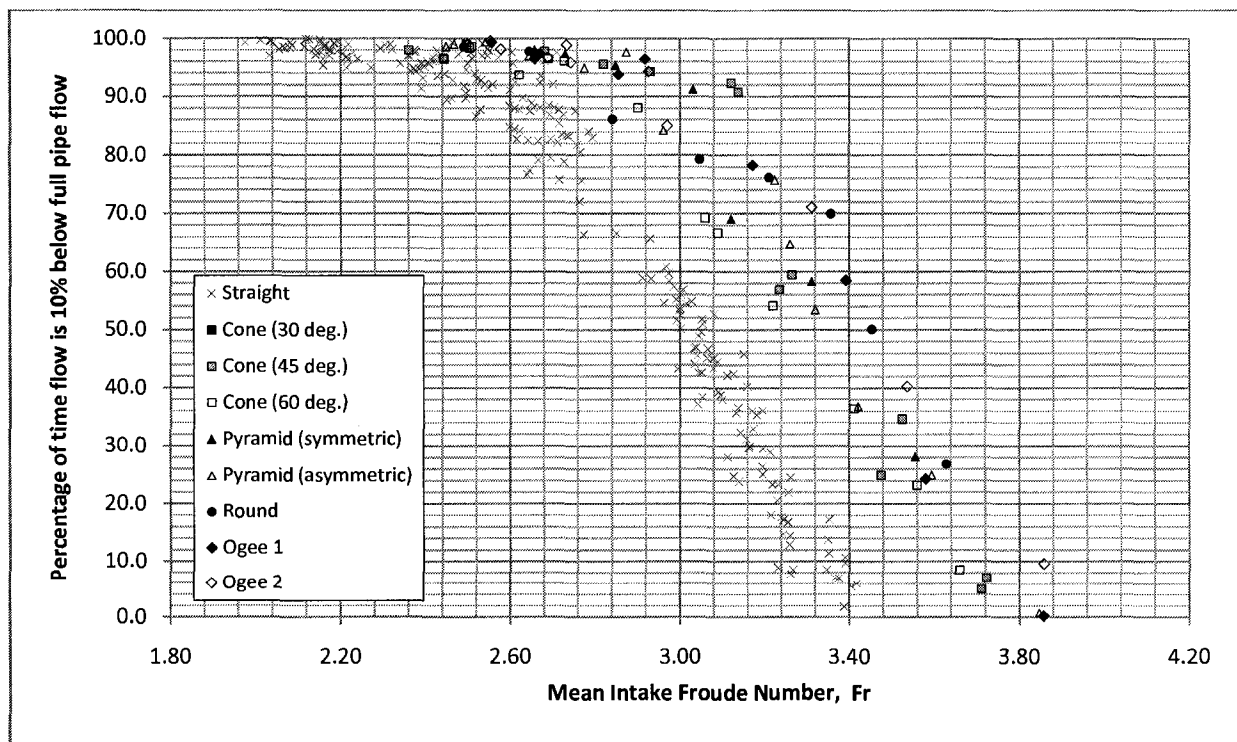


Figure 5.37: Percentage of time flow is 10% below full-pipe flow vs. intake Froude number

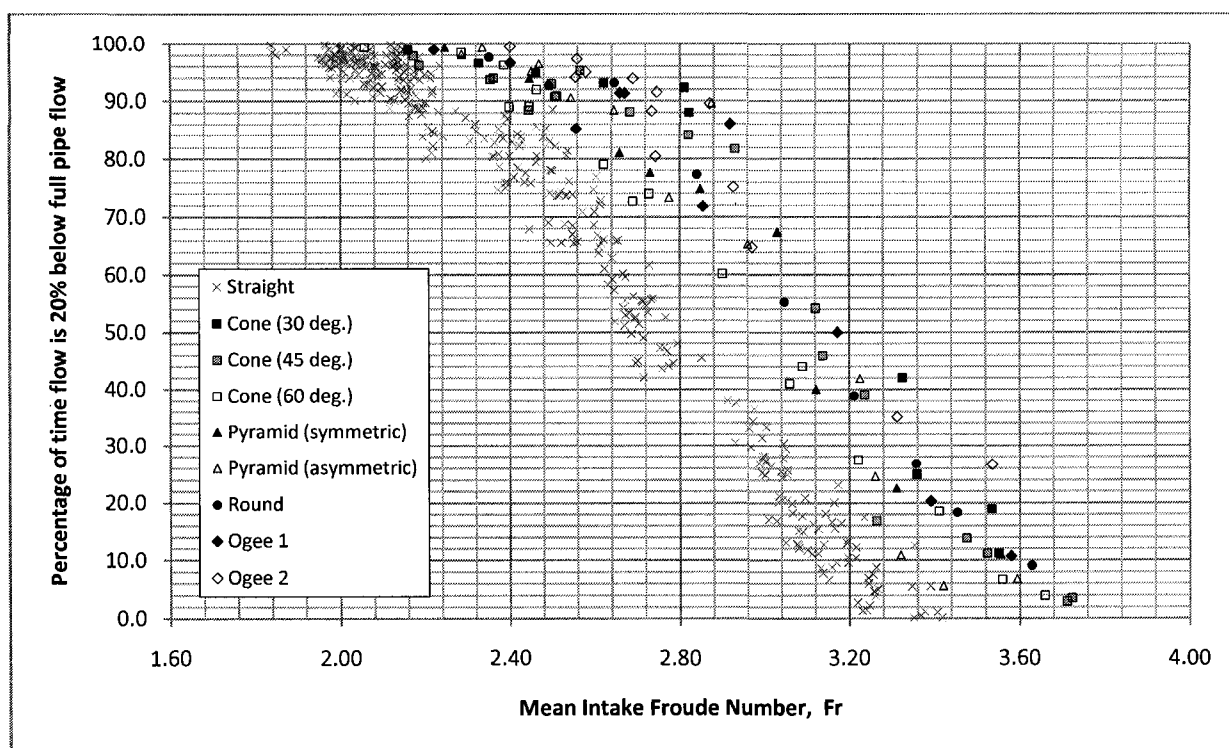


Figure 5.38: Percentage of time flow is 20% below full-pipe flow vs. intake Froude number

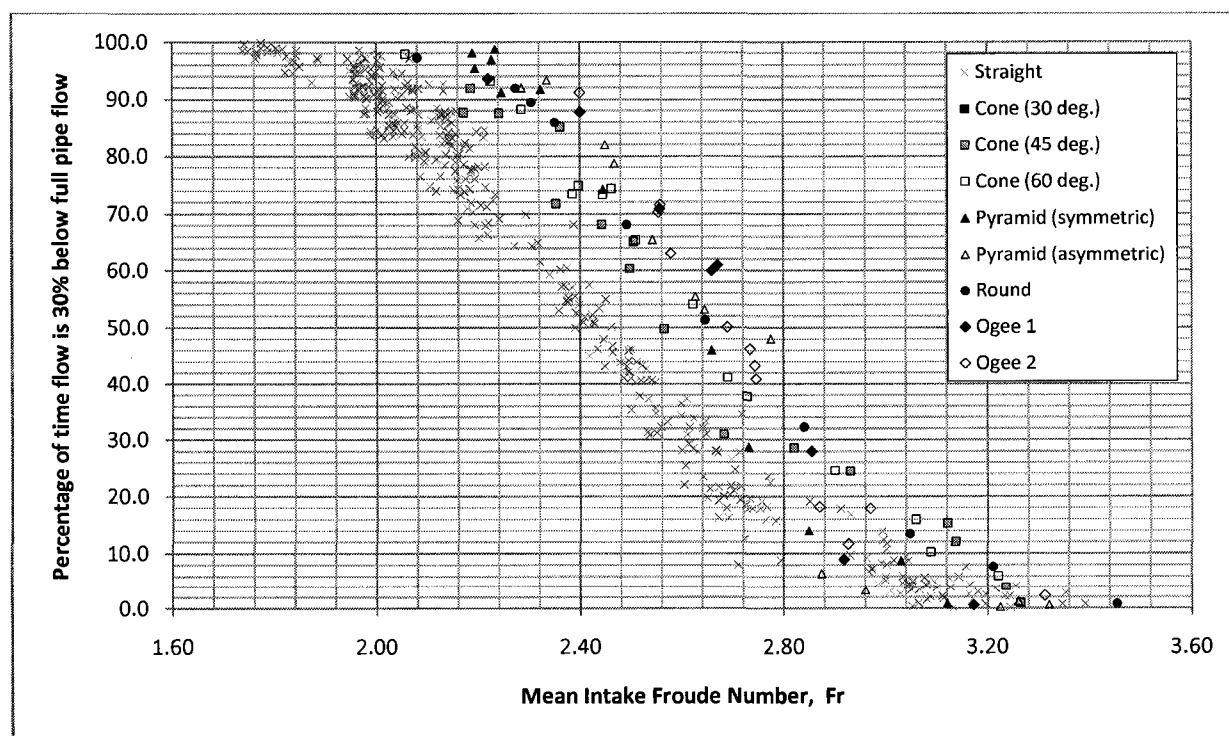


Figure 5.39: Percentage of time flow is 30% below full-pipe flow vs. intake Froude number

It can be seen in these figures that the results obtained from the different intake shapes follow a very similar trend as the one observed in the reference case; therefore, similar vortex dynamics were observed. However, again, the comparable results do not occur at the same Froude number. For the intakes that exhibited the highest full-pipe flow (e.g. the ogee, round, and 30° cone shapes), the vortices appear to form at larger Froude numbers than those that did not perform as well. Therefore, it was considered that this may be due to the fact that, because different shapes perform better under full-pipe conditions, the vortices may be initially formed at a higher flow. To investigate this further, the above results regarding vortex behavior are plotted against the relative intake submergence rather than the intake Froude number.

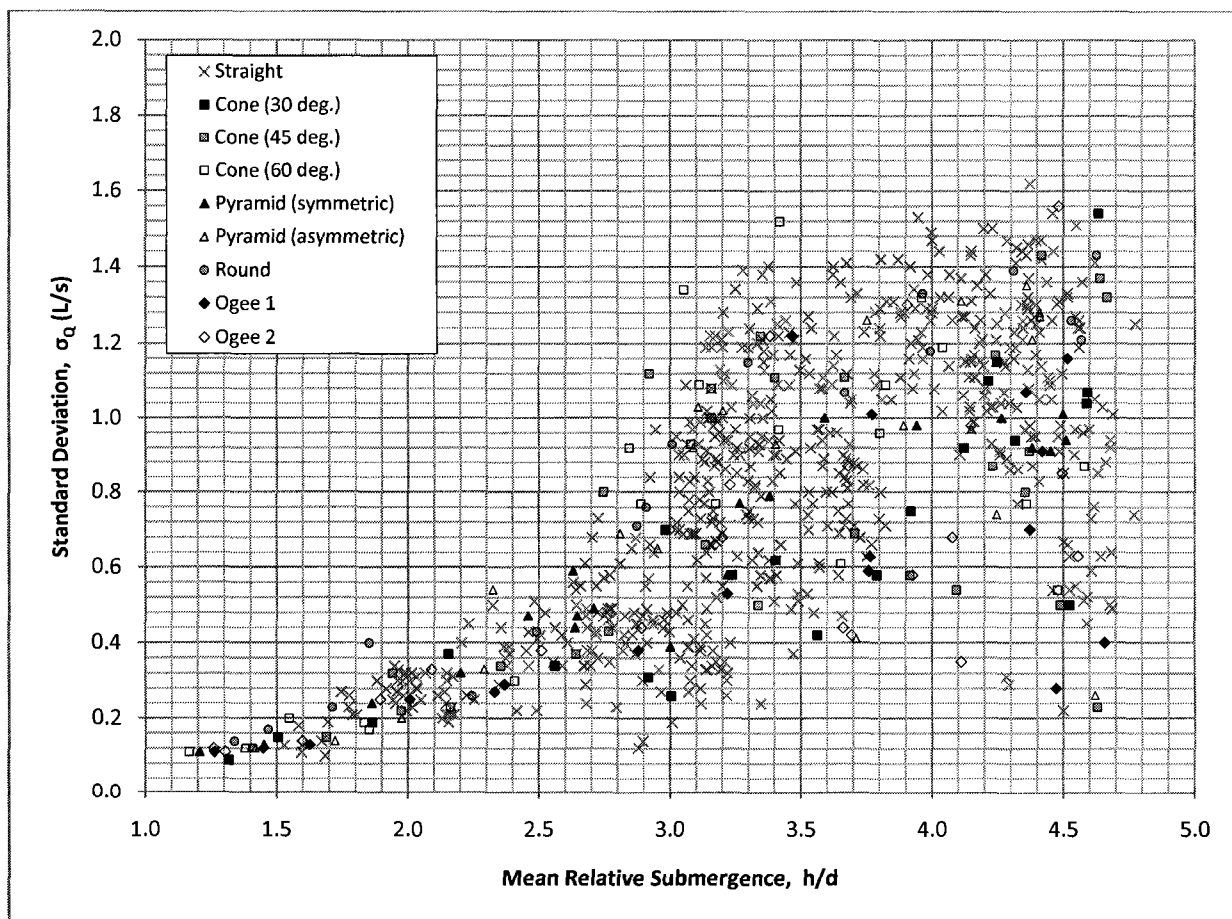


Figure 5.40: Standard deviation of flow vs. relative intake submergence for all intake shapes

