7-2008

INVESTIGATION OF THE DISCHARGE COEFFICIENT FOR CIRCULAR ORIFICES IN RISER PIPES

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Recommended Citation

Prohaska, David, "INVESTIGATION OF THE DISCHARGE COEFFICIENT FOR CIRCULAR ORIFICES IN RISER PIPES" (2008). *All Theses*. 407.
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INVESTIGATION OF THE DISCHARGE COEFFICIENT FOR CIRCULAR ORIFICES IN RISER PIPES

A Thesis
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Civil Engineering

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by
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August 2008

Accepted by:
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ABSTRACT

The purpose of this study is to examine the discharge coefficient as it pertains to flow through a circular orifice cut into a thin-walled vertical riser pipe. Perforated riser pipes are a popular outlet control structure for stormwater detention basins. These basins are used to store and release stormwater runoff from impervious areas of developed sites. Federal, state, and local regulatory agencies provide requirements for the quality of stormwater runoff, as well as the maximum peak discharges from a developed site. Accurately determining the flow rate from a perforated vertical riser pipe is crucial to meeting these requirements and protecting the environment from pollutants found in stormwater runoff.

This study therefore investigated several factors that may affect the value of the discharge coefficient. A physical model was built and various size riser pipes were installed in the tank to simulate a detention basin. The discharge through the orifice was determined by measuring the rate of change of the water level in the tank versus time. A water level versus volume drained calibration was used to find the rate of change of volume over time, and hence the discharge coefficient.

The study determined that the discharge coefficient increased with decreasing head values. The study also found that the discharge coefficient decreased as the height above the floor was increased, up to a certain point. Another factor found to affect the discharge coefficient was the orifice diameter to riser diameter, or d/D ratio. The

discharge coefficient decreases as the d/D ratio is increased. It is postulated that most of the changes to the discharge coefficient are a result of changes to the contraction of the jet exiting the orifice.

For orifices away from the influence of the bed, the discharge coefficient vlaues were normalized and compiled to fit a single curve that could be used to determine the discharge coefficient for any orifice size in any riser pipe diameter, for a particular head to orifice diameter ratio.

Multiple orifices in the same vertical plane were investigated as a secondary part of the study, but no effect on the discharge was found for the orifice spacings tested.

ACKNOWLEDGMENTS

I would like to thank Dr. Abdul Khan for his assistance and guidance throughout this investigation. Dr. Nigel Kaye's involvement in this study was invaluable. Without the help of their knowledge and expertise in every facet of the study, from formulating the premise to analyzing the results, this investigation could not have been completed. I would also like to thank the committee member, Dr. Firat Testik, for his comments and suggestions.

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LIST OF SYMBOLS

Symbol

$C_d =$ Discharge coefficient

$d =$ Orifice diameter (m)

$D =$ Riser pipe diameter (m)

$Q =$ Volumetric flow rate (m^3/s)

$A_\circ =$ Orifice area (m^2)

$g =$ Acceleration due to gravity

$h_\circ =$ Head above the center of the orifice (m)

$C_c =$ Contraction coefficient

$C_v =$ Velocity coefficient

$A_2 =$ Cross-sectional area of flow at the vena contracta (m^2)

$h_L =$ Head loss across the orifice (m)

$b =$ Orifice width (Eq. 2.9) or half-width (Figure 2.1)

$h_1 =$ Head above the bottom of the orifice (m)

$h_2 =$ Head above the top of the orifice (m)

$V_d =$ Volume drained from the test tank (Liters)

$h_f =$ Orifice height above the tank floor (m)

$C_\circ =$ Experimental discharge coefficient when $h/d = 20$

CHAPTER 1

INTRODUCTION

As urban and suburban development continues to dominate the cultures of the world, stormwater runoff rates also continue to increase. Developing land almost always increases the impervious area when compared to its undeveloped state. Parking lots, roads, sidewalks, and building roofs are all impervious areas that retain very little water that falls as precipitation. Instead, most of the rainwater runs off the impervious areas and onto an adjacent land or into a nearby water body. If not contained, stormwater runoff can result in flooding and erosion, as well as destroy surrounding property (Akan and Houghtalen, 2003). Runoff may also contain various pollutants which can be harmful to people, plants, and animals. Sediment is another harmful constituent of stormwater runoff. Sediment can carry many harmful substances, decrease storage capacity of retention ponds, and compromise downstream drainage systems. Stormwater runoff must be properly managed in order to protect the environment from land use changes.

In order to contain and manage runoff, the United States Environmental Protection Agency (US EPA) regulates the discharge of stormwater runoff into natural water bodies. Developers must obtain permits in order to disturb natural land and before beginning any construction. These permits, along with various local and state regulations, require that runoff discharge rates of a developed site not exceed the pre-development peak flow rate. Regulators also require that developers remove potential pollutants and contaminants to the maximum extent practical (Struble et al., 1997). Managing stormwater quantity and quality is often done with the use of detention basins that collect, store, and discharge runoff at appropriate times and rates. The outlet control structure for these basins is therefore crucial to ensuring the proper function of these ponds.

One popular outlet control device is a perforated riser, either a constructed box structure or a vertical pipe cut with orifices of varying size and number. The flow through these orifices is calculated using a form of the standard orifice equation. For a box structure, the orifices are cut into a flat wall and represent the typical orifice plate configuration (orifice in a flat wall). A vertical riser pipe, however, has a curved surface which may affect the nature of the flow through the orifice. This would be represented by a change in the discharge coefficient $\left(C_d\right)$. This discharge coefficient has been studied extensively, but almost exclusively for the case of the orifice in a flat wall. Studies of orifice flow in a circular pipe are typically limited to cases of pressurized flow through a sparger or manifold. Here the flow exits a pipe, which is opposite to the case of a riser pipe outlet structure where the fluid enters the pipe.

The effect of the pipe curvature on the orifice is quantified by relating the orifice diameter to the riser diameter (d/D ratio). This study will investigate a wide range of d/D ratios, ranging from 0.0417 to 0.5. Other factors believed to have an effect on the discharge coefficient will be investigated here, including the height of an orifice from the basin floor. The proximity of boundaries to an orifice can affect the contraction that the orifice jet experiences. This may reduce the contraction and increase the discharge coefficient. Five different orifice heights from the bottom of the tank will be studied to determine if there is any variation in the discharge coefficient. This may have an application for detention ponds, as sediment filling the pond will constantly change the relative orifice height above the floor. The study will also investigate the effect of falling head on the orifice discharge coefficient. The study utilizes a transient method, in which water will be allowed to drain naturally as the height is monitored. This will reveal if the discharge coefficient changes as head values decrease. For lower heads the pressure distribution across the face of the orifice cannot be neglected, as it is with the standard orifice equation. This may result in an increase in the discharge coefficient, as the orifice changes from a small orifice to a large orifice.

To properly investigate the scenario of a perforated vertical riser pipe as an outlet device for a detention basin, a physical model was built and equipped with necessary instruments. The model provided for the rapid changing of riser pipes of various orifice sizes, as well as varying the riser pipe diameter. Data was collected using LabView and analyzed in Microsoft Excel. The objectives of this study are summarized below:

- Determine the effects of varying the d/D ratio on the orifice discharge coefficient for orifices cut into a thin-walled pipe,
- Determine the effect of head values on the orifice discharge coefficient,

- Determine the effects of varying the orifice height above the basin floor on the orifice discharge coefficient,
- Investigate two different riser pipe diameters to determine if there is a change in the discharge coefficient for similar orifice sizes and d/D ratios,
- Investigate the effect of multiple orifices and the spacing of orifices on the discharge coefficient,

Chapter 2 of this study presents a thorough review of current and classical research concerning orifice discharge coefficients and stormwater runoff quality and management. Chapter 3 discusses the setup of the physical model and the experimental procedure employed. Chapter 4 discusses the analytical procedure used to analyze the test results. Chapter 5 presents the results of the study, along with appropriate discussions of the data, and Chapter 6 includes conclusions reached and recommendations for future studies.

CHAPTER 2

LITERATURE REVIEW

Introduction

Previous research on orifice discharge coefficients primarily focuses on the typical case of an orifice cut into a flat wall. Some research discusses orifices cut into a thin-walled pipe, but this often applies to flow through a sparger or manifold, where the flow exits a pressurized pipe through multiple orifices cut into the wall of the pipe (Gregg et al., 2003 and Werth et al., 2005). The case of the stormwater detention pond with a vertical perforated riser outlet structure is different from this case as there is no velocity parallel to the orifice. Also, the flow is exiting the orifice through a concave section in the case of a sparger or manifold, whereas the flow enters the orifice through a convex section for a vertical riser pipe. Stormwater storage facilities are typically designed to allow a sufficient residence time of runoff to facilitate the settlement of sediment and solid particles. Detention basins are also designed to store and release a specific volume of water at a flow rate which should not exceed that of the pre-developed condition. Overdesign of outlet structures can lead to rapid dewatering and deficient water quality of the released water volume (Jarrett, 1993).

Background

Increasing urban and suburban development is continuously leading to increases in stormwater runoff volume and flow rates and can lead to increased flooding and sometimes severe downstream erosion (Akan and Houghtalen, 2003). Management of stormwater runoff has become a primary concern for local, state, and federal regulatory agencies. Two aspects of stormwater management typically dominate regulatory practices and include water quantity and water quality. Detention basins are widely used to control both of these aspects. Detention basins capture and store runoff for a designated period of time, and release the runoff through one or more outlet structures. A perforated vertical riser is one popular outlet structure used to control dewatering, defined as the slow, controlled removal of runoff from a detention basin (Jarrett, 1993). Detention basins manage stormwater volume by the size of the basin and the stage-storage-outflow relationship. For basins with a regular shape, the geometry can be used to determine the stage-storage relationship. Contour maps of the basin are used for unusual-shaped basins (Akan and Houghtalen, 2003). The size and design of the outlet structure and the maximum stage determine the maximum flow rate from the detention basin. Most regulatory agencies require that this flow rate not exceed the pre-development peak flow rate from the disturbed area for a given storm event.

Water quality is most often addressed by providing sufficient residence time of runoff in the basin for sediment and other suspended solids to settle out of the runoff.

The United States Environmental Protection Agency (US EPA) introduced the National Pollutant Discharge Elimination System (NPDES), which is a permitting program designed to help control non-point source pollutants from being discharged into natural receiving water bodies (Tsihrintzis and Hamid, 1997). The program was launched as part of the Clean Water Act. Most states have the control to issue permits on behalf of the US EPA, and states also have the authority to develop their own regulatory practices. Some states, such as Pennsylvania, enforce a minimum and maximum dewatering time for a specific rainfall event. This is to ensure adequate time for the runoff to settle out suspended solids and sediment. A maximum dewatering time ensures that a basin has enough capacity to store runoff from future storm events (Jarrett, 1993).

Even with local and state regulatory requirements, the efficiency of detention basins can vary greatly. A study by Millen et al. (1997) investigated different outlet structures and different basin configurations and evaluated their effectiveness at removing a particular sediment loading. The study employed a perforated riser outlet structure as well as a floating riser, or skimmer. Also evaluated was a basin with and without filter fabric barriers designed to increase the length of the flow path from the inflow to the outlet structures. The fabric divided the basin into three nearly equal sections, with openings in the fabric at opposite ends to achieve maximum effectiveness. A known sediment loading was mixed with the inflow, and the sediment concentrations at the outflow were measured over time. The basin was designed to dewater within 24 hours for a 2-year storm event.

The research found that the floating skimmer outlet structure retained significantly more sediment than the perforated riser, and the skimmer also produced a lower peak flow rate from the basin. In the case of the perforated riser, the fabric barriers helped to lower the sediment outflow rate. However, the barriers had little effect on the efficiency of the floating skimmer. The study was conclusive in showing how certain detention basin design procedures could lead to significantly increased sediment trapping efficiency. Unfortunately, floating skimmers are rarely used and thus do not have much use in practical applications (Millen et al., 1997).

The design of detention basins and their associated outlet structures can play a large role in preventing pollution and erosion of the natural water bodies in which they discharge. The accurate calculation of flow rate from a perforated riser therefore becomes critical. Thus, it is necessary to accurately determine the discharge coefficient for various sizes of orifices cut into a thin-walled pipe.

Discharge coefficient

The standard equation used to estimate flow through a small orifice (small infers that the pressure distribution across the orifice can be neglected, i.e., head is high compared to the diameter of the orifice) discharging in atmosphere can be written as:

$$Q = C_d A_\circ \sqrt{2gh_\circ} \qquad 2.1$$

Where:

$Q =$ flow rate (m^3/s)

C_d = dimensionless discharge coefficient

$A_\circ$ = orifice area (m^2)

g = acceleration due to gravity

$h_\circ$ = head above the center of the orifice (m)

An understanding of how the discharge coefficient was developed is crucial to being able to evaluate its effectiveness. Brater et al. (1996) provides a discussion on the origins and the development of the discharge coefficient. They describe how the overall discharge coefficient is actually a combination of two separate coefficients, C_c and C_v. C_c is a contraction coefficient evaluated at the vena contracta of a jet issuing from an orifice. Streamlines flowing towards an orifice come from all directions, and in three dimensions. For all streamlines except those exactly normal to the orifice, there is a lateral component of velocity which must be dissipated as the water exits the orifice. These lateral velocity components cause the jet to contract as they round the sharp edges of an orifice. The flow contracts up to a point, known as the vena contracta. For a circular orifice, the vena contracta is located approximately ½ diameters downstream of the inner face of the orifice plate (Brater et al., 1996). Because of this phenomenon, the area of the orifice is larger than the actual area of flow from the orifice. These two areas are related by the equation:

$$A_2 = C_c A_\circ \qquad 2.2$$

Here A_2 is the cross-sectional area of the jet at the vena contracta, $A_\circ$ is the orifice area, and C_c is the coefficient of contraction. Values of C_c have been found to be about 0.67 for a 2 cm orifice and 0.614 for a 6 cm orifice, for heads that are greater than 1.2 m. The value of C_c increases as head values decrease, to as high as 0.72 for a 2 cm orifice under 6 cm of head (Smith and Walker, 1923). The coefficient of contraction can be increased (decreasing the effect of lateral velocity components and reducing the amount of contraction) by increasing the roughness around the orifice, and also by rounding the inner edge of the orifice. The contraction can be completely eliminated if the edge can be rounded to exactly conform to the shape of the contracting jet (Brater et al., 1996). This would increase C_c and therefore increase C_d.

The velocity coefficient, C_v, represents head loss that is experienced as water moves from a reservoir and through an orifice. Taking the standard form of the energy equation between two points, point 2 being at the vena contracta and point 1 being some point well within the tank and at the same elevation as the orifice, the following equation can be written:

$$\frac{p_1}{\gamma}+\frac{V_1^2}{2g}=\frac{p_2}{\gamma}+\frac{V_2^2}{2g}+h_L \qquad 2.3$$

It can be assumed that the pressure at point 2 is zero if the orifice discharges into the atmosphere, and the velocity at point 1 is small enough that the velocity head can be neglected. Equation 2.3 can therefore be rewritten, solving for V_2 and replacing p_1/γ with $h_\circ$, as:

$$V_2 = \sqrt{2g\left(h_\circ - h_L\right)} \tag{2.4}$$

Instead of subtracting the head loss, it is convenient to rewrite the equation with the velocity coefficient, resulting in:

$$V_2 = C_v\sqrt{2gh_\circ} \tag{2.5}$$

Combining equations 2.4 and 2.5, the velocity coefficient can be written as:

$$C_v = \sqrt{\left(h_\circ - h_L\right)/h_\circ} \tag{2.6}$$

Also, the discharge is the product of the velocity and area of flow at the vena contracta and can be written as:

$$Q = V_2 A_2 \tag{2.7}$$

Substituting from equations 2.2 and 2.5, the following equation can be written:

$$Q = C_c A_\circ C_v \sqrt{2gh_\circ} \tag{2.8}$$

A comparison of equations 2.1 and 2.8 reveals that the discharge coefficient is simply the product of the velocity coefficient and the contraction coefficient. Values of the velocity coefficient have been determined experimentally to range from about 0.951 to 0.993 for orifices between 2 – 6 cm diameter and for heads between 0 – 30 m. The velocity coefficient decreases slightly with decrease in head (Smith and Walker, 1923).

Velocity coefficient values approaching unity show that the contraction coefficient plays a major role in determining the value of discharge coefficient.

Factors affecting the discharge coefficient

Effect of cutting method

Previous research typically focuses on cases of orifices cut into a flat wall. When an orifice is cut into a curved surface, such as a vertical riser, other variables may have to be considered in determining the discharge coefficient for the orifice. The method in which an orifice is cut can affect the area of the orifice. A study by Gregg et al. (2003) investigates the difference in discharge coefficients for different cutting methods. When an orifice is cut into a flat plate, the calculation of its cross-sectional area is straight-forward. But when an orifice is cut into a curved pipe, the projected area of the orifice is different than the actual surface area. If an orifice is cut with a circular boring bit, the projected area of the orifice will be a circle, while the actual surface area will be an ellipse. This is preferred since it is generally accepted that the correct area to use in flow calculations is the projected area of flow (Gregg et al., 2003). This is common among pipe fitters for orifices cut into standard riser pipe sizes.

If a template is used that has a circular area when laid flat, its projection will not be circular when laid over a curved pipe. However, the surface area of the orifice will be circular. The calculation of the non-circular projected area in this case can be quite difficult. It is common to use circular area for discharge calculations in both cases

(Gregg et al., 2003). This requires calculating discharge coefficient independently for both cases since the projected areas are different.

Circular projected area is a common way of cutting orifices in riser pipes and outlet structure construction (Gregg et al., 2003). For this study, all orifices are cut with a boring bit, ensuring that the orifices have a circular projected area, which is then used in the orifice equation.

Effect of pipe curvature and orifice size

As previously discussed, the effects of cutting an orifice into a curved pipe as opposed to a flat plate can create some unique circumstances which remain largely unstudied in many ways. It is important to note that the degree of curvature the orifice experiences may have a significant effect on the flow conditions and the discharge coefficient. The degree of curvature is most often accounted for by relating the orifice diameter, d, with the riser or trunk line diameter, D. The d/D ratio describes the orifice geometry as it relates to the size of the riser pipe. The d/D ratio is also an indication of the difference between the surface area and the projected area of an orifice, as a high d/D ratio indicates a greater relative difference in the area than a low d/D ratio. A study by Werth et al. (2005) examines various d/D ratios for in-line orifices in pressurized hydraulic spargers used in cooling tower or power generation applications. For orifices in pipes with very low d/D ratios $\left(d/D < 0.1\right)$, the curvature effect becomes negligible. The study by Werth et al. (2005) also investigates various

V_h/E ratios, relating the upstream velocity head in the pipe to the total energy in the pipe upstream of the orifice. The results indicate that for all V_h/E ratios, the discharge coefficient increases with increasing d/D ratios (Werth et al., 2005). The differences are explained by the fact that the flow must turn to exit the sparger through the orifice, with flow having less space to turn in case of a smaller orifice thus reducing the discharge coefficient. Greater orifice diameters provide a longer distance for the flow to make this turn, yielding more flow and a higher discharge coefficient for the higher d/D ratios.

The study by Werth et al. (2005) inspects flow out of the orifices from a main trunk line. However, this is the opposite case that is seen with vertical risers associated with stormwater detention basins. Stormwater applications typically involve the flow exiting a basin through orifices and into a main trunk line. This scenario requires that the orifice plane has a convex curve, whereas the previous study involves a concave section. For a given d/D ratio, an increase in C_d can be expected for the concave scenario, as the curvature of the pipe facilitates the streamlines of fluid exiting the orifice. Gregg et al. (2003) study supports this concept, finding C_d values greater than the typical 0.6, which is commonly used for an orifice in a flat plate. Following this reasoning, a reduction in C_d value is expected in this study as the orifices lie in a convex plane. The effect of increasing the d/D ratio for orifices in convex planes is unknown. It might be expected that the discharge coefficient should decrease further as the d/D

ratio is increased. This is because the higher the d/D ratio, the higher the curvature effect, and in the convex case this hinders the flow. More curvature means that flow streamlines will be exiting the orifice from more oblique angles in relationship to the orifice. These angles will introduce increasingly higher transverse velocity components, which will increase the contraction and thereby decrease C_d.