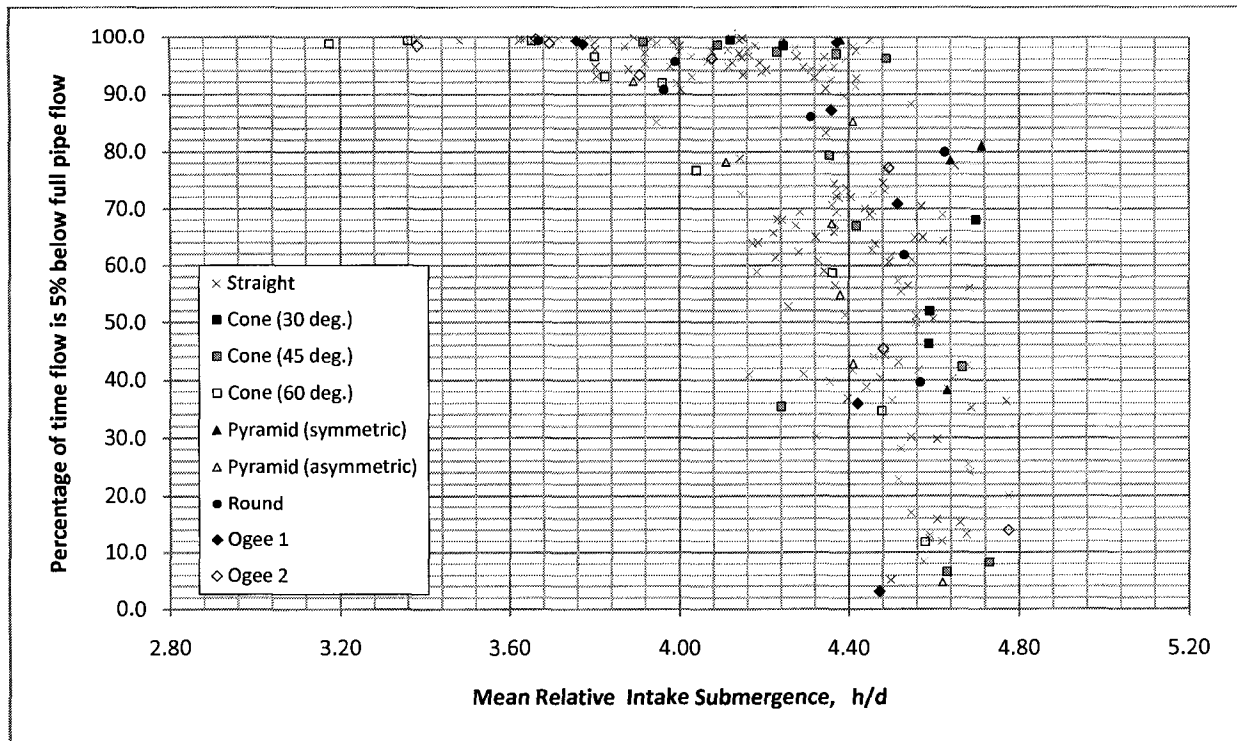


Figure 5.41: Percentage of time flow is 5% below full-pipe flow vs. relative intake submergence

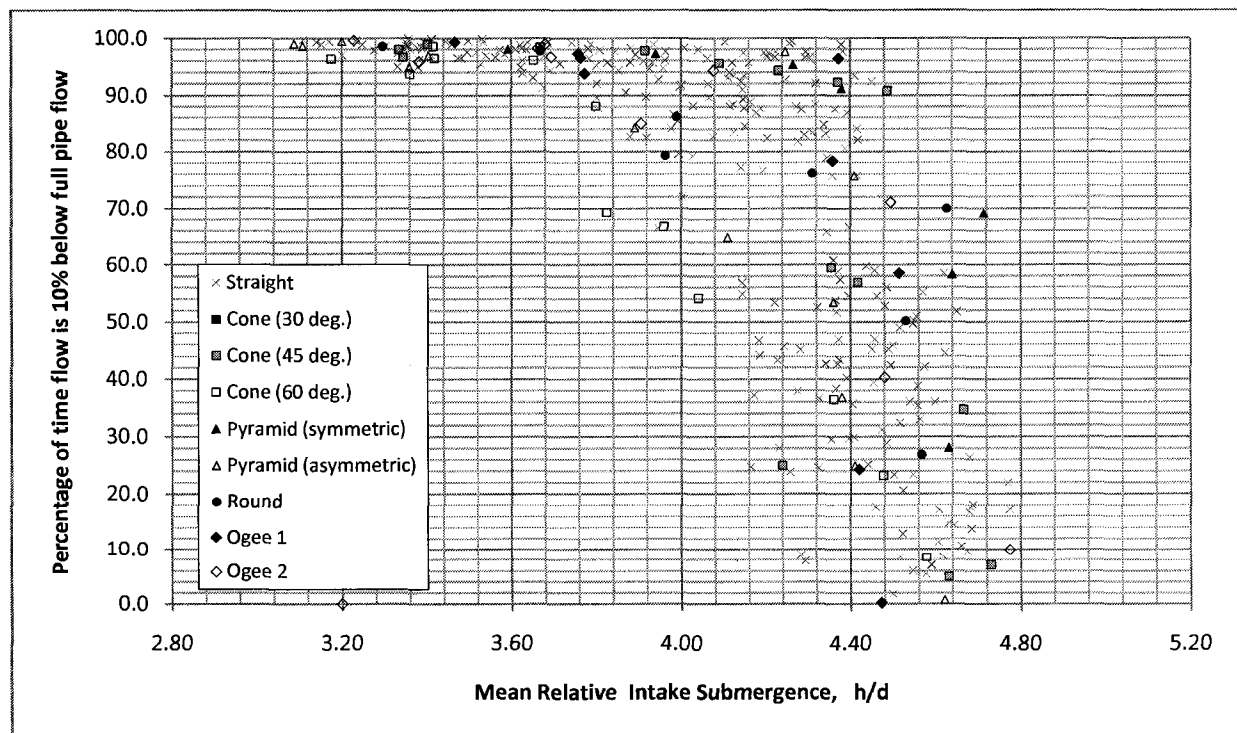


Figure 5.42: Percentage of time flow is 10% below full-pipe flow vs. relative intake submergence

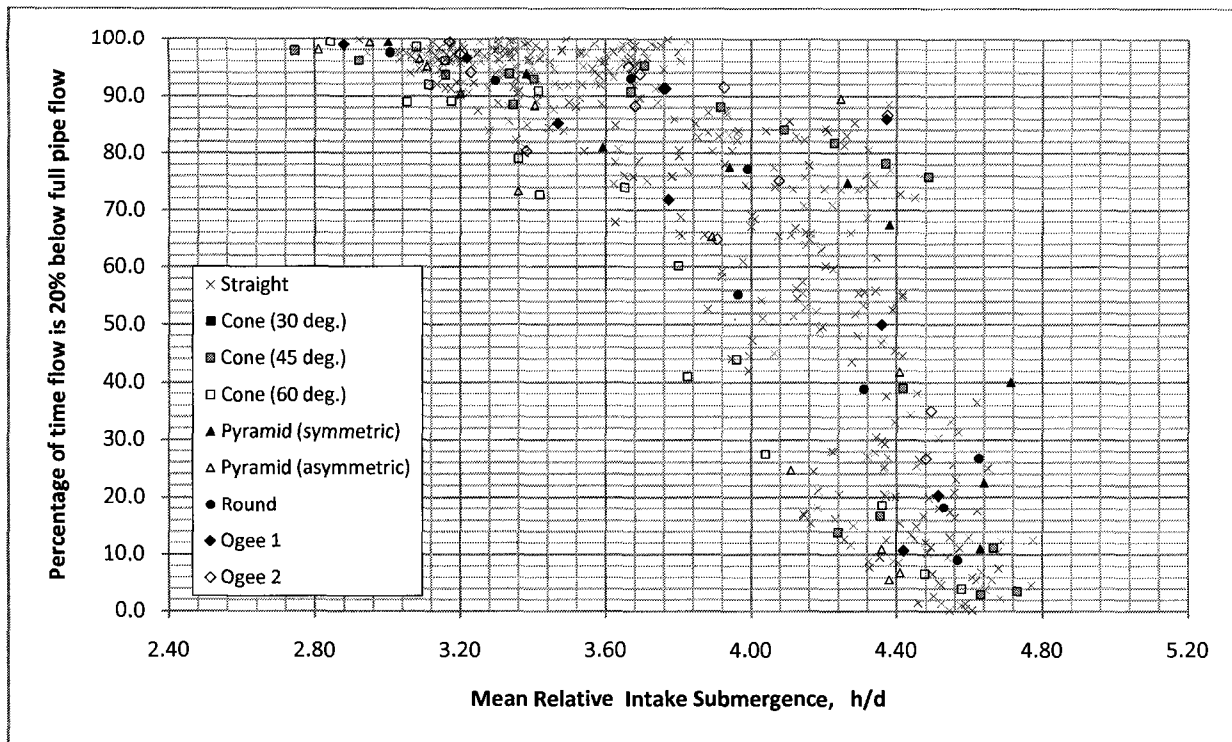


Figure 5.43: Percentage of time flow is 20% below full-pipe flow vs. relative intake submergence

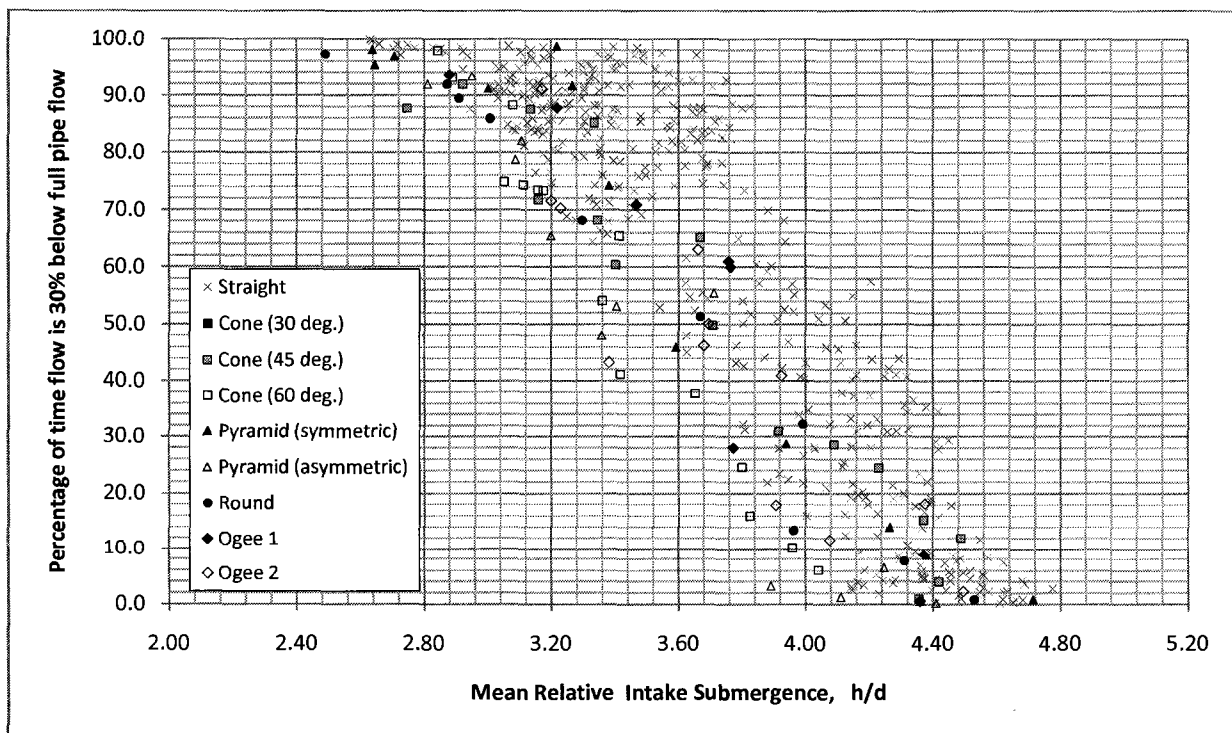


Figure 5.44: Percentage of time flow is 30% below full-pipe flow vs. relative intake submergence