Effect of head above the orifice

In almost all design calculations, a single discharge coefficient is used to determine outflow rate from a vertical riser pipe for any head above the orifice. Some research shows that for large heads (greater than a few meters) the discharge coefficient varies only slightly. The research also reveals that as the head above the orifice decreases, the discharge coefficient begins to increase, with a drastic increase for head values below one meter (Smith, 1886). This is significant due to the fact that many stormwater detention basins in suburban and rural areas are relatively shallow and may operate under low-head conditions for extended periods of time. If the actual value of C_d is much higher than the design C_d, the potential exists for the outflow from a basin to exceed what is allowed by state and local regulatory agencies. Also, the high C_d value will reduce the residence time of the stormwater in the detention pond, impacting the quality of the released water. It is apparent that there exists a need to investigate the effects of head variation on the orifice discharge coefficient in circular pipes.

One reason for an increase in discharge coefficient with decreasing head is related to the pressure distribution across the vertical face of the orifice. In the conventional orifice equation (Eq. 2.1) the height of water above the orifice, $h_\circ$, is taken from the orifice centerline with the assumption that the hydrostatic pressure difference between the bottom and top of the orifice is negligible. This assumption is valid only for large $h_\circ/d$ ratios as pointed out by Bryant et al. (2008). If the pressure distribution across an orifice cannot be ignored then the discharge through a rectangular orifice in a flat plate can be written as (Gupta, 2008):

$$Q = C_d b\sqrt{2g}\int_{h_2}^{h_1} \sqrt{h}\, dh \qquad 2.9$$

Here h_1 and h_2 are the heights from the water surface to the bottom and top of the orifice, respectively, h is the height above an arbitrary point in the orifice, and b is the width of the orifice. In this scenario the velocity across the orifice is no longer uniform (Bryant et al., 2008). The corresponding equation for a circular orifice of diameter d is given by taking the partial flow through a thin strip of the orifice, as shown in Figure 2.1. The flow dQ through the strip (accounting for both halves of the orifice) can be written as:

$$dQ = 2C_d\sqrt{2gh}\cdot bdh \qquad 2.10$$

Using the Pythagorean Theorem to find b, the above equation can be written as:

$$dQ = 2C_d\sqrt{2gh}\cdot\sqrt{d^2/4-(h_\circ-h)^2}\,dh \qquad 2.11$$

The above equation can be integrated to yield Equation 2.12:

$$Q = C_d\sqrt{8g}\int_{h_2}^{h_1}\sqrt{\left(d^2/4-\left(h_\circ-h\right)^2\right)h}\,dh \qquad 2.12$$

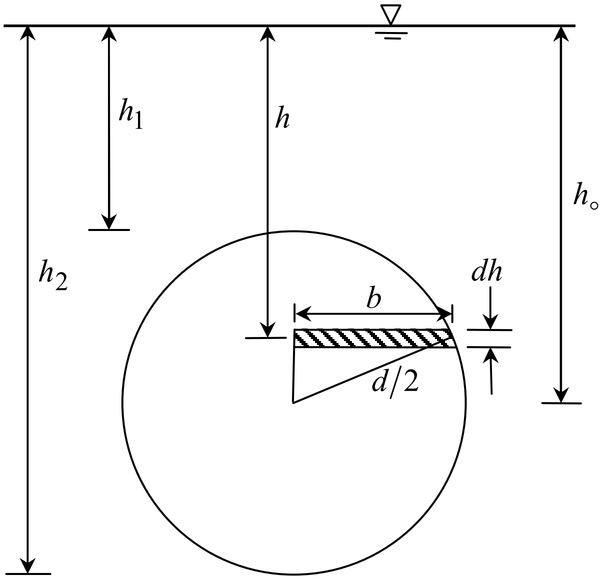

Figure 2.1: Large orifice integration setup

This investigation aims to establish the relationship between the discharge coefficient and the head above the orifice. This is achieved by varying the head from 1 m above the orifice to the top of the orifice.

Effect of orifice height above the floor

As previously discussed, it has been determined that several factors may influence the value of the discharge coefficient, C_d. Among these are the head above the orifice and the d/D ratio. Another potential influencing factor may be the distance the orifice lies above the bottom of the tank or detention basin. As one side of an orifice approaches a wall or boundary, the streamlines on that side will gradually become more parallel to the boundary. This will reduce the amount of contraction the jet experiences, which means the contraction and discharge coefficients will be higher. Knowing the effect and the extent of suppression can be useful in determining a minimum height an orifice should be placed above the floor of the detention basin. This may be especially useful in design when accounting for the sedimentation rate of a stormwater basin. As a basin fills with sediment over time, the effective height between the basin floor and the orifice will decrease. This could lead to an increase in suppression and therefore an increase in C_d. In this investigation, several orifice heights above the tank floor will be tested to determine the effect of suppression on the discharge coefficient.

CHAPTER 3

EXPERIMENTAL SETUP AND METHODOLOGY

The objective of this experiment was to determine the discharge coefficient for an orifice cut into the side of a circular pipe, and to determine the effects of pipe curvature, head above the orifice, and orifice height above the tank floor on the discharge coefficient. An existing model was adapted and a procedure was developed in order to accurately determine the discharge coefficient. The procedure for the experiment utilized a transient method, where a tank was filled with water and allowed to drain naturally through single and multiple orifices of various sizes cut into risers of multiple diameters. A pressure transducer was installed to measure the water level in the tank. A volume-height relationship was developed and used to determine the change in volume of the tank over time as the water level dropped. This information was used in the orifice discharge equation to solve for the discharge coefficient, C_d .

Physical model setup

The experiment was performed in the hydraulics laboratory of Lowry Hall at Clemson University in Clemson, SC. The plan and cross-section views of the physical model are shown in Figures 3.1 and 3.2. The physical model consists of a primary tank with perforated vertical riser, a secondary discharge basin, and a pump and pipe system is used to fill the tank to the desired level. The discharge basin collects the outflow from the tank during the test and serves as a sump that is used to fill the primary tank

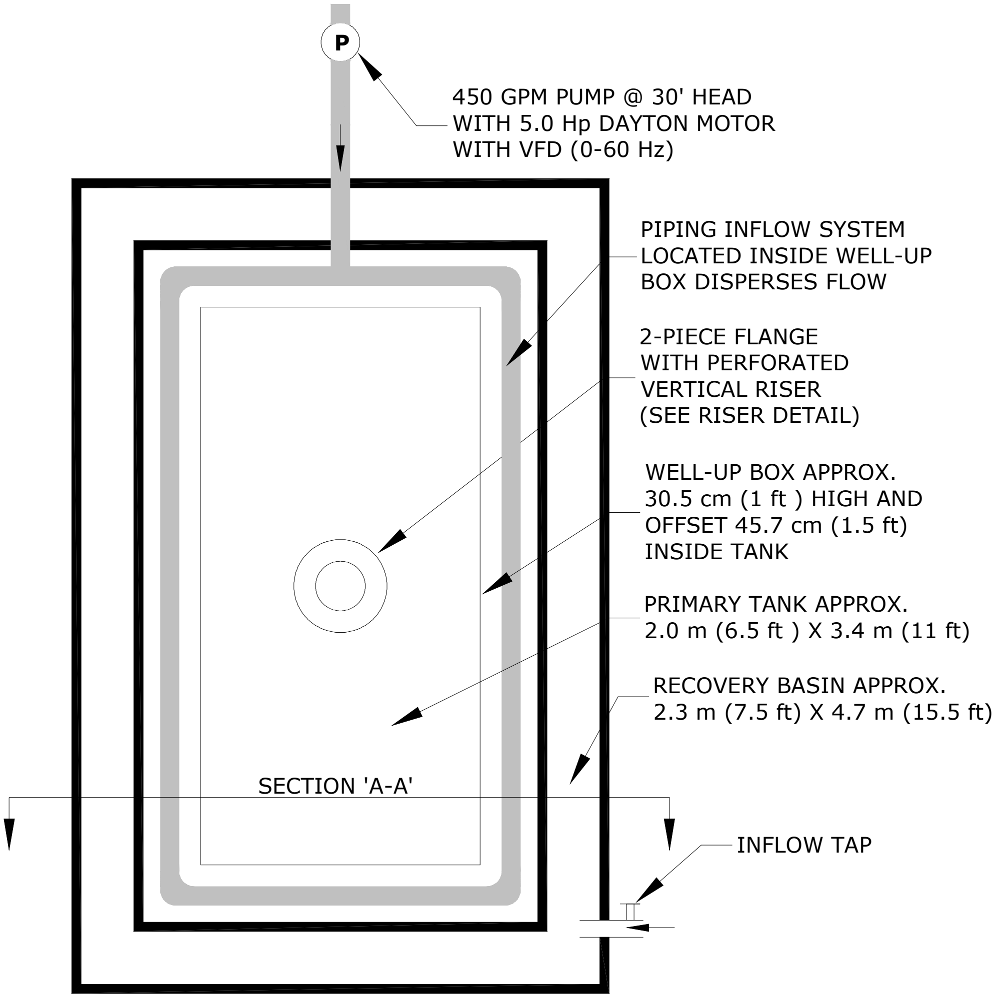

Figure 3.1: Model Plan View (drawing not to scale)

initially. The basin is approximately 4.72 m (15.5 ft) long by 2.29 m (7.5 ft) wide, and 0.76 m (2.5 ft) deep. The primary tank is situated inside of the discharge basin and is approximately 1.98 m (6.5 ft) by 3.35 m (11 ft) and 1.22 m (4 ft) deep. The discharge basin can be drained by either of two PVC drains with valves. A 1/2 horsepower submersible pump is also often used to drain the discharge basin. The drains are used to make certain that the water level in the discharge basin is lower than the bottom of the main tank during tests. The tank is raised 38 cm (15 inches) off the floor of the discharge basin by concrete blocks. This ensures that the outflow from the tank through an orifice in the standpipe is discharging in the atmosphere, i.e., the water level in the sump is always below the bottom of the main tank. Both tanks are framed with pine lumber and sheathed with 1.9 cm (3/4”) plywood. Both tanks are also coated with Hydrostop brand waterproofing sealant, first by applying multiple base coats and afterwards a finishing coat.

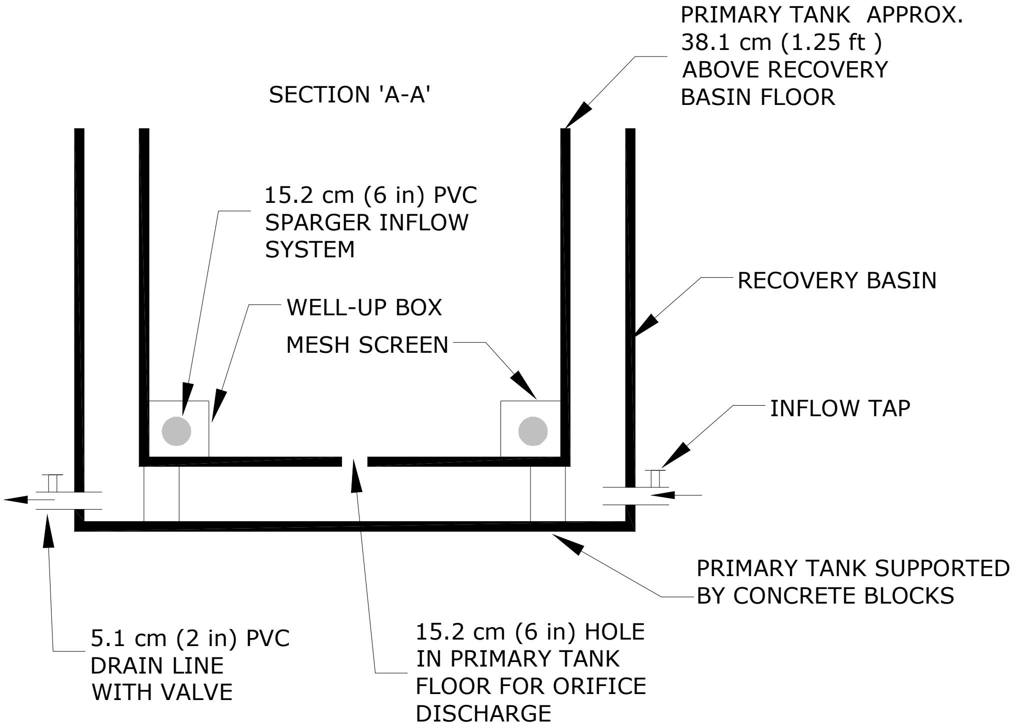

Figure 3.2: Model Section ‘A-A’ (drawing not to scale)

The main tank is filled using a pump and a perforated pipe (sparger) system as shown in Figures 3.1 and 3.2. The sparger is laid along the perimeter at the bottom of the tank and forms a closed loop. The holes in the sparger point toward the bed to minimize the disturbances caused by the inflow in the tank. A well-up box surrounds the sparger and is covered with fine mesh at the top to further dissipate the inflow velocities and turbulence.

The primary tank contained the perforated riser located in the center of the tank. The various perforated risers were attached to the floor of the tank by a two-piece flange, and the pipe and flange were sealed with silicone at all joints to ensure a waterproof fit. The flange, along with the non-adhesive silicone, allowed for the pipes to be easily changed throughout the experiment. This made it simple to investigate several different orifice sizes at several different heights along the riser. Figure 3.3 shows the details of the perforated riser.

Attached to the tank is a stilling well of 5.1 cm diameter (2 inches) acrylic tube, which reflects the water level in the tank. A pressure transducer is fitted at the base of the stilling well and records the water level in the tank. The stilling well is connected through a clear vinyl tube (1.6 cm, 5/8 inch diameter) to a metal pipe located 15.2 cm from the bottom of the main tank as shown in Figure 3.4. The metal pipe near the bottom of the tank has a valve that allows draining the tank. This drain was mainly used during developing the water depth versus volume relationship.

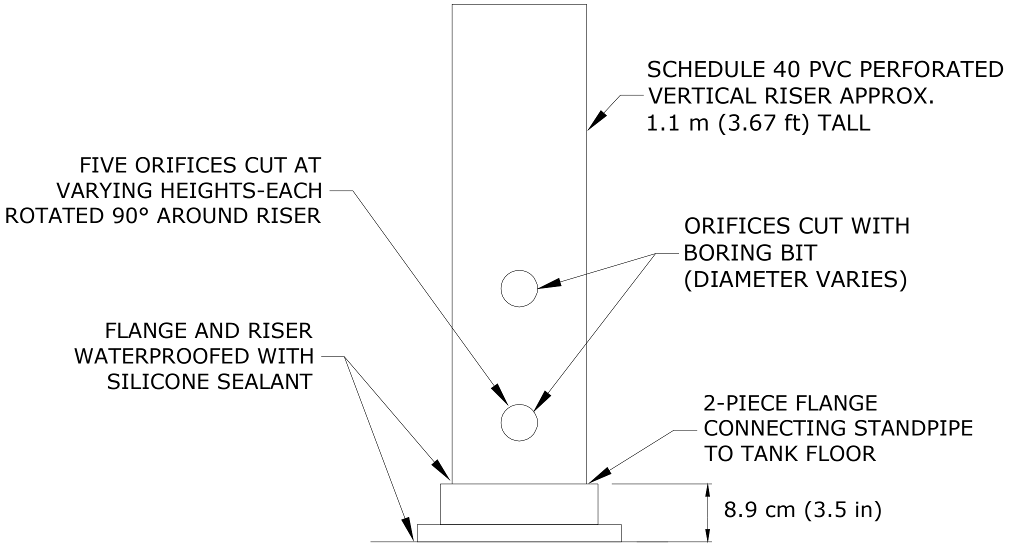

Figure 3.3: Perforated Riser Detail (drawing not to scale)

Tank volume calibration

In order to calculate the discharge coefficient for a particular orifice, it was necessary to know the rate of change in volume of water in the main tank with time. The measuring device used was a pressure transducer, Omega PX303 – 015G5V. For a constant surface area of the tank, it would be sufficient to know the change in water level to find the volume of water released. However as the tank is filled, the walls of the tank may bow, changing the surface area. Also, the walls may have imperfections and may not be perfectly vertical. This implies that the surface area of the tank may vary with height. As such, simply measuring a cross-section of the tank is insufficient for accurately calculating the volume for a corresponding change in depth.

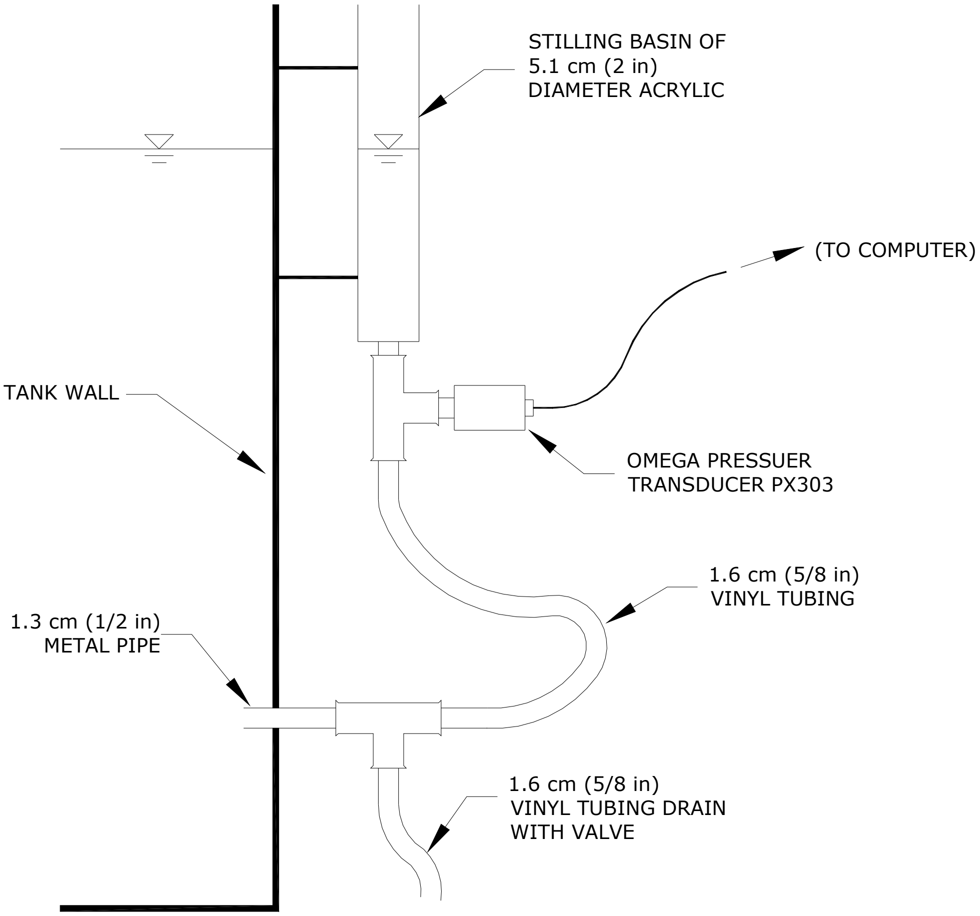

Figure 3.4: Stilling Well Detail (drawing not to scale)

To determine volume versus depth relationship, the tank was filled up to the fill line (1.1 m from the bottom of the tank). The fill line marks the zero-volume-drained point. The water was drawn in 18.9 liters (5 gallons) increments from the tank and the corresponding change in water depth was recorded using the pressure transducer. The pressure transducer outputs voltage based on the water depth above it and has a linear relationship between voltage and pressure. The output voltage range is 0.5 to 5.5 volts with a gauge pressure range of 0 to 103.42 kPa (15 psig). The accuracy of the transducer as determined by the manufacturer is 0.25% of the full scale.

Figure 3.5 shows the tank volume calibration curve. A second-order polynomial curve fits the data well, revealing that the volume of the tank was not exactly linear with height. This curve is used to determine the volume drained for a corresponding change in water level.