In Figure 5.40, the standard deviation is plotted against the mean relative intake submergence. In this figure, it can be seen that the deviation observed with the different intake shapes compares quite well with the deviation observed with the abrupt-entry intake. Figure 5.41 through Figure 5.44 present the results from the vortex intensity analysis plotted against the intake submergence and, again, aside from Figure 5.44, a much better comparison is found in these figures. These results suggest that the behavior of the established vortices is mainly governed by the submergence of the intake and that the entrance shape is of lesser importance. It should be noted however, by inspection of Figure 5.44, it appears that, when using the intakes with more gradual contractions, the deviation from full-pipe flow is decreasing with submergence.

In order to further analyze these results, the different types of flow encountered under unstable-vortex flow must first be discussed. At higher flows and submergence conditions, vortex formation is intermittent; therefore, the intake may be operating under either full-pipe or vortex flow. As discussed in Section 3.1.8.3, under vortex flow, the total flow can be separated into a radial component associated with the bottom boundary layer and an axial component near the centre of the vortex. According to Echavez and McCann (2002) the proportion of the total discharge associated with the radial bottom boundary layer can vary between 15% and 70% and that this proportion increases with increasing circulation strength (decreasing submergence).

If it is assumed that vortices of equal size/strength produce equal axial vortex flow components, then, at the relatively low submergence conditions in which full-pipe flow very rarely occurs, the larger flow observed using the gradually contracting intake shapes must be due to an increase in the radial boundary layer flow. Following this reasoning, it is believed that in the unstable flow region, the increase in flow observed with the different shaped intakes is due to increases in both the full-pipe and radial boundary layer flows and not due to reduced vortex strength. As an augmentation of the radial boundary flow will have the effect of increasing the overall flow through the intake, it provides a possible explanation to the result observed in Figure 5.44.

5.3.3 STABLE-VORTEX FLOW

Figure 5.45 and Table 5.4 present the results obtained from the different intake shapes under stable-vortex flow conditions. In Figure 5.45, it can be seen that all the intake shapes produced a larger flow than the reference case. In this range of flow, the asymmetrical pyramid and ogee 2 intakes were found to be most efficient.

If the logic established in the previous section is followed, mainly that vortex intensity is governed by the intakes submergence rather than by its local shape, the observed increase in flow (relative to the reference case) must be due to an increase in the radial boundary layer flow.

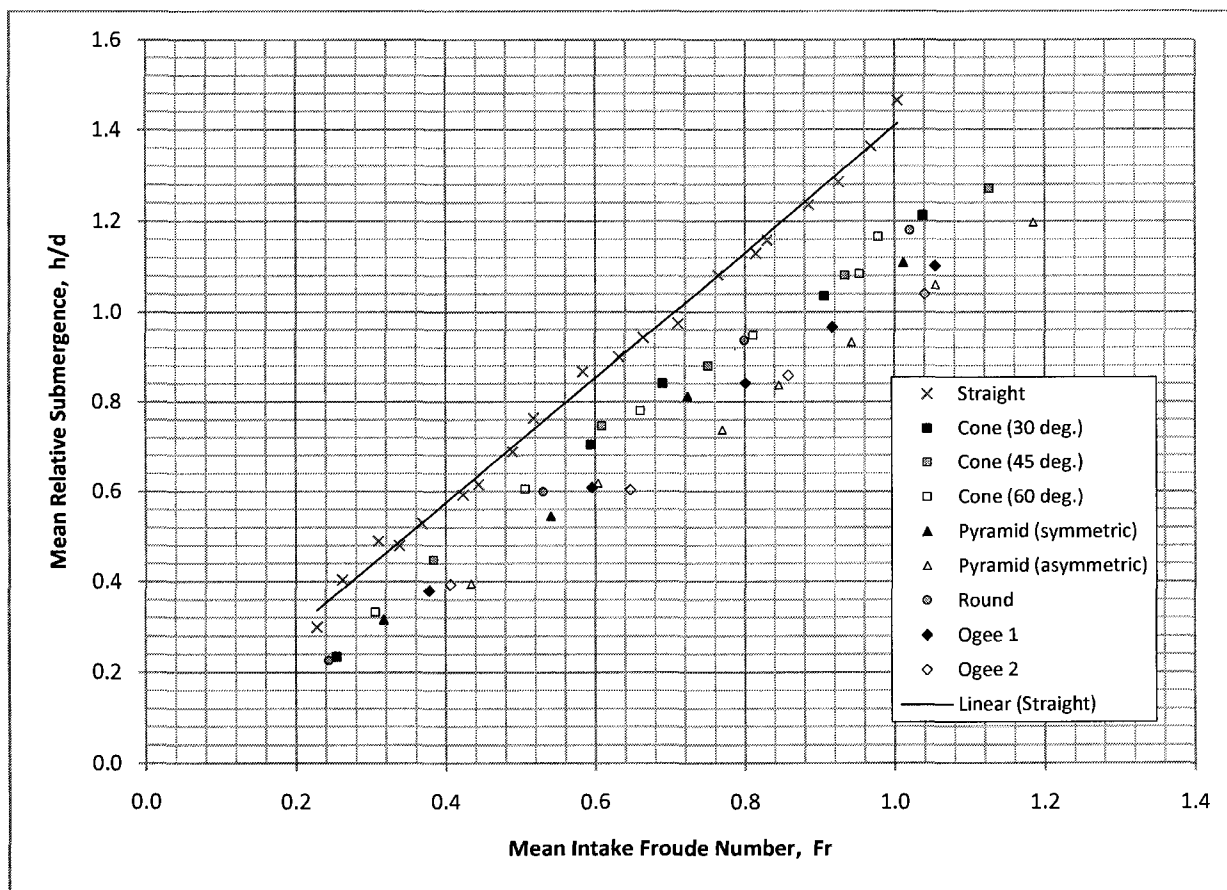


Figure 5.45: Relative submergence vs. intake Froude number for all intakes under stable-vortex flow

Table 5.4: Intake shape results under stable-vortex flow conditions

[h/d]	Difference in flow compared to the reference case (%)			
	1.0	0.8	0.6	0.4
Cone (30 deg.)	20.8	22.8	26.2	9.6
Cone (45 deg.)	22.5	21.5	19.7	8.4
Cone (60 deg.)	20.8	21.8	23.4	8.1
Pyramid (sym.)	28.6	31.5	36.4	7.1
Pyramid (asym.)	41.9	45.8	52.4	9.4
Round	22.1	24.4	28.5	10.4
Ogee 1	34.9	36.6	39.4	10.7
Ogee 2	28.6	29.6	31.3	11.0

5.3.4 SUMMARY

It has been determined that, under full-pipe flow conditions, the intake shape does indeed influence the discharge capacity of the intake. This influence is likely due to reduced head loss imparted on the flow by the intakes that have a more gradual contraction than the abrupt-entry intake. The largest improvements in efficiency were observed by the two ogee shapes while comparable results, with only slightly smaller improvements in efficiency, were observed in the case of the rounded intake and, more significantly, the 30° cone shaped intake. This is significant because of the comparative ease and low cost of the 30° cone shaped intake's construction with respect to that of an ogee profile. Therefore, aside from very large installations (power plants, etc.), the relative increase in discharge capacity obtained through the use of an ogee intake, rather than a 30° conical one, may not justify the additional expense incurred by its complexity. With respect to the three cone-type intakes, the flow capacity increased as the cone angle decreased. This seems to suggest that, under full-pipe flow conditions, the discharge through a vertical intake will increase if an intake is used that increases in the ratio of axial-to-radial intake velocity components.

In the unstable-vortex flow range, it has been determined that the local intake entrance shape has, at most, a minor effect on the flow circulation and vortex dynamics as the critical submergence and vortex behavior analysis both showed only relatively minor variations from shape to shape. Vortex intensity and stability were found to be governed

primarily by the submergence of the intake, which in this case, is governed by the flow through the intake. In this range of flow, all the intake shapes tested produced a larger flow than the abrupt-entry intake. However, due to a large amount of scattering in the data, it was difficult to identify which intakes performed best under all submergence conditions. Despite this, the most efficient intakes appeared to be the Ogee 2, the asymmetrical pyramid, and the 60° cone intakes. As it appears that the intake entrance shape has little influence on the dynamics of the established vortices and considering that, at lower submergence conditions, full-pipe flow rarely occurs, it has also been concluded that the intake shape must influence the radial boundary flow such that its magnitude is increased. Unfortunately, however, the radial boundary flow was not measured in the experiments so this conclusion is relatively uncertain.

Lastly, in the stable-vortex flow region, it was again found that all the intake shapes produced a larger flow than the abrupt-entry intake. Again, considering that vortex intensity showed little dependence on intake shape, the increased flow must be mostly due to an increase in the radial boundary flow. This makes sense as, according to Echavez and McCann (2002), the proportion of the total discharge associated with the radial boundary flow increases with increasing circulation strength. In this range of flow, the most efficient intakes were found to be the asymmetrical pyramid, Ogee 1 and symmetrical pyramid intakes.

As different intake shapes were found to perform most efficiently under the different types of flow, it is difficult to conclude which shape would perform best when subjected to all three flow types. In an attempt to draw this conclusion, the results presented in Table 5.1, Table 5.3 and Table 5.4 were combined and an average percentage improvement that considered all submergence conditions and types of flow was calculated. These results are presented in Table 5.5. From these results, it can be seen that, in consideration of all types of flow, the most efficient intake shapes were found to be the asymmetrical pyramid and two ogee shapes.

Table 5.5: Average difference in flow relative to reference case considering all flow types

	Average difference in flow (%)
Cone (30 deg.)	12.5
Cone (45 deg.)	14.0
Cone (60 deg.)	14.4
Pyramid (sym.)	15.6
Pyramid (asym.)	21.4
Round	17.4
Ogee 1	19.3
Ogee 2	19.5

5.4 INFLUENCE OF BOUNDARY PROXIMITY

In this section, the experimental results from tests performed under altered geometrical boundary arrangements are presented. The tests were performed using the geometrical arrangements identified in Section 4.3 and following the procedure outlined in Section 4.4. The abrupt-entry intake was used throughout these tests for direct comparison to the reference case. Figure 5.46 presents the results obtained using the various 'back wall' arrangements shown in Figure 4.8. Figure 5.47 presents the results obtained using the 'side wall' arrangements shown in Figure 4.9 and Figure 5.48 presents the results obtained using the 'middle curtain' arrangements.