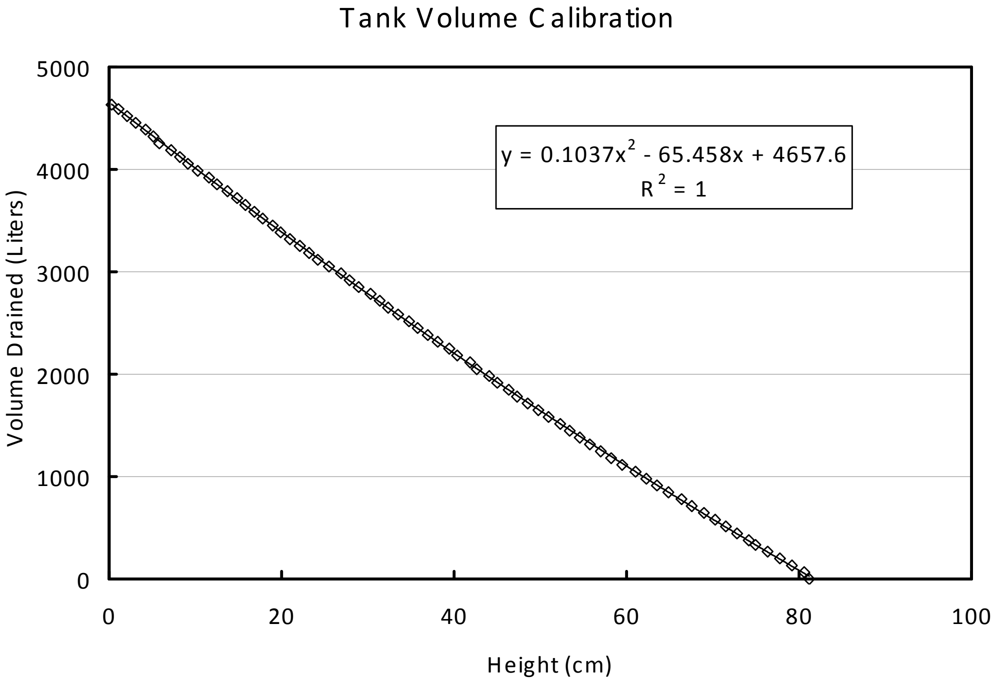

Figure 3.5: Tank volume calibration curve of water level versus volume drained

Experimental procedure

The following is a summary of the procedure that was developed and used throughout the experiment.

1. A vertical riser with a selected orifice diameter and orifice location above the bottom of tank is inserted in the flange and sealed with silicone.
2. The inflow tap is opened and the discharge basin is filled with water.

3. Once the discharge basin is sufficiently full, the pump is started, and the valve leading to the primary tank is opened. The main tank begins filling with water.
4. As the water level in the main tank approaches the fill line (1.1 m), the inflow to the discharge basin is cut off. This helps in keeping the water level in the discharge basin well below the bottom of the main tank.
5. When the water level in the head tank reaches above the fill line, the LabView program is started. The inflow to the main tank is cut off immediately and the pump is stopped. The tank drains through the orifice and water level versus time data is recorded using the LabView program.

At this point, the tank is freely discharging with no inflow from the pump. The tank is filled above the fill line to ensure that disturbances caused by the inflow are dissipated by the time the water level reaches the fill line. Dye tests showed that there were no secondary flow patterns in the tank and the flow existed only around the orifice. By the time the water level reaches the zero-volume drained mark, the system is in equilibrium and the test results are recorded.

Scope of this study

This aim of this study is to investigate the effect of several factors on the discharge coefficient for orifices cut into thin-walled pipes. The study will use vertical perforated riser pipes of two different diameters, 15.2 cm (6 in) and 30.5 cm (12 in). The 15.cm riser has a pipe wall thickness of 7.7 mm and the 30.5 cm riser has a wall thickness of 10.9 mm. For each diameter riser, five different orifice sizes (i.e., five different d/D ratios) will be studied. See Table 3.1 below for a list of the orifice sizes and d/D ratios being investigated. Each orifice size will be tested at five different heights above the tank floor. These heights will be 15.2 cm (6 in), 25.4 cm (10 in), 35.6 cm (14 in), 45.7 cm (18 in), and 55.9 cm (22 in) from the tank bottom to the orifice centerline.

Riser Diameter					
15.2 cm (6 in)			**30.5 cm (12 in)**		
Orifice Size		**d/D Ratio**	**Orifice Size**		**d/D Ratio**
1.27 cm	0.5 in	0.083	1.27 cm	0.5 in	0.042
2.54 cm	1.0 in	0.167	2.54 cm	1.0 in	0.083
3.81 cm	1.5 in	0.250	5.08 cm	2.0 in	0.167
5.08 cm	2.0 in	0.333	7.62 cm	3.0 in	0.250
7.62 cm	3.0 in	0.500	12.7 cm	5.0 in	0.417

Table 3.1: Description of orifice sizes and d/D ratios investigated in the study

As a secondary part of the study, the effect, if any, on the discharge coefficient of multiple orifices spaced vertically at several distances will be investigated. For this part of the study a 5.1 cm (2 in) and a 7.6 cm (3 in) diameter orifice in a 30.5 cm (12 in) diameter riser will be used. Two orifices in the same vertical plane will be tested, with the lower orifice at a constant 25.4 cm (10 in) from the tank floor, and the upper orifice varying in distance from the lower orifice based on the orifice diameter, d. A spacing of $2d$, $4d$, $6d$, and $8d$ will be investigated for the 5.1 cm orifice, and a spacing of $2d$, $4d$, and $6d$ will be used for the 7.6 cm orifice in an attempt to determine if an interaction of the flow between the orifices causes a reduction in the discharge coefficient.

CHAPTER 4

ANALYTICAL PROCEDURE

After each test is completed, the data is analyzed to find the discharge versus head relationship. The output from LabView is the voltage at each time interval as designated by the sampling rate, set before the test. The sampling rates vary from 1 to 8 samples per second, depending on the orifice size. Each test results in at least one thousand data points, which is sufficient to analyze the discharge coefficient.

The voltage-versus-time readings are then copied into an Excel template to analyze the raw data. A voltage-height calibration equation is used to convert the readings into the corresponding water level. This equation was developed by filling the stilling well to several heights and then running the LabView program to obtain an average voltage reading for each height. A calibration equation was obtained from the water level versus voltage plot. This procedure was repeated several times throughout testing in order to check the calibration equation. A typical plot of water level versus voltage and the calibration equation is shown in Figure 4.1. The transducer was installed 27.5 cm (10.81 in) above the floor of the tank. The centerline of the orifice above the tank's floor is varied between 15.2 cm (6 in) to 55.9 cm (22 in). To determine the head over an orifice, the difference in the height (from the floor) between the pressure transducer and the orifice is added to the water level registered by the transducer.

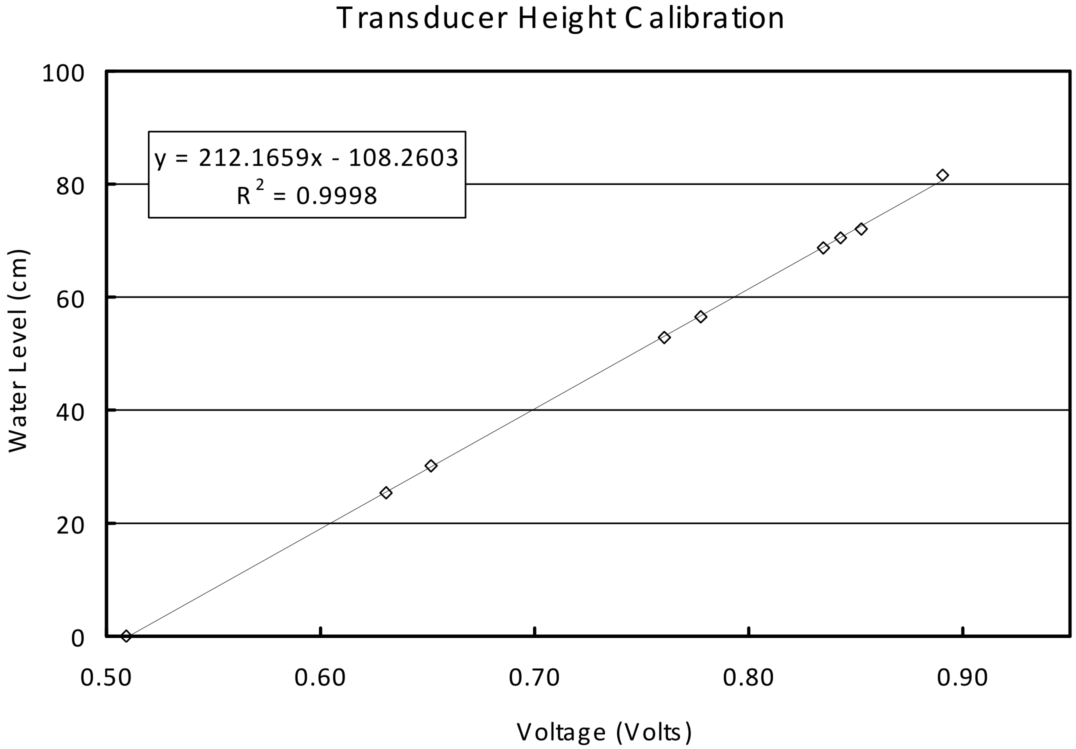

Figure 4.1: Calibration curve for converting pressure readings to water level

The volume drained (V_d) as a function of time is then calculated using the height versus volume relationship discussed earlier (See Figure 3.5). Volume drained in liters is then plotted versus time. A second-order polynomial fits the data well, as shown in Figure 4.2, and provides a trend for volume drained (V_d) versus time. Figure 4.2 shows the results from a 15.2 cm diameter riser with a 2.54 cm orifice located 15.2 cm from the tank floor. Note that this and many other plots throughout show a reduced number of data points from the actual test for the sake of clarity.

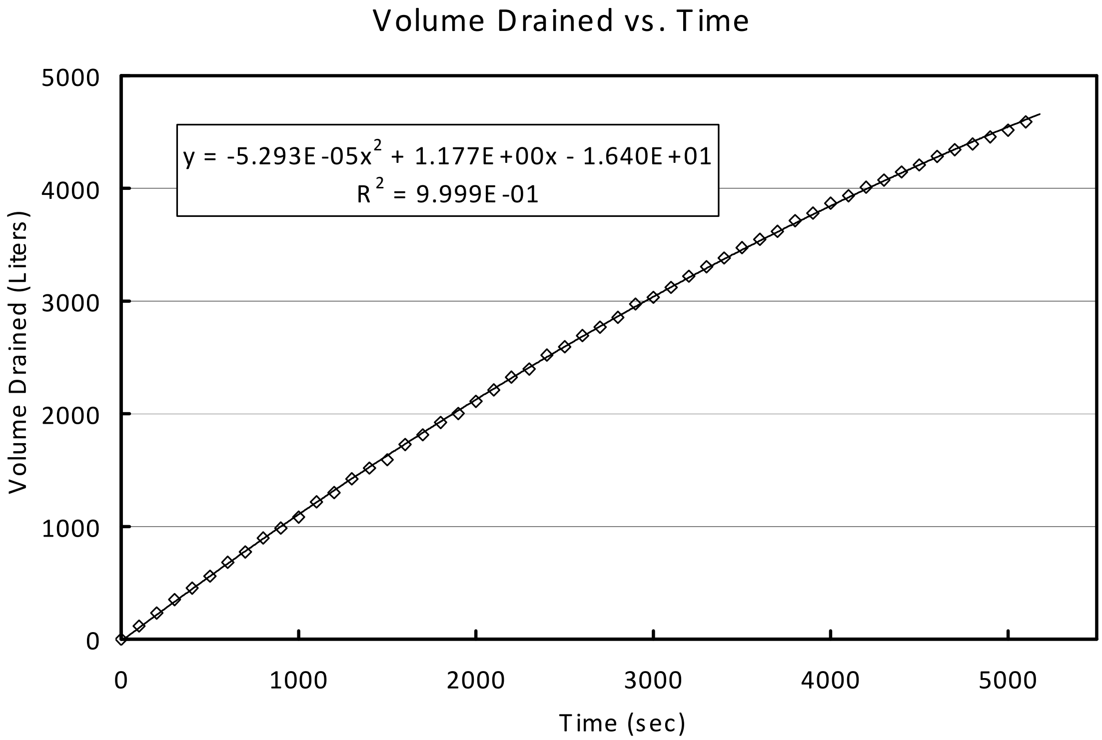

Figure 4.2: Sample volume drained versus time graph

Taking the first derivative of the trend line equation yields an expression for dV/dt. The derivative is then used to find the discharge coefficient at any time using the equation below

$$C_d = \frac{dV/dt}{A_\circ\sqrt{2gh_\circ}} \tag{4.1}$$

Knowing dV/dt and $h_\circ$ at time t, the discharge coefficient at that time is found from the above equation for all tests. A plot of C_d versus $h_\circ$ is developed to analyze the variation of discharge coefficient with head above the orifice. A typical plot of C_d versus $h_\circ$ is shown in Figure 4.3, taken from the same test as Figure 4.2.

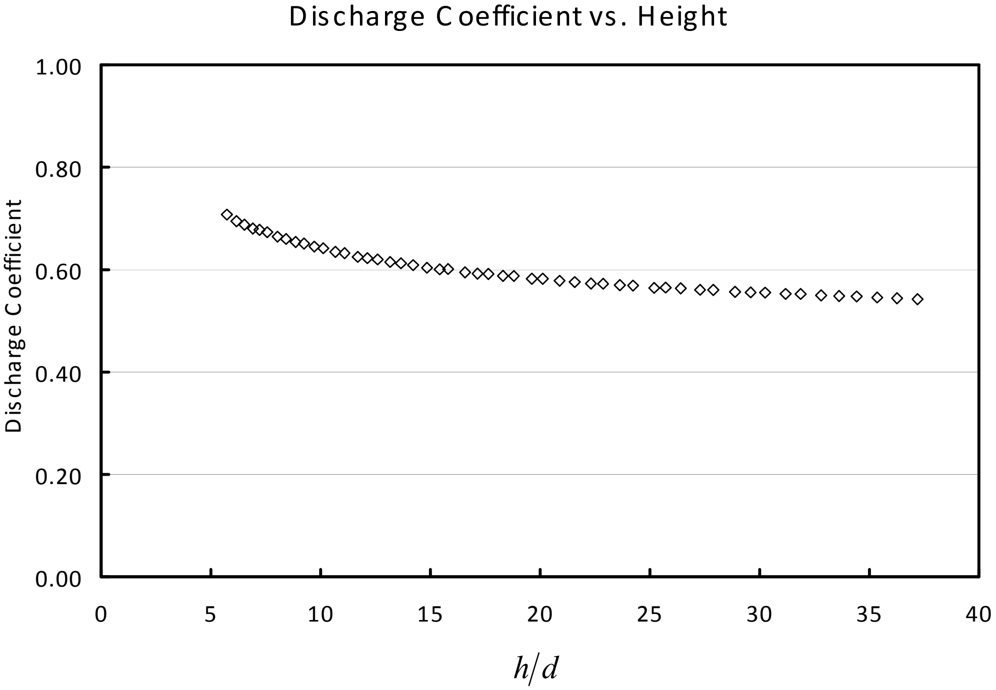

Figure 4.3: Example plot of C_d versus $h_\circ$

The test results were first analyzed and the discharge coefficient calculated using Equation 4.1, a form of the orifice equation which neglects the pressure distribution across the orifice. The discharge coefficient was then evaluated using Equation 4.2, a form of the orifice equation that accounts for the difference in pressure head at the top and bottom of the orifice:

$$dV / dt = C_d \sqrt{8g} \int_{h_2}^{h_1} \sqrt{\left(d^2/4 - \left(h_\circ - h \right)^2 \right) h} \, dh \qquad 4.2$$

where h_1 and h_2 are the heights from the water surface to the bottom and top of the orifice, respectively, h is the height above an arbitrary point in the orifice, and d is the orifice diameter. A numerical solution for the integral in Equation 4.2 was evaluated for each orifice size, and a polynomial expression for the integral in terms of $h_{\circ}$ was developed. This allowed for the simultaneous calculation of C_d using both the small orifice equation (Eq. 4.1) and the large orifice equation (Eq. 4.2). The analysis found that for the orifice sizes and head values tested, there was only a slight variation in C_d between the two formulas. Figure 4.4 shows a plot of C_d for a 12.7 cm orifice in a 30.5 cm riser located 25.4 cm from the tank floor using both methods. Note the large orifice equation yields slightly larger C_d values at the very lowest heads. The difference in C_d values was even smaller for the smaller diameter orifices. This implies that variation of the discharge coefficient is independent of the method used to calculate the flow rate.

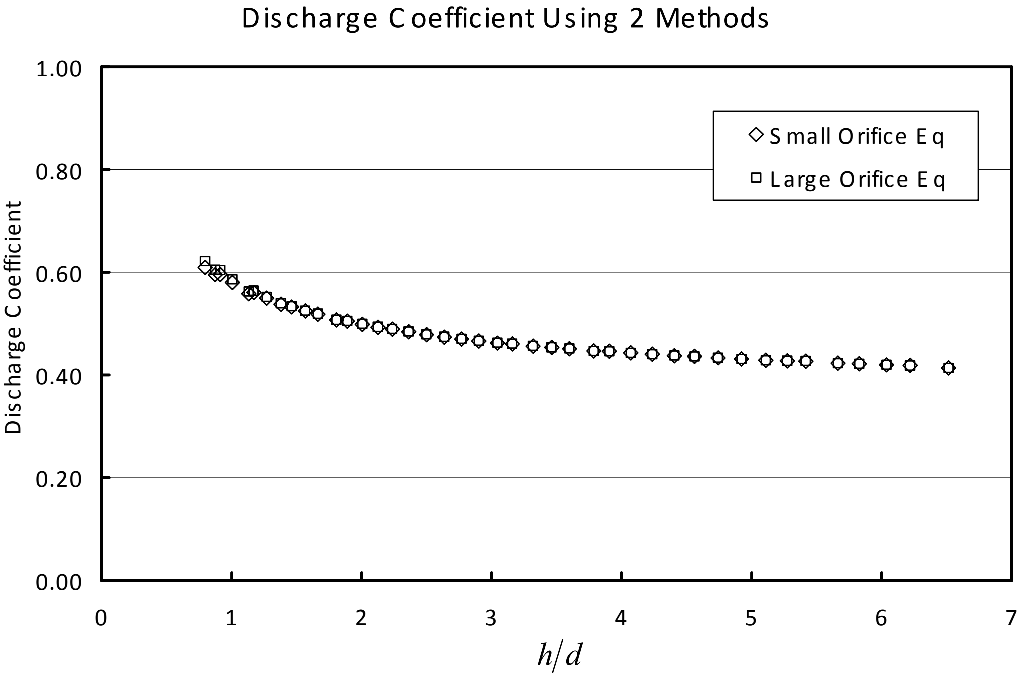

Figure 4.4: Comparison of C_d with small and large orifice equation

CHAPTER 5

TEST RESULTS

The primary study focused on the effect of d/D ratio, orifice height from the floor, and the head above the orifice on the discharge coefficient. The secondary portion of this study tested the influence of spacing on discharge coefficient for multiple orifices. The primary study utilized two different sizes of standpipes having diameter of 15.2 cm (6 in) and 30.5 cm (12 in) and five different sizes of orifices as shown in Table 3.1. Each orifice size in a given riser pipe was tested at five different locations above the floor of the tank (details given in Chapter 3). For each orifice size, at least one of the tests was run multiple times to ensure repeatability.

Figures 5.1 – 5.10 were normalized by dividing the water level height by the orifice size (h/d), which was constant in each plot. Figures 5.11 – 5.20 contained all different orifice sizes in each plot, so the length scale was normalized by dividing the water level by the riser diameter (h/D), which was constant for each plot. Normalizing these figures by orifice size would have led to different length scales in each plot, and made it difficult to view trends in the data. As noted in Chapter 3, all figures shown have reduced data points for clarity in viewing the test results.

Effect of the head above the orifice

Figures 5.1 – 5.20 show the compiled data for both riser diameters and all orifice heights and sizes. As the same method was utilized for each test, each plot shows the effect of changing head values on the discharge coefficient. The most noticeable characteristic of these plots is that for a given orifice size the C_d increases as the head decreases. This phenomenon was observed with every orifice size at every floor height for both risers. For most cases, the increase in C_d became more drastic as head values approached the top of the orifice. This is expected as the velocity exiting the orifice reduces with decreasing head over the orifice. As head decreases, flow streamlines approach the orifice at increasingly lower velocities. This leads to an increase in the area of the jet at the vena contracta and an increase in the contraction coefficient, C_c. Since the discharge coefficient is influenced by the contraction coefficient, any increase in C_c will increase C_d. In addition, for a given orifice size, the discharge coefficient reaches a constant value at high head values.

Effect of orifice height above the floor

The influence of the orifice height above the floor on the discharge coefficient is shown in Figures 5.1 – 5.10. Each figure shows test results for a given orifice size and riser pipe at all locations above the floor of the tank. The data show that location effects are less pronounced at higher head values. The figures also show that the discharge coefficient decreases with the increase in the height of the orifice from the floor. This is consistent with the notion discussed in Chapter 2 that an orifice may experience suppression of the jet contraction as it approaches a boundary. The boundary may force the flow streamlines to enter the orifice at increasingly normal angles, resulting in less contraction of the jet. The exceptions to this trend can be seen with a 1.3 cm and 2.5 cm orifice in the 15.2 cm diameter riser (Figures 5.1 and 5.2) and with a 1.3 cm orifice in the 30.5 cm riser (Figure 5.6). These were cases of the smallest orifice sizes and d/D ratios investigated. One explanation for the discrepancy could be that the area from which an orifice draws its flow increases with orifice size, and the flow field for these orifices may not have interacted with the floor of the tank. It may be that the orifices would experience an increase in C_d if they were located much closer to the floor of the tank. However, the flange used to install the riser pipes prevented tests from being run at heights lower than 15.2 cm.