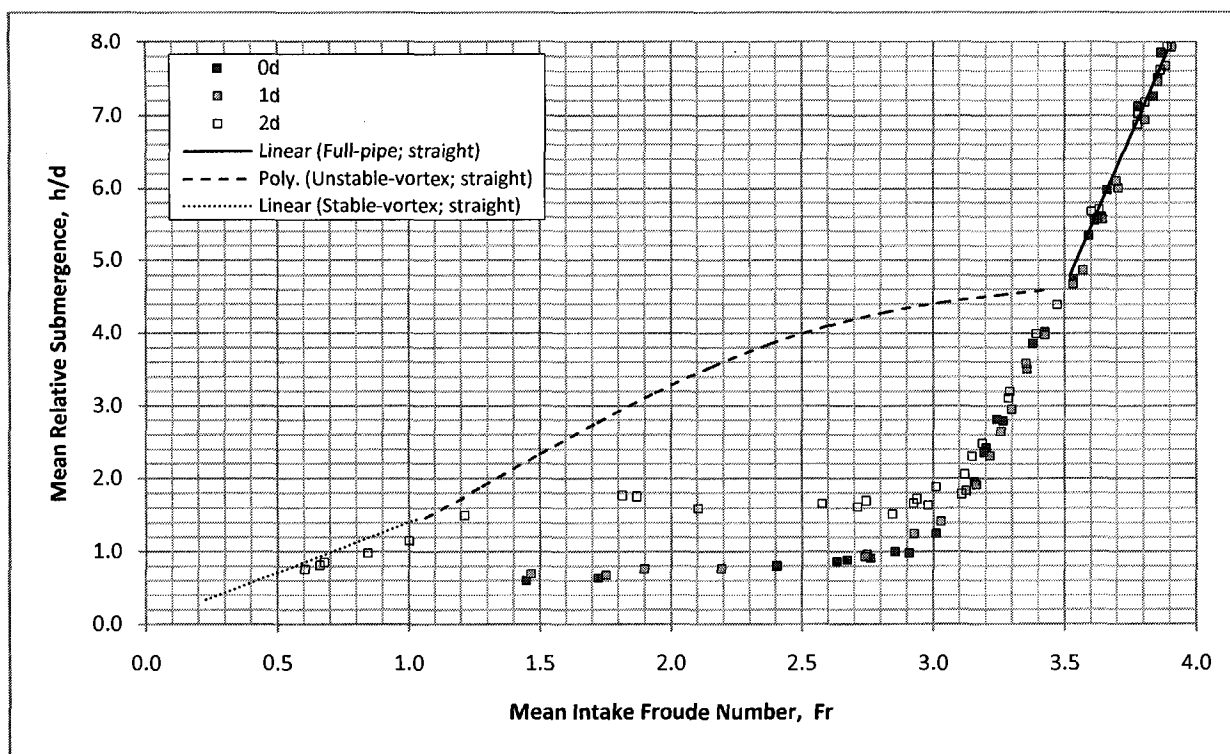


Figure 5.46: Relative submergence vs. intake Froude number for back wall arrangements

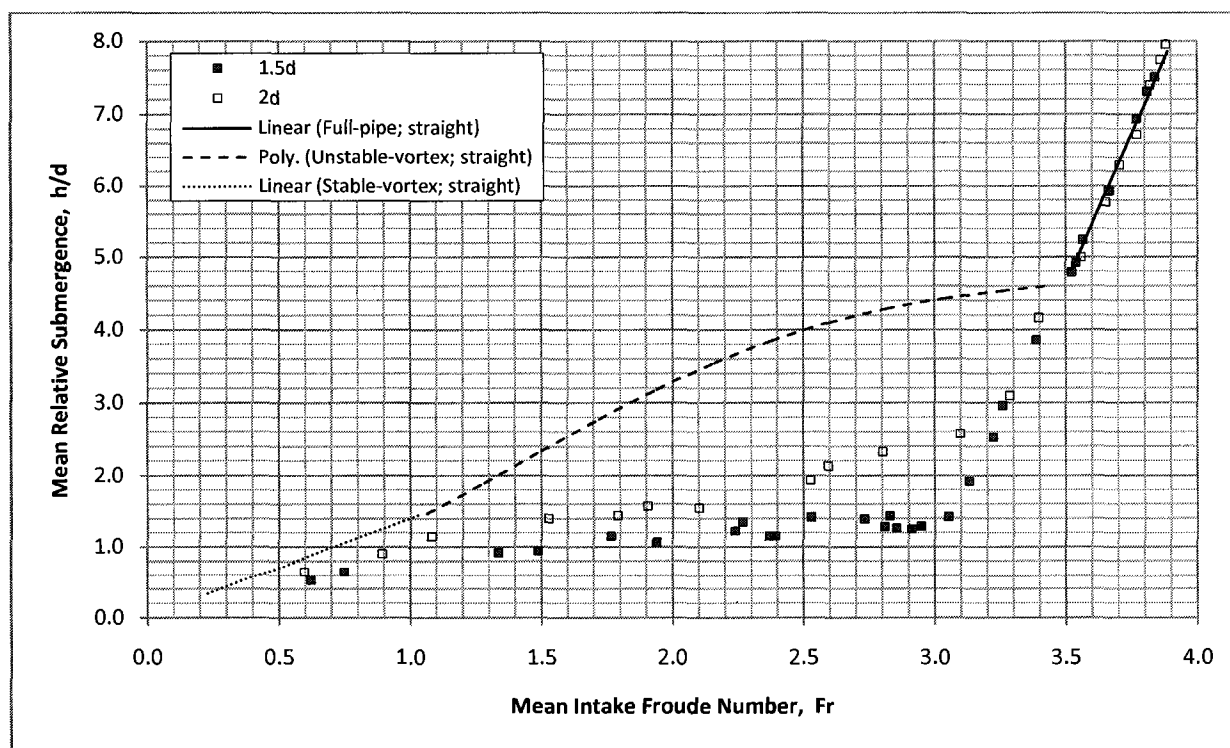


Figure 5.47: Relative submergence vs. intake Froude number for side wall arrangements

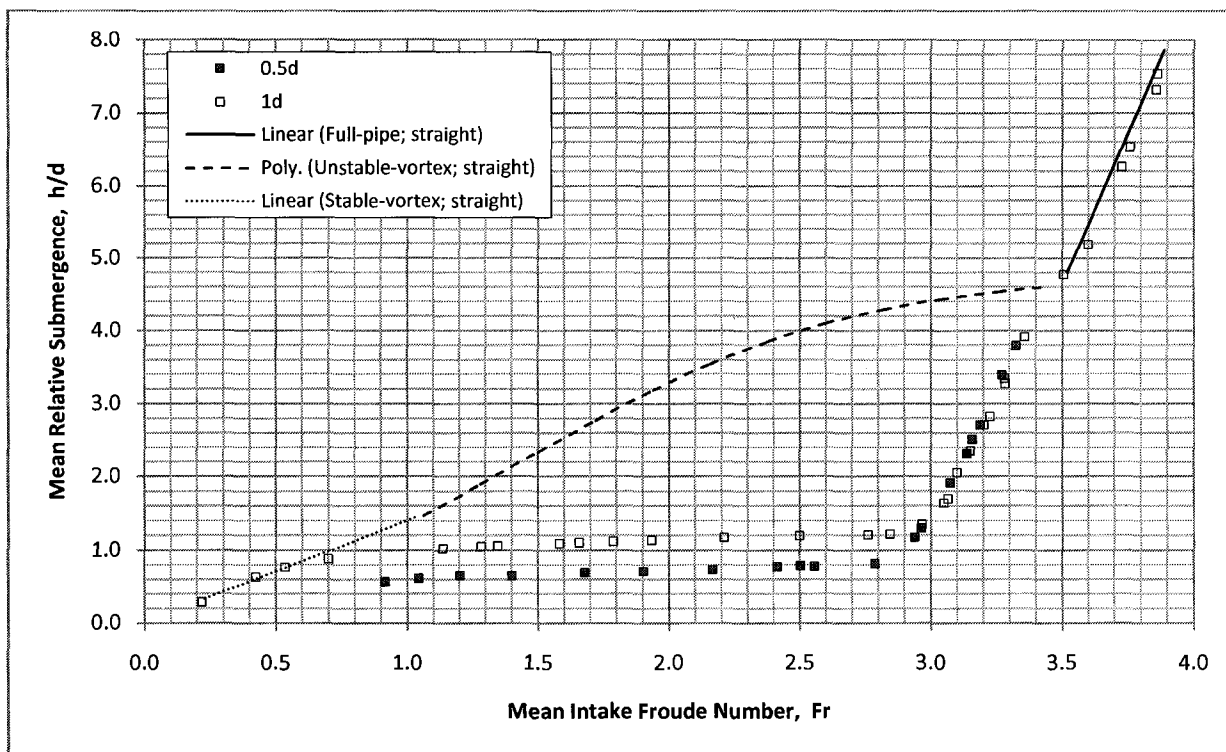


Figure 5.48: Relative submergence vs. intake Froude number for middle 'curtain' arrangements

In Figure 5.46 through Figure 5.48, it can be observed that results identical to those observed in the reference case are obtained when the intake is flowing full. However, the presence of the closer boundary causes full-pipe flow to be observed at submergence depths much less than in the reference case. This is presumably due to a reduction in circulation caused by increased frictional resistance, but may also be partly due to the fact that there is insufficient space for circulation to develop. The reduction in critical submergence was observed with all of the interior wall arrangements and the magnitude of the reduction was found to increase as the boundaries were moved closer to the intake. This result also suggests that an increase in boundary roughness may further impede the formation of vortices.

It should be noted that in this section, the term *critical submergence* is used to describe the submergence at which air is first entrained by the intake and not necessarily the depth at which vortex formation occurs. In all the boundary arrangements tested, with the

exception of the $0d$ back wall case, a distinct vortex was observed. However, with the $0d$ back wall arrangement, a fully developed vortex was not able to form. Instead, although still displaying a spiraling motion, air was entrained in a 'gulping' fashion.

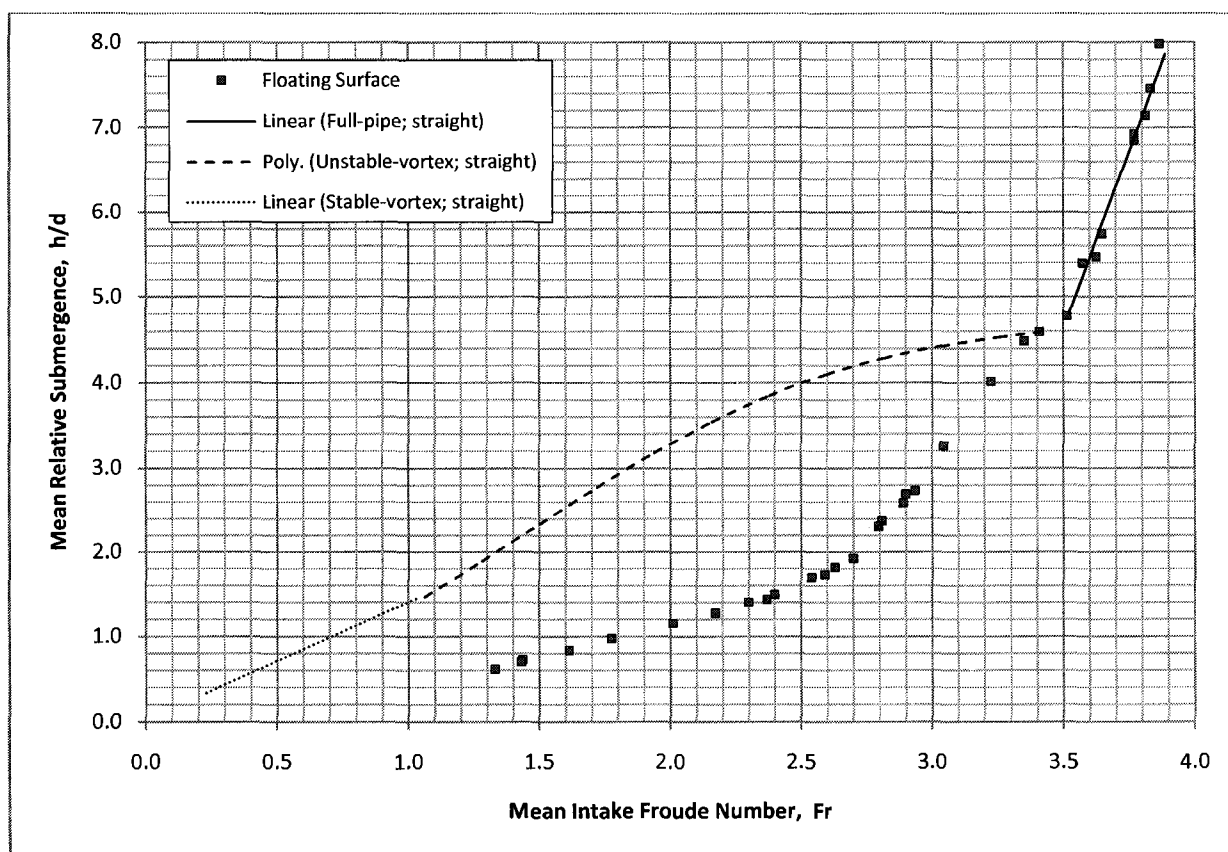


Figure 5.49: Relative submergence vs. intake Froude number for floating surface arrangement

Figure 5.49 presents the results obtained using the Styrofoam floating surface. The floating surface effectively cut-off the flow of air to the intake, however, it did not reduce the circulation in the flow as the vertical walls did. Consequently, a submerged vortex was formed at approximately the same critical submergence as the reference case. A submerged vortex is formed because of low pressure near the centre of the intake created by a high tangential velocity. An example of such a vortex is provided in Figure 5.50. In the experiments, the submerged vortices did not entrain air and therefore, did not produce the large fluctuations in flow that were generated by the surface vortices in the previous tests.