It can also be noted from Figures 5.1 – 5.10 that for a given orifice the discharge coefficient tends to become independent of the orifice’s location as the height of the orifice above the floor increases. The C_d curves for locations of 45.7 cm and 55.9 cm above the floor are nearly the same. These two orifice heights were further analyzed and are discussed later.

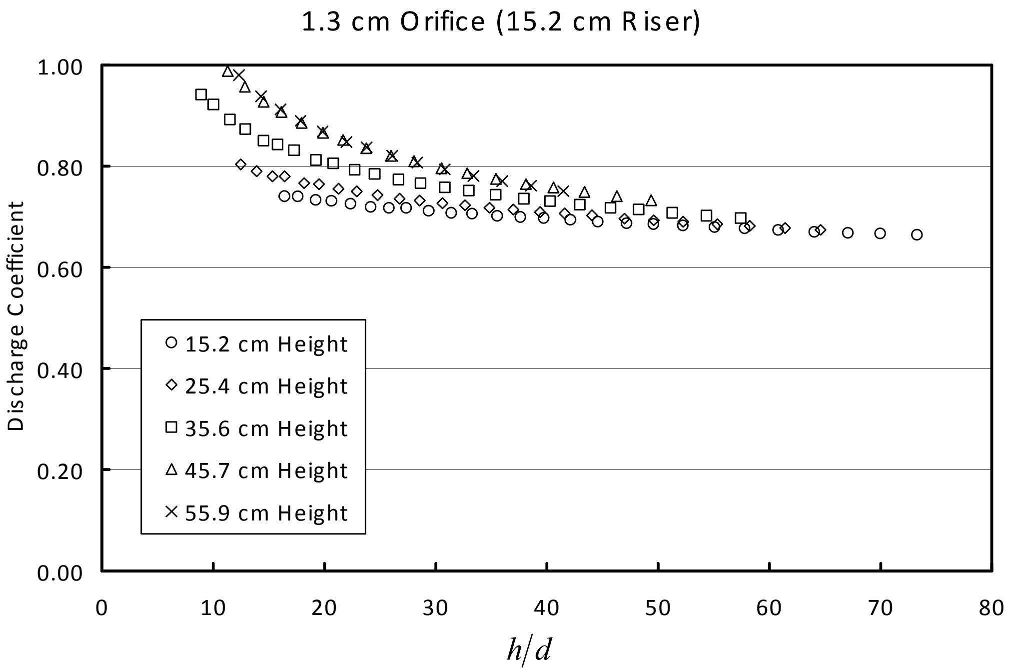

Figure 5.1: 1.3 cm orifice in a 15.2 cm riser

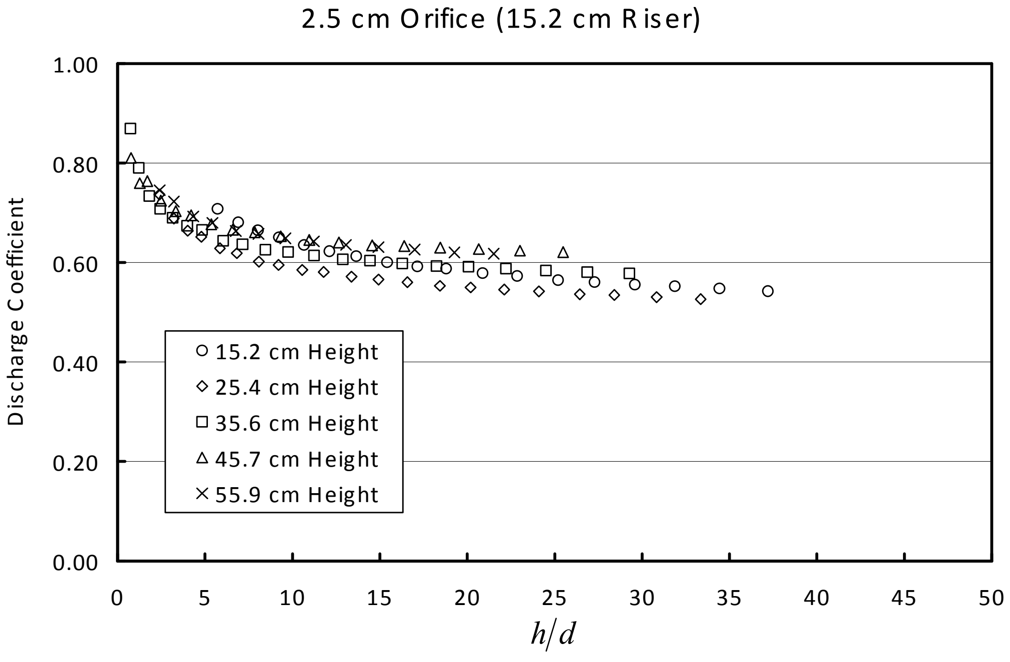

Figure 5.2: 2.5 cm orifice in a 15.2 cm riser

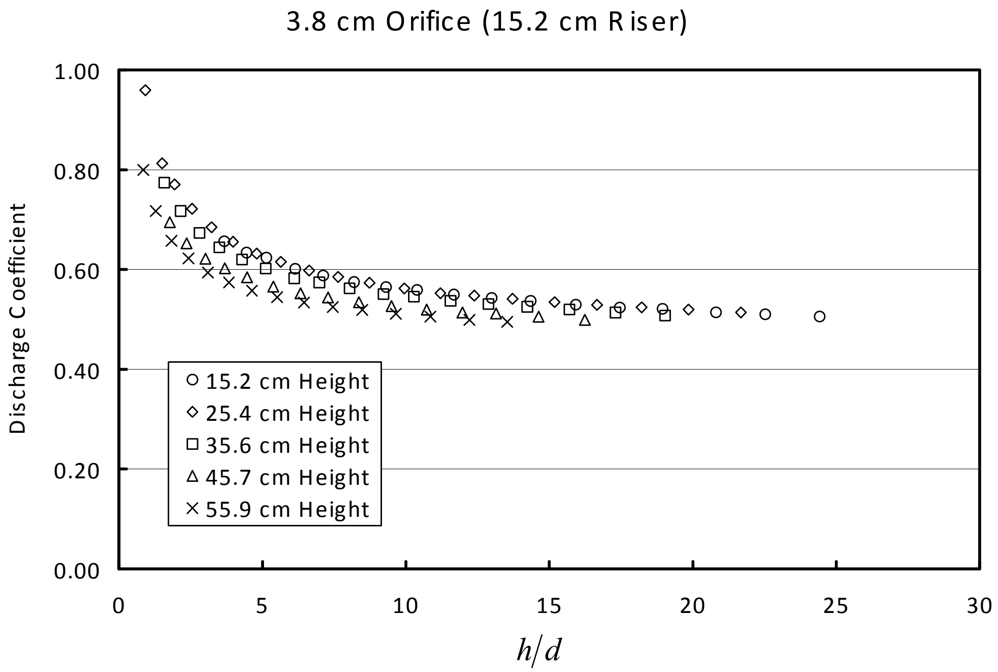