Below the critical submergence, the standard deviation of the flow was found to be, on average, approximately 0.11 L/s and did not vary much with the submergence depth. Thus, the established submerged vortices are considered to be steady.

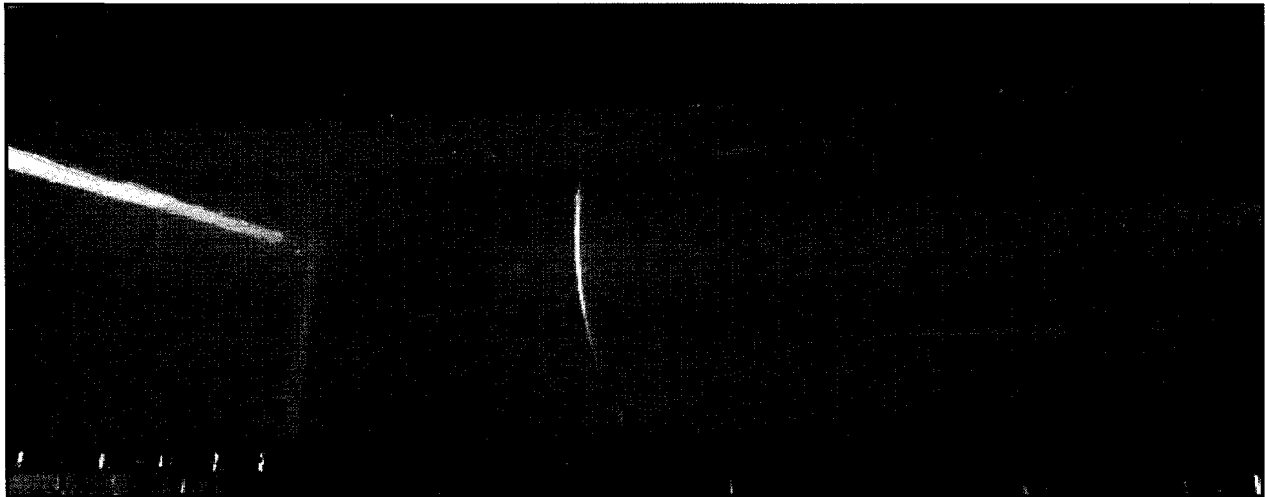


Figure 5.50: Submerged vortex observed during experiments with floating surface

Although not entraining air, submerged vortices do entrain a large amount of swirl. This entrained swirl causes the water to spiral down the vertical shaft and therefore, increases the amount of head loss that is generated. This increased head loss resulted in a lower flow than the established full-pipe flow when the submerged vortex was present. The magnitude of this reduction in flow was found to increase as the submergence was decreased, thus indicating that the strength of the submerged vortex and the amount of entrained swirl increase with decreasing submergence.

It should also be noted that at very low submergence conditions, the suction created by the intake velocity caused the Styrofoam surface to be pulled down against the floor of the structure. This caused the intake to be covered and accordingly, the flow was drastically reduced.

5.4.1 SUMMARY

The experimental results confirm the logic established in Section 3.1.4. Mainly, that a decrease in boundary proximity will reduce flow circulation and thus reduce vortex formation. For comparison, Figure 5.51 presents the results of all of the geometrical arrangements tested. In this figure, it can be seen that the reduction in critical submergence appears to be maximum under the $0d$ back wall and $0.5d$ middle curtain arrangements. This makes sense because under these arrangements, the boundaries are closest to the intake; therefore, the reduction of circulation should be maximum.

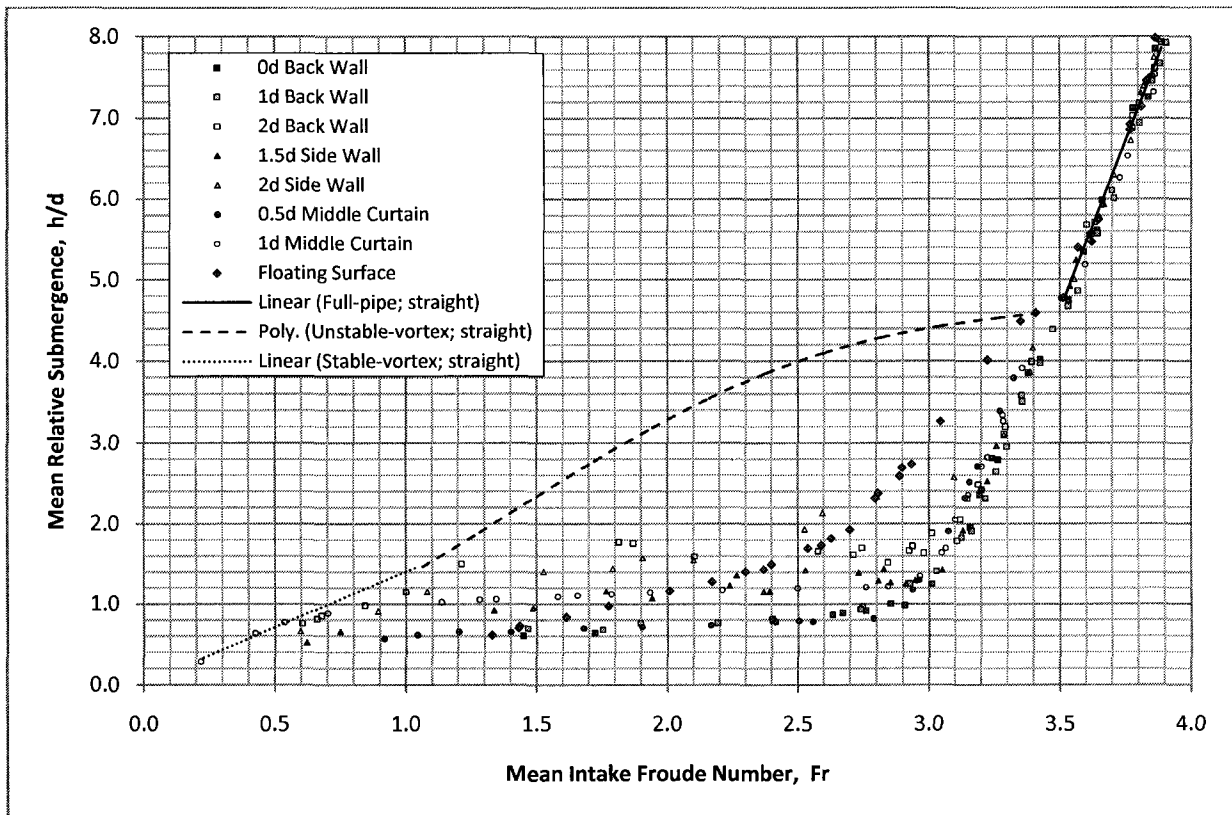


Figure 5.51: Relative submergence vs. intake Froude number for all geometrical arrangements

Table 5.6 shows the critical submergence depths observed under the different geometrical arrangements. These results show that if a boundary is placed within $1d$ of the intake, the critical submergence can be reduced by roughly 70%. The maximum reduction was achieved under the $0d$ back wall arrangement and was found to be approximately 77%.

In comparing the different types of arrangements, it appears that the back wall produced a greater decrease in critical submergence than the side walls. This can be seen by comparing the results from both the $2d$ back and side wall arrangements. The back wall and middle curtain arrangements, on the other hand, produced more comparable results and no such conclusion could be reached.

Table 5.6: Critical submergence depths observed under geometrical arrangements

Geometrical arrangement	Observed $[h/d]_{cr}$	Fr	Difference in $[h/d]_{cr}$ from reference case (%)
0d Back Wall	1.08	2.96	-77.4
1d Back Wall	1.34	3.00	-72.0
2d Back Wall	1.96	3.09	-59.1
1.5d Side Walls	1.48	3.05	-69.1
2d Side Walls	2.81	3.24	-41.3
0.5d Middle Curtain	1.12	2.91	-76.7
1d Middle Curtain	1.40	3.02	-70.8
Floating Surface*	4.78	3.49	-0.2

In summary, it was found that the submergence depth at which air is first entrained is heavily influenced by the intake's proximity to its nearby boundaries such that, an increased reduction in critical submergence is observed as the boundaries are moved closer to the intake. A maximum reduction of roughly 77% was achieved by the placement of a back wall directly behind the intake. It was also found that the use of a back wall will produce a greater reduction in critical submergence than the use of side walls and that the full-pipe discharge capacity of the intake is not significantly influenced by the location of the surrounding boundaries. Lastly, it was determined that a floating surface will effectively inhibit the entrainment of air into the intake, but will not cause a significant reduction in flow circulation, thereby resulting in the generation of a submerged vortex and a large amount of entrained swirl which results in increased frictional losses and, consequently, a decrease in flow.

6. CONCLUSIONS

6.1 SUMMARY OF CONCLUSIONS

Based on the results of this study the following conclusions can be drawn:

- The entry flow to a vertically-oriented intake structure is subject to three distinct types of flow, namely, full-pipe flow, unstable-vortex flow and stable-vortex flow.
- The formation of surface vortices results in significant air entrainment and a large decrease in flow through the intake. Therefore, an efficient intake must minimize vortex occurrence.
- The local shape of the intake has an influence on the full-pipe and radial boundary layer flow through the intake, but has a minimal influence on the critical submergence depth or the behavior of the established vortices.
- Under constant boundary conditions, vortex behavior is primarily governed by the submergence of the intake.
- The use of an intake with a gradual contraction will reduce head losses and increase the full-pipe and radial boundary flow through the intake.
- The intake's proximity to its surrounding boundaries has a significant influence on the amount of circulation in the flow and therefore, the critical submergence of the intake such that the critical submergence is reduced as the boundaries approach the intake.
- The use of a back wall produces a greater reduction in critical submergence than the use of side walls.
- Significant reduction in circulation can be achieved by the introduction of a vertical wall directly behind the intake. This arrangement produced a decrease of roughly 77% in the depth at which air is entrained by the intake. A comparable decrease can be achieved through the use of a 'middle curtain' hung directly above the intake at a distance of $0.5d$.
- Placement of a vertical boundary at a distance of $1d$ from the intake can result in approximately a 70% decrease in the depth at which air is entrained.
- A floating surface can effectively eliminate the entrainment of air but does little to dissipate flow circulation and thus, submerged vortices can be generated which produce a large amount of swirl in the downstream pipe.

6.2 DESIGN RECOMMENDATIONS

The results of this study suggest that the most important consideration in design is choosing the optimal location of the intake. If proper understanding of the vortex formation process is achieved, the designing engineer will be able to either eliminate or minimize vortex formation by properly selecting the site conditions that are least likely to promote and/or most likely to dissipate flow circulation. The following recommendations should be considered when designing an intake structure of the type used in this study:

- The submergence of the intake should be maximized to reduce the probability of vortex formation.
- If possible, the critical submergence depth, once determined, should be maintained.
- The intake location should be chosen where the velocity variation relative to the intake is minimal, in other words, where the approach conditions are uniform and free from obstruction.
- Upstream flow conditions should be improved in the sense of providing a more uniform distribution of the approaching velocity.
- Intake entrances with gradual contractions should be used to increase the full-pipe and radial boundary layer flow.
- The intake should be located as close to a vertical boundary as possible as this will reduce both the circulation in the approaching flow and the submergence depth at which air is entrained.
- If very low submergence conditions are expected, vanes or guide walls should be employed to induce a more radial entrance flow.
- If the approaching velocity can be controlled, it should be done so in a way to avoid or minimize flow separation as this can generate flow vorticity.
- If hydraulic machinery is to be installed downstream of the intake, it should be located at a distance sufficient enough for the swirl entrained by vortices to fully dissipate.
- In all cases, the 'wait-and-see' approach of designing and constructing an intake should be avoided because, once installed, a problematic intake can have significant mitigation costs associated with it.
- If it is imperative that vortices are avoided, a Froude scaled hydraulic model study should be performed such that the radial Reynolds number is greater than 3×10^4 (Anwar's (1968) criterion).

6.3 RECOMMENDATIONS FOR FUTURE RESEARCH

In this study, the parameters most intimately related to vortex strength (e.g. maximum tangential velocity, air core diameter) were not measured as doing so would have involved a great deal of difficulty and would likely have disrupted the overall flow through the structure. Therefore, in order to confirm that the local intake shape has little effect on the development and intensity of vortices, in the future, a similar experimental study should be performed in which vortex strength is more directly measured. Through such a study, the influence of the entrance shape, although minor, could be more accurately determined. In addition to this, measurement of the flow associated with the bottom boundary layer would allow for further investigation into the conclusion that the radial boundary layer flow is significantly influenced by the entrance shape of the intake.

It is also suggested that tests of longer duration be performed on the different intake entrance shapes. If the flow behavior through these shapes is measured over a longer period of time, a more detailed investigation into the periodicity of vortex occurrence could be performed through spectral analysis. Such an analysis would allow for a thorough evaluation of the stability of the vortices induced by the different entrance shapes.

Lastly, it is the author's belief that, due to the relatively simple geometry of the experimental setup, the results from the present study may, in the future, be used as a means to validate the results from an analytical numerical study. Such a study may be possible through the use of a three-dimensional, unsteady numerical model; however, it is believed that such an endeavor would likely to be a difficult and uncertain task.

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APPENDICES

APPENDIX A – STRUCTURAL DRAWINGS

Note: All dimensions in meters (m)

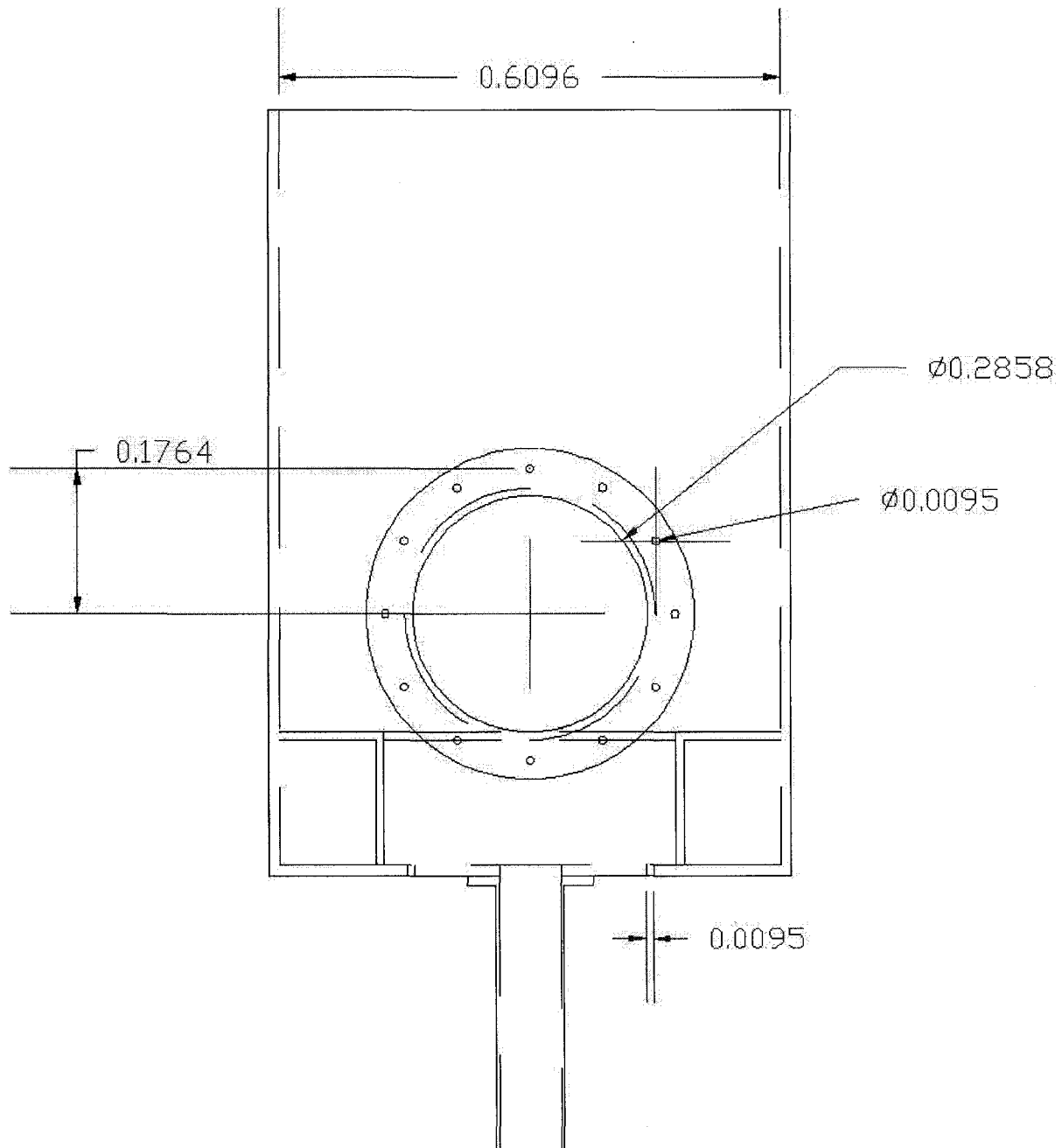


Figure A.1: Front view

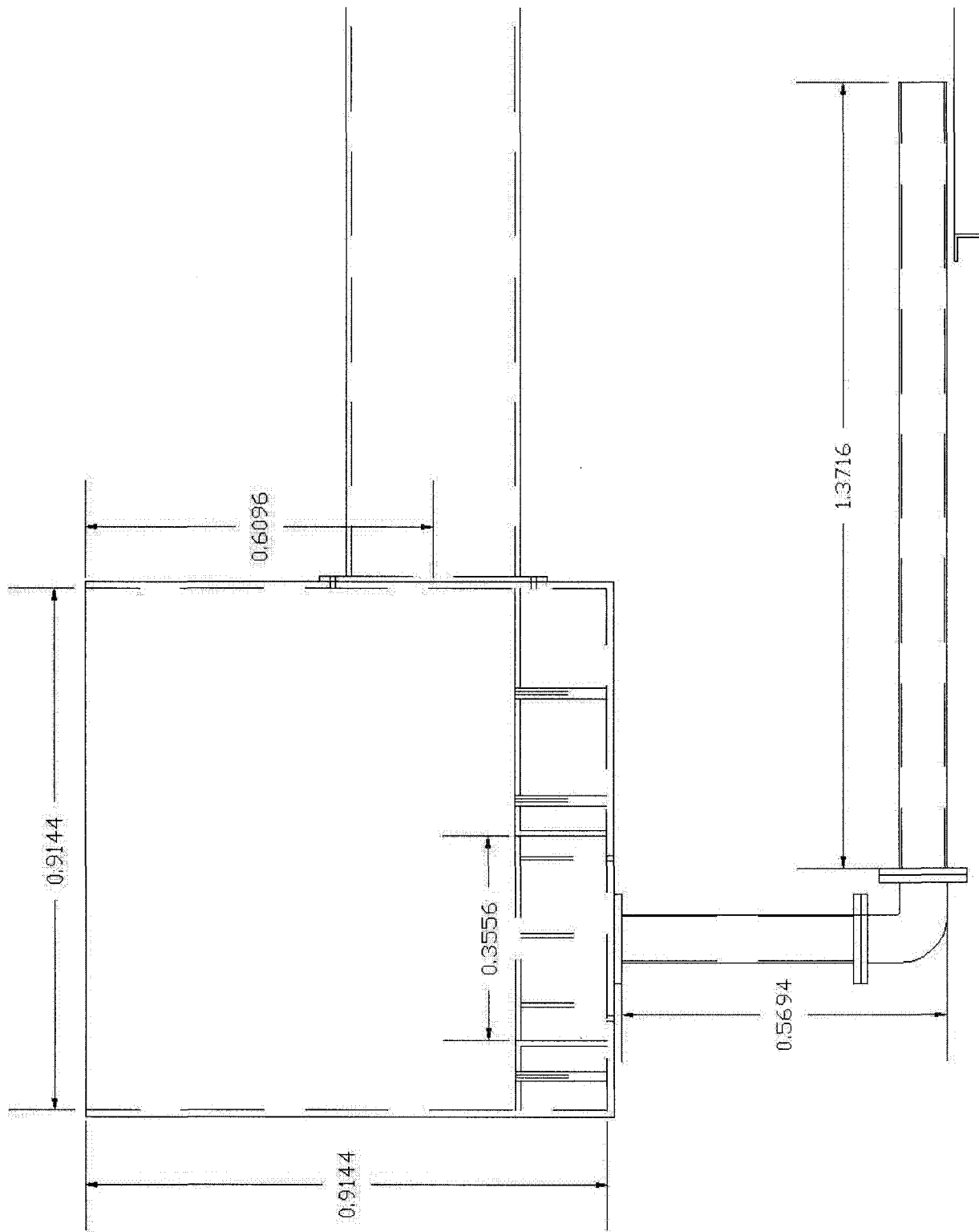


Figure A.2: Longitudinal cross-section

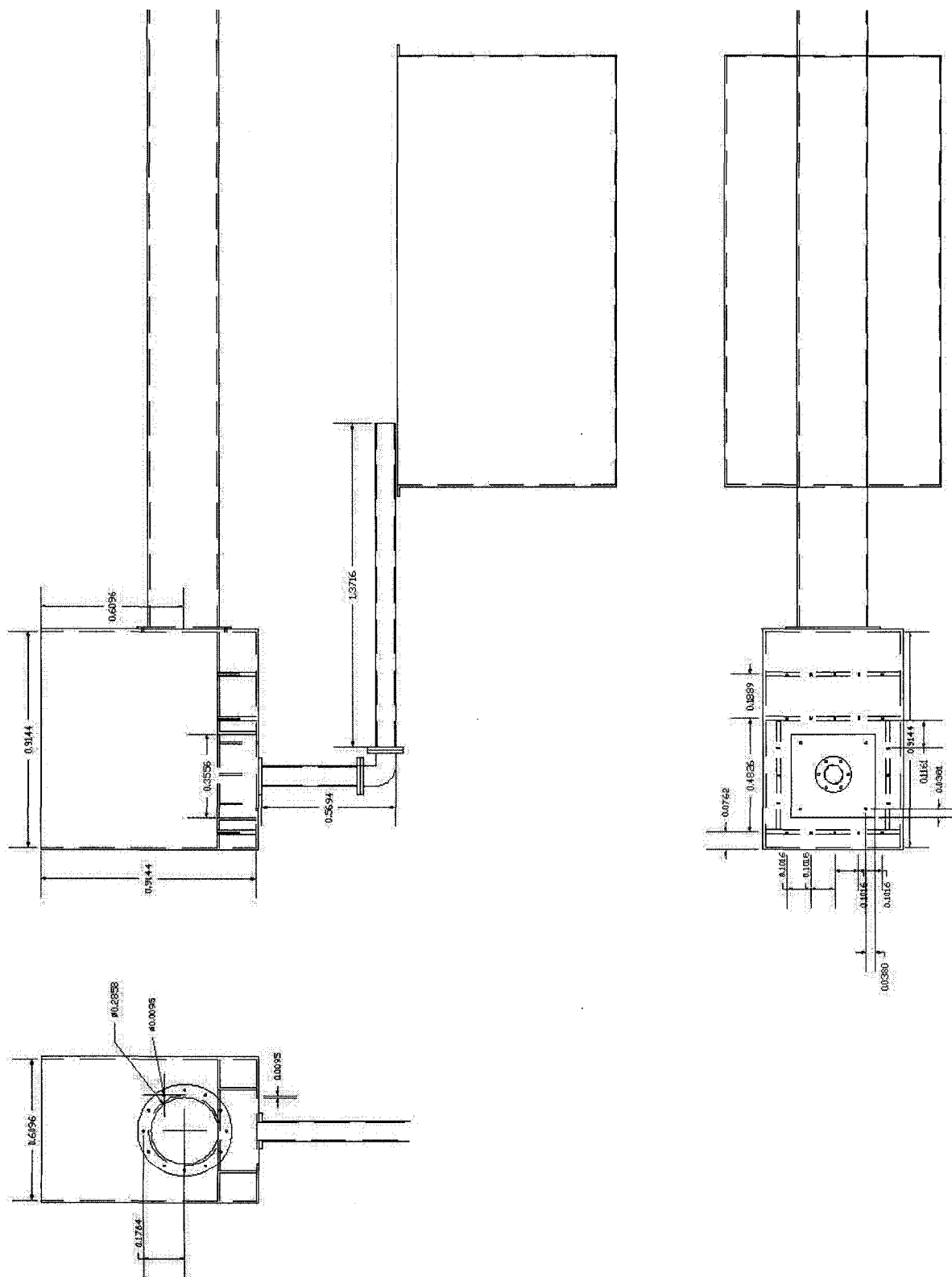


Figure A.4: Overall setup

APPENDIX B – OGEE AND ROUND ENTRANCE SHAPE COORDINATES

Meters (m)					
OGEE 1		OGEE 2		Round	
y	x	y	x	y	x
0.0000	0.106700	0.0000	0.127100	0.0000	0.114300
-0.0005	0.103240	-0.0005	0.123578	-0.0005	0.105585
-0.0010	0.101428	-0.0010	0.121475	-0.0010	0.101995
-0.0015	0.100047	-0.0015	0.119836	-0.0015	0.099255
-0.0020	0.098900	-0.0020	0.118455	-0.0020	0.096956
-0.0025	0.097789	-0.0025	0.117247	-0.0025	0.094941
-0.0030	0.096740	-0.0030	0.116100	-0.0030	0.093129
-0.0035	0.095746	-0.0035	0.114983	-0.0035	0.091471
-0.0040	0.094800	-0.0040	0.113922	-0.0040	0.089936
-0.0045	0.093897	-0.0045	0.112911	-0.0045	0.088502
-0.0050	0.093033	-0.0050	0.111944	-0.0050	0.087153
-0.0055	0.092204	-0.0055	0.111017	-0.0055	0.085876
-0.0060	0.091407	-0.0060	0.110127	-0.0060	0.084663
-0.0065	0.090640	-0.0065	0.109270	-0.0065	0.083506
-0.0070	0.089900	-0.0070	0.108444	-0.0070	0.082398
-0.0075	0.089255	-0.0075	0.107646	-0.0075	0.081335
-0.0080	0.088621	-0.0080	0.106874	-0.0080	0.080313
-0.0085	0.087998	-0.0085	0.106127	-0.0085	0.079328
-0.0090	0.087385	-0.0090	0.105403	-0.0090	0.078377
-0.0095	0.086782	-0.0095	0.104700	-0.0095	0.077457
-0.0100	0.086189	-0.0100	0.104034	-0.0100	0.076566
-0.0105	0.085606	-0.0105	0.103378	-0.0105	0.075702
-0.0110	0.085032	-0.0110	0.102731	-0.0110	0.074863
-0.0115	0.084467	-0.0115	0.102093	-0.0115	0.074048
-0.0120	0.083911	-0.0120	0.101464	-0.0120	0.073255
-0.0125	0.083364	-0.0125	0.100844	-0.0125	0.072483
-0.0130	0.082825	-0.0130	0.100232	-0.0130	0.071731
-0.0135	0.082294	-0.0135	0.099628	-0.0135	0.070998
-0.0140	0.081771	-0.0140	0.099032	-0.0140	0.070283
-0.0145	0.081256	-0.0145	0.098444	-0.0145	0.069585
-0.0150	0.080749	-0.0150	0.097864	-0.0150	0.068903
-0.0155	0.080249	-0.0155	0.097291	-0.0155	0.068237
-0.0160	0.079756	-0.0160	0.096725	-0.0160	0.067585
-0.0165	0.079271	-0.0165	0.096167	-0.0165	0.066948
-0.0170	0.078793	-0.0170	0.095616	-0.0170	0.066324
-0.0175	0.078321	-0.0175	0.095071	-0.0175	0.065714
-0.0180	0.077856	-0.0180	0.094533	-0.0180	0.065116
-0.0185	0.077398	-0.0185	0.094002	-0.0185	0.064530
-0.0190	0.076946	-0.0190	0.093477	-0.0190	0.063956
-0.0195	0.076501	-0.0195	0.092959	-0.0195	0.063394
-0.0200	0.076062	-0.0200	0.092447	-0.0200	0.062843
-0.0205	0.075629	-0.0205	0.091941	-0.0205	0.062302
-0.0210	0.075202	-0.0210	0.091441	-0.0210	0.061772
-0.0215	0.074781	-0.0215	0.090947	-0.0215	0.061252
-0.0220	0.074366	-0.0220	0.090459	-0.0220	0.060741
-0.0225	0.073956	-0.0225	0.089976	-0.0225	0.060240

-0.0230	0.073550	-0.0230	0.089499	-0.0230	0.059748
-0.0235	0.073148	-0.0235	0.089027	-0.0235	0.059265
-0.0240	0.072749	-0.0240	0.088561	-0.0240	0.058791
-0.0245	0.072354	-0.0245	0.088100	-0.0245	0.058325
-0.0250	0.071963	-0.0250	0.087644	-0.0250	0.057867
-0.0255	0.071576	-0.0255	0.087193	-0.0255	0.057417
-0.0260	0.071192	-0.0260	0.086748	-0.0260	0.056975
-0.0265	0.070812	-0.0265	0.086308	-0.0265	0.056541
-0.0270	0.070436	-0.0270	0.085873	-0.0270	0.056115
-0.0275	0.070063	-0.0275	0.085442	-0.0275	0.055696
-0.0280	0.069694	-0.0280	0.085016	-0.0280	0.055284
-0.0285	0.069328	-0.0285	0.084595	-0.0285	0.054879
-0.0290	0.068966	-0.0290	0.084179	-0.0290	0.054481
-0.0295	0.068607	-0.0295	0.083767	-0.0295	0.054090
-0.0300	0.068252	-0.0300	0.083357	-0.0300	0.053706
-0.0305	0.067900	-0.0305	0.082948	-0.0305	0.053328
-0.0310	0.067551	-0.0310	0.082542	-0.0310	0.052956
-0.0315	0.067206	-0.0315	0.082139	-0.0315	0.052591
-0.0320	0.066864	-0.0320	0.081739	-0.0320	0.052232
-0.0325	0.066525	-0.0325	0.081342	-0.0325	0.051879
-0.0330	0.066189	-0.0330	0.080948	-0.0330	0.051532
-0.0335	0.065857	-0.0335	0.080557	-0.0335	0.051191
-0.0340	0.065528	-0.0340	0.080169	-0.0340	0.050856
-0.0345	0.065202	-0.0345	0.079783	-0.0345	0.050526
-0.0350	0.064879	-0.0350	0.079400	-0.0350	0.050202
-0.0355	0.064559	-0.0355	0.079020	-0.0355	0.049883
-0.0360	0.064242	-0.0360	0.078643	-0.0360	0.049570
-0.0365	0.063928	-0.0365	0.078268	-0.0365	0.049262
-0.0370	0.063617	-0.0370	0.077896	-0.0370	0.048959
-0.0375	0.063309	-0.0375	0.077527	-0.0375	0.048662
-0.0380	0.063004	-0.0380	0.077161	-0.0380	0.048370
-0.0385	0.062702	-0.0385	0.076797	-0.0385	0.048083
-0.0390	0.062403	-0.0390	0.076436	-0.0390	0.047801
-0.0395	0.062107	-0.0395	0.076077	-0.0395	0.047524
-0.0400	0.061814	-0.0400	0.075721	-0.0400	0.047252
-0.0405	0.061524	-0.0405	0.075368	-0.0405	0.046984
-0.0410	0.061236	-0.0410	0.075017	-0.0410	0.046721
-0.0415	0.060951	-0.0415	0.074669	-0.0415	0.046463
-0.0420	0.060669	-0.0420	0.074323	-0.0420	0.046210
-0.0425	0.060390	-0.0425	0.073980	-0.0425	0.045961
-0.0430	0.060114	-0.0430	0.073639	-0.0430	0.045717
-0.0435	0.059840	-0.0435	0.073301	-0.0435	0.045477
-0.0440	0.059569	-0.0440	0.072965	-0.0440	0.045242
-0.0445	0.059301	-0.0445	0.072631	-0.0445	0.045011
-0.0450	0.059035	-0.0450	0.072300	-0.0450	0.044784
-0.0455	0.058772	-0.0455	0.071971	-0.0455	0.044562
-0.0460	0.058512	-0.0460	0.071645	-0.0460	0.044344
-0.0465	0.058254	-0.0465	0.071321	-0.0465	0.044130
-0.0470	0.057999	-0.0470	0.070999	-0.0470	0.043920
-0.0475	0.057746	-0.0475	0.070680	-0.0475	0.043715
-0.0480	0.057496	-0.0480	0.070363	-0.0480	0.043514
-0.0485	0.057249	-0.0485	0.070048	-0.0485	0.043317

-0.0490	0.057004	-0.0490	0.069736	-0.0490	0.043124
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-0.0505	0.056285	-0.0505	0.068812	-0.0505	0.042569
-0.0510	0.056050	-0.0510	0.068509	-0.0510	0.042392
-0.0515	0.055818	-0.0515	0.068208	-0.0515	0.042219
-0.0520	0.055588	-0.0520	0.067909	-0.0520	0.042050
-0.0525	0.055360	-0.0525	0.067612	-0.0525	0.041884
-0.0530	0.055135	-0.0530	0.067317	-0.0530	0.041722
-0.0535	0.054912	-0.0535	0.067025	-0.0535	0.041564
-0.0540	0.054692	-0.0540	0.066735	-0.0540	0.041410
-0.0545	0.054474	-0.0545	0.066447	-0.0545	0.041260
-0.0550	0.054258	-0.0550	0.066161	-0.0550	0.041113
-0.0555	0.054045	-0.0555	0.065877	-0.0555	0.040970
-0.0560	0.053834	-0.0560	0.065595	-0.0560	0.040831
-0.0565	0.053626	-0.0565	0.065315	-0.0565	0.040695
-0.0570	0.053420	-0.0570	0.065037	-0.0570	0.040563
-0.0575	0.053216	-0.0575	0.064762	-0.0575	0.040435
-0.0580	0.053014	-0.0580	0.064489	-0.0580	0.040310
-0.0585	0.052815	-0.0585	0.064218	-0.0585	0.040189
-0.0590	0.052618	-0.0590	0.063949	-0.0590	0.040071
-0.0595	0.052423	-0.0595	0.063682	-0.0595	0.039957
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-0.0605	0.052041	-0.0605	0.063154	-0.0605	0.039739
-0.0610	0.051853	-0.0610	0.062893	-0.0610	0.039635
-0.0615	0.051667	-0.0615	0.062634	-0.0615	0.039535
-0.0620	0.051484	-0.0620	0.062377	-0.0620	0.039438
-0.0625	0.051303	-0.0625	0.062122	-0.0625	0.039345
-0.0630	0.051137	-0.0630	0.061869	-0.0630	0.039255
-0.0635	0.050972	-0.0635	0.061618	-0.0635	0.039169
-0.0640	0.050808	-0.0640	0.061369	-0.0640	0.039086
-0.0645	0.050646	-0.0645	0.061122	-0.0645	0.039007
-0.0650	0.050485	-0.0650	0.060877	-0.0650	0.038931
-0.0655	0.050325	-0.0655	0.060633	-0.0655	0.038858
-0.0660	0.050166	-0.0660	0.060391	-0.0660	0.038789
-0.0665	0.050008	-0.0665	0.060151	-0.0665	0.038723
-0.0670	0.049851	-0.0670	0.059913	-0.0670	0.038661
-0.0675	0.049695	-0.0675	0.059677	-0.0675	0.038602
-0.0680	0.049540	-0.0680	0.059443	-0.0680	0.038546
-0.0685	0.049387	-0.0685	0.059211	-0.0685	0.038494
-0.0690	0.049235	-0.0690	0.058981	-0.0690	0.038445
-0.0695	0.049084	-0.0695	0.058752	-0.0695	0.038399
-0.0700	0.048934	-0.0700	0.058525	-0.0700	0.038357
-0.0705	0.048785	-0.0705	0.058300	-0.0705	0.038318
-0.0710	0.048637	-0.0710	0.058077	-0.0710	0.038282
-0.0715	0.048490	-0.0715	0.057856	-0.0715	0.038249
-0.0720	0.048344	-0.0720	0.057637	-0.0720	0.038220
-0.0725	0.048199	-0.0725	0.057419	-0.0725	0.038194
-0.0730	0.048055	-0.0730	0.057203	-0.0730	0.038171
-0.0735	0.047912	-0.0735	0.056989	-0.0735	0.038152
-0.0740	0.047771	-0.0740	0.056777	-0.0740	0.038136
-0.0745	0.047631	-0.0745	0.056567	-0.0745	0.038123

-0.0750	0.047492	-0.0750	0.056358	-0.0750	0.038113
-0.0755	0.047354	-0.0755	0.056151	-0.0755	0.038107
-0.0760	0.047217	-0.0760	0.055946	-0.0760	0.038100
-0.0765	0.047081	-0.0765	0.055743	-0.0765	0.038100
-0.0770	0.046946	-0.0770	0.055541	-0.0770	0.038100
-0.0775	0.046812	-0.0775	0.055341	-0.0775	0.038100
-0.0780	0.046679	-0.0780	0.055143	-0.0780	0.038100
-0.0785	0.046547	-0.0785	0.054947	-0.0785	0.038100
-0.0790	0.046416	-0.0790	0.054752	-0.0790	0.038100
-0.0795	0.046286	-0.0795	0.054559	-0.0795	0.038100
-0.0800	0.046157	-0.0800	0.054368	-0.0800	0.038100
-0.0805	0.046030	-0.0805	0.054179	-0.0805	0.038100
-0.0810	0.045904	-0.0810	0.053991	-0.0810	0.038100
-0.0815	0.045779	-0.0815	0.053805	-0.0815	0.038100
-0.0820	0.045655	-0.0820	0.053621	-0.0820	0.038100
-0.0825	0.045532	-0.0825	0.053438	-0.0825	0.038100
-0.0830	0.045410	-0.0830	0.053257	-0.0830	0.038100
-0.0835	0.045289	-0.0835	0.053078	-0.0835	0.038100
-0.0840	0.045169	-0.0840	0.052895	-0.0840	0.038100
-0.0845	0.045050	-0.0845	0.052710	-0.0845	0.038100
-0.0850	0.044932	-0.0850	0.052526	-0.0850	0.038100
-0.0855	0.044815	-0.0855	0.052343	-0.0855	0.038100
-0.0860	0.044699	-0.0860	0.052162	-0.0860	0.038100
-0.0865	0.044584	-0.0865	0.051982	-0.0865	0.038100
-0.0870	0.044470	-0.0870	0.051803	-0.0870	0.038100
-0.0875	0.044357	-0.0875	0.051625	-0.0875	0.038100
-0.0880	0.044245	-0.0880	0.051449	-0.0880	0.038100
-0.0885	0.044134	-0.0885	0.051274	-0.0885	0.038100
-0.0890	0.044024	-0.0890	0.051100	-0.0890	0.038100
-0.0895	0.043915	-0.0895	0.050927	-0.0895	0.038100
-0.0900	0.043807	-0.0900	0.050755	-0.0900	0.038100
-0.0905	0.043700	-0.0905	0.050585	-0.0905	0.038100
-0.0910	0.043594	-0.0910	0.050416	-0.0910	0.038100
-0.0915	0.043490	-0.0915	0.050248	-0.0915	0.038100
-0.0920	0.043387	-0.0920	0.050081	-0.0920	0.038100
-0.0925	0.043285	-0.0925	0.049915	-0.0925	0.038100
-0.0930	0.043184	-0.0930	0.049750	-0.0930	0.038100
-0.0935	0.043084	-0.0935	0.049587	-0.0935	0.038100
-0.0940	0.042985	-0.0940	0.049425	-0.0940	0.038100
-0.0945	0.042887	-0.0945	0.049264	-0.0945	0.038100
-0.0950	0.042790	-0.0950	0.049104	-0.0950	0.038100
-0.0955	0.042694	-0.0955	0.048945	-0.0955	0.038100
-0.0960	0.042599	-0.0960	0.048788	-0.0960	0.038100
-0.0965	0.042495	-0.0965	0.048632	-0.0965	0.038100
-0.0970	0.042402	-0.0970	0.048477	-0.0970	0.038100
-0.0975	0.042310	-0.0975	0.048323	-0.0975	0.038100
-0.0980	0.042219	-0.0980	0.048170	-0.0980	0.038100
-0.0985	0.042129	-0.0985	0.048018	-0.0985	0.038100
-0.0990	0.042040	-0.0990	0.047868	-0.0990	0.038100
-0.0995	0.041952	-0.0995	0.047719	-0.0995	0.038100
-0.1000	0.041865	-0.1000	0.047571	-0.1000	0.038100
-0.1005	0.041779	-0.1005	0.047424	-0.1005	0.038100

-0.1010	0.041694	-0.1010	0.047278	-0.1010	0.038100
-0.1015	0.041610	-0.1015	0.047133	-0.1015	0.038100
-0.1020	0.041527	-0.1020	0.046989	-0.1020	0.038100
-0.1025	0.041445	-0.1025	0.046847	-0.1025	0.038100
-0.1030	0.041364	-0.1030	0.046706	-0.1030	0.038100
-0.1035	0.041284	-0.1035	0.046566	-0.1035	0.038100
-0.1040	0.041205	-0.1040	0.046427	-0.1040	0.038100
-0.1045	0.041127	-0.1045	0.046289	-0.1045	0.038100
-0.1050	0.041050	-0.1050	0.046152	-0.1050	0.038100
-0.1055	0.040974	-0.1055	0.046016	-0.1055	0.038100
-0.1060	0.040899	-0.1060	0.045882	-0.1060	0.038100
-0.1065	0.040825	-0.1065	0.045749	-0.1065	0.038100
-0.1070	0.040752	-0.1070	0.045617	-0.1070	0.038100
-0.1075	0.040680	-0.1075	0.045486	-0.1075	0.038100
-0.1080	0.040609	-0.1080	0.045356	-0.1080	0.038100
-0.1085	0.040539	-0.1085	0.045227	-0.1085	0.038100
-0.1090	0.040470	-0.1090	0.045099	-0.1090	0.038100
-0.1095	0.040402	-0.1095	0.044972	-0.1095	0.038100
-0.1100	0.040335	-0.1100	0.044846	-0.1100	0.038100
-0.1105	0.040269	-0.1105	0.044722	-0.1105	0.038100
-0.1110	0.040204	-0.1110	0.044599	-0.1110	0.038100
-0.1115	0.040140	-0.1115	0.044477	-0.1115	0.038100
-0.1120	0.040077	-0.1120	0.044356	-0.1120	0.038100
-0.1125	0.040015	-0.1125	0.044236	-0.1125	0.038100
-0.1130	0.039954	-0.1130	0.044117	-0.1130	0.038100
-0.1135	0.039894	-0.1135	0.043999	-0.1135	0.038100
-0.1140	0.039835	-0.1140	0.043882	-0.1140	0.038100
-0.1145	0.039777	-0.1145	0.043766	-0.1145	0.038100
-0.1150	0.039720	-0.1150	0.043652	-0.1150	0.038100
-0.1155	0.039664	-0.1155	0.043539	-0.1155	0.038100
-0.1160	0.039609	-0.1160	0.043427	-0.1160	0.038100
-0.1165	0.039555	-0.1165	0.043316	-0.1165	0.038100
-0.1170	0.039502	-0.1170	0.043206	-0.1170	0.038100
-0.1175	0.039450	-0.1175	0.043097	-0.1175	0.038100
-0.1180	0.039399	-0.1180	0.042989	-0.1180	0.038100
-0.1185	0.039349	-0.1185	0.042882	-0.1185	0.038100
-0.1190	0.039300	-0.1190	0.042776	-0.1190	0.038100
-0.1195	0.039252	-0.1195	0.042671	-0.1195	0.038100
-0.1200	0.039205	-0.1200	0.042567	-0.1200	0.038100
-0.1205	0.039159	-0.1205	0.042464	-0.1205	0.038100
-0.1210	0.039114	-0.1210	0.042363	-0.1210	0.038100
-0.1215	0.039070	-0.1215	0.042263	-0.1215	0.038100
-0.1220	0.039027	-0.1220	0.042164	-0.1220	0.038100
-0.1225	0.038985	-0.1225	0.042066	-0.1225	0.038100
-0.1230	0.038944	-0.1230	0.041969	-0.1230	0.038100
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-0.1240	0.038864	-0.1240	0.041778	-0.1240	0.038100
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-0.1285	0.038549	-0.1285	0.040970	-0.1285	0.038100
-0.1290	0.038519	-0.1290	0.040886	-0.1290	0.038100
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-0.1320	0.038360	-0.1320	0.040403	-0.1320	0.038100
-0.1325	0.038337	-0.1325	0.040326	-0.1325	0.038100
-0.1330	0.038315	-0.1330	0.040250	-0.1330	0.038100
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-0.1380	0.038150	-0.1380	0.039547	-0.1380	0.038100
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-0.1440	0.038100	-0.1440	0.038845	-0.1440	0.038100
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-0.1450	0.038100	-0.1450	0.038742	-0.1450	0.038100
-0.1455	0.038100	-0.1455	0.038692	-0.1455	0.038100
-0.1460	0.038100	-0.1460	0.038643	-0.1460	0.038100
-0.1465	0.038100	-0.1465	0.038595	-0.1465	0.038100
-0.1470	0.038100	-0.1470	0.038548	-0.1470	0.038100
-0.1475	0.038100	-0.1475	0.038502	-0.1475	0.038100
-0.1480	0.038100	-0.1480	0.038457	-0.1480	0.038100
-0.1485	0.038100	-0.1485	0.038413	-0.1485	0.038100
-0.1490	0.038100	-0.1490	0.038370	-0.1490	0.038100
-0.1495	0.038100	-0.1495	0.038328	-0.1495	0.038100
-0.1500	0.038100	-0.1500	0.038287	-0.1500	0.038100
-0.1505	0.038100	-0.1505	0.038247	-0.1505	0.038100
-0.1510	0.038100	-0.1510	0.038208	-0.1510	0.038100
-0.1515	0.038100	-0.1515	0.038170	-0.1515	0.038100
-0.1520	0.038100	-0.1520	0.038133	-0.1520	0.038100
-0.1524	0.038100	-0.1524	0.038100	-0.1524	0.038100