Figure 5.3: 3.8 cm orifice in a 15.2 cm riser

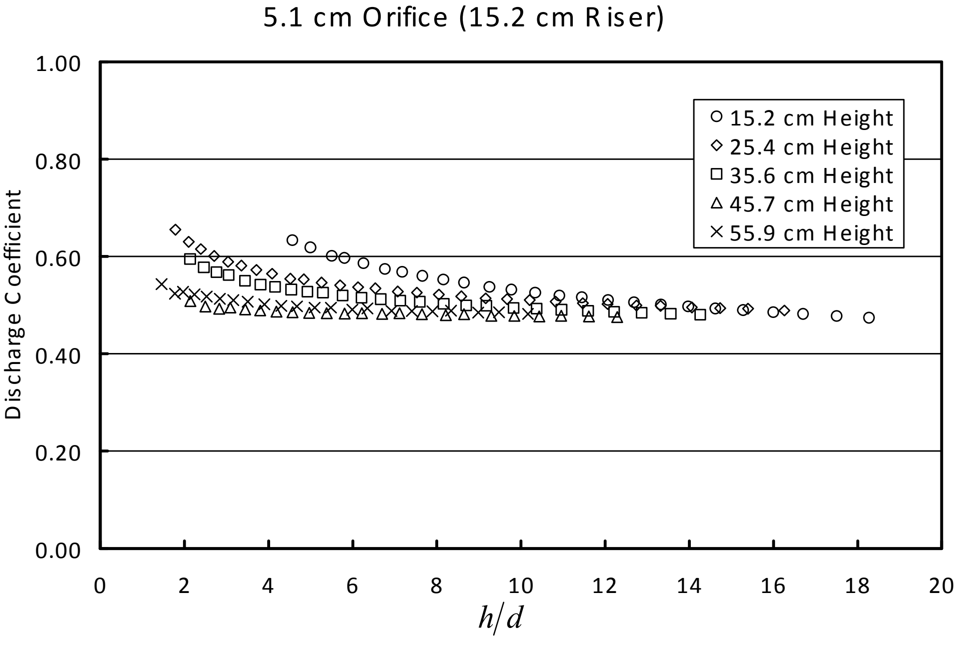

Figure 5.4: 5.1 cm orifice in a 15.2 cm riser

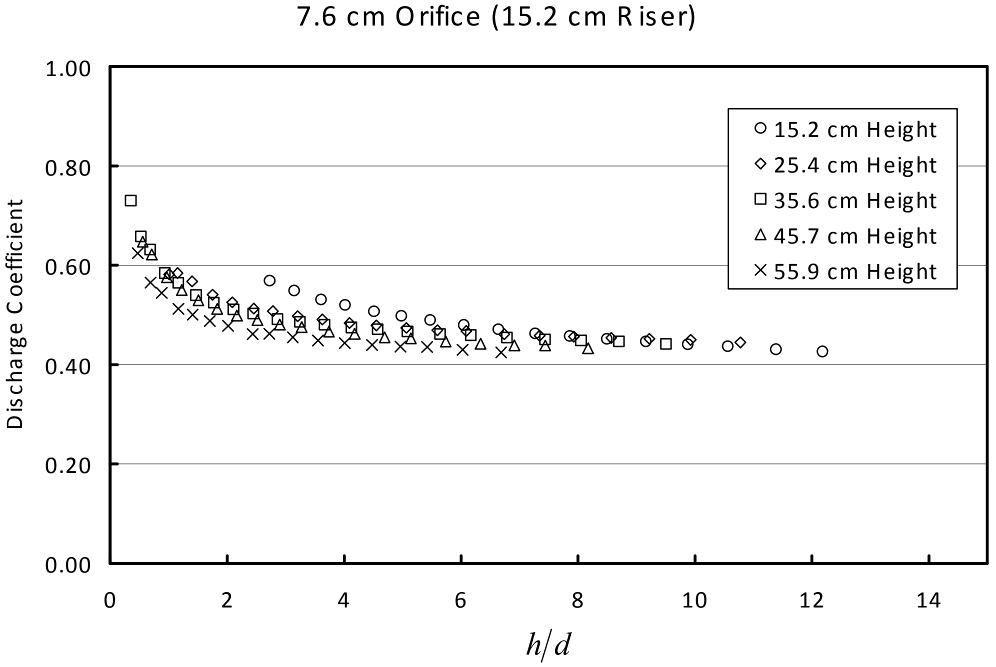

Figure 5.5: 7.6 cm orifice in a 15.2 cm riser

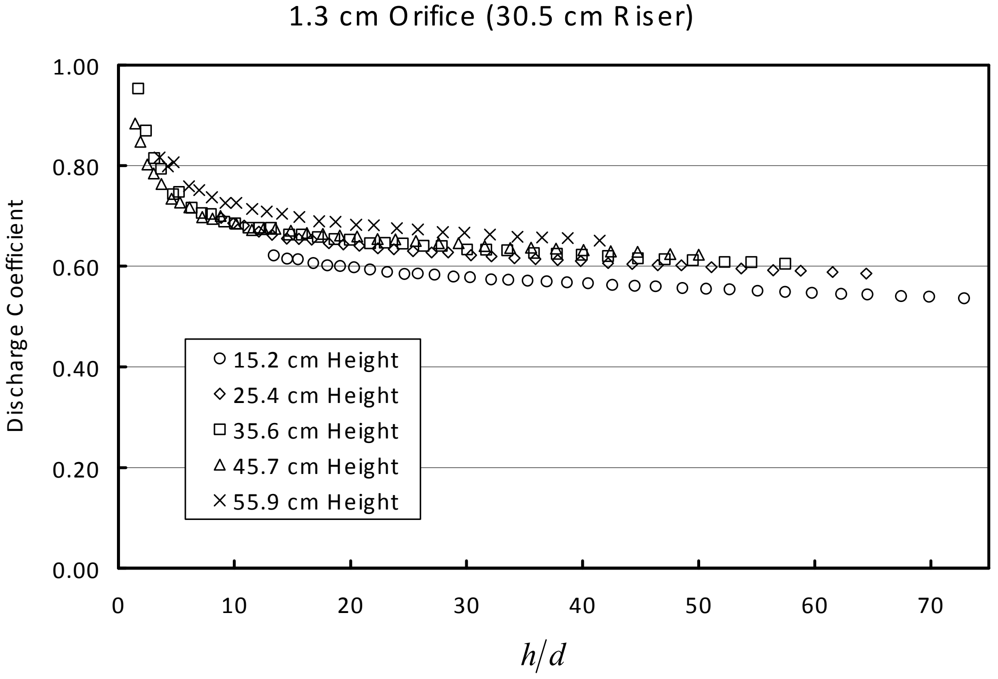

Figure 5.6: 1.3 cm orifice in a 30.5 cm riser

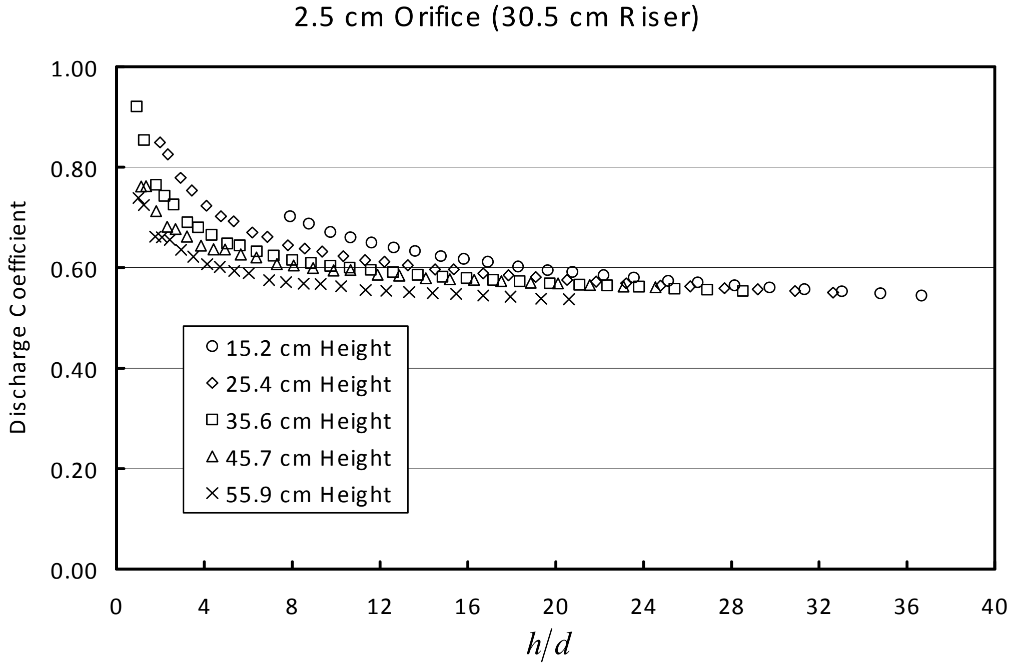

Figure 5.7: 2.5 cm orifice in a 30.5 cm riser

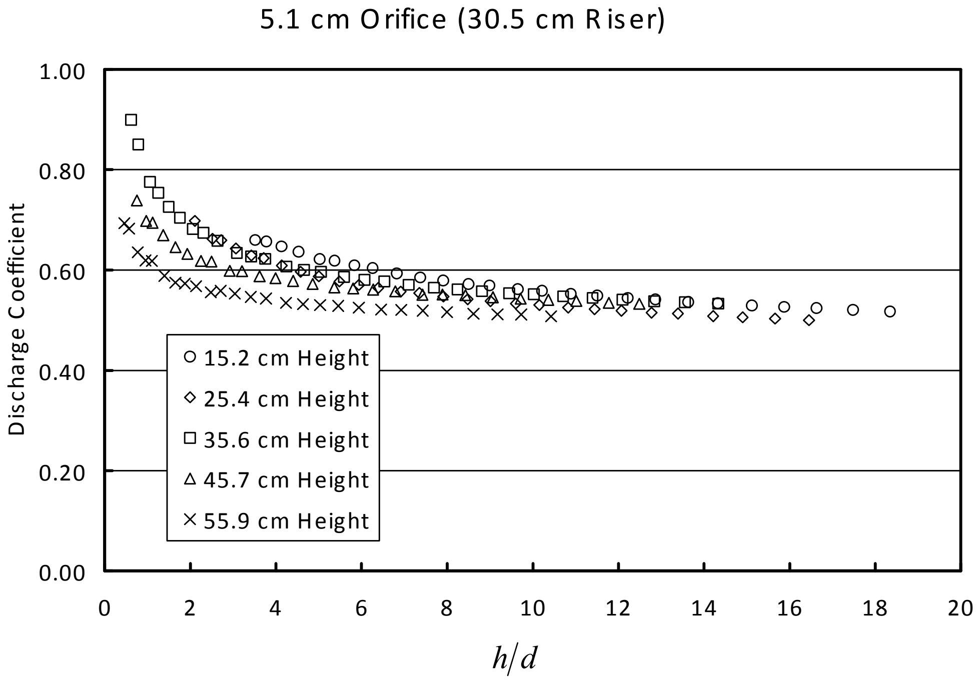

Figure 5.8: 5.1 cm orifice in a 30.5 cm riser

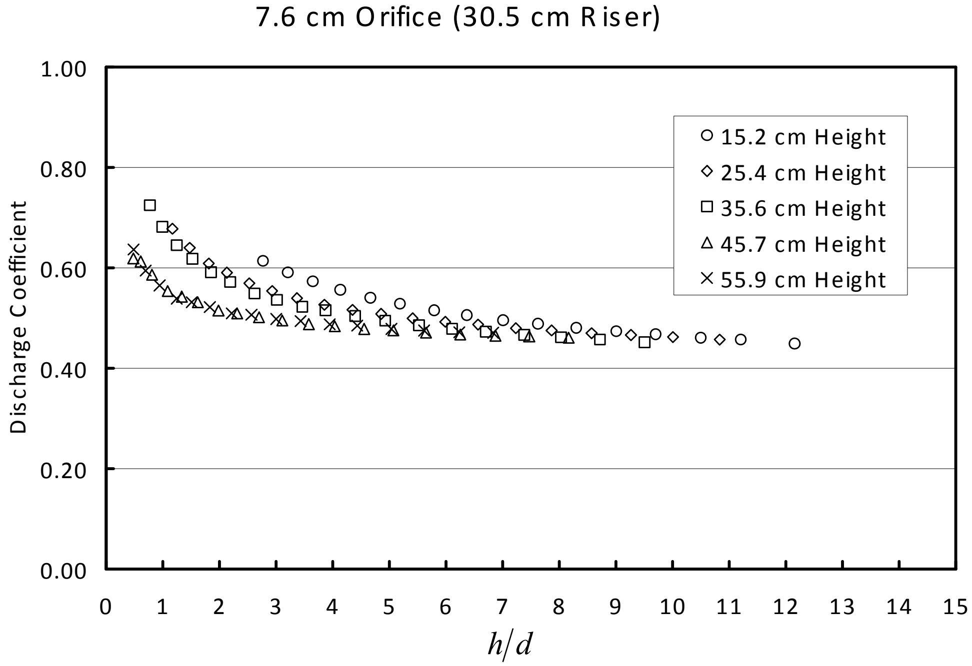

Figure 5.9: 7.6 cm orifice in a 30.5 cm riser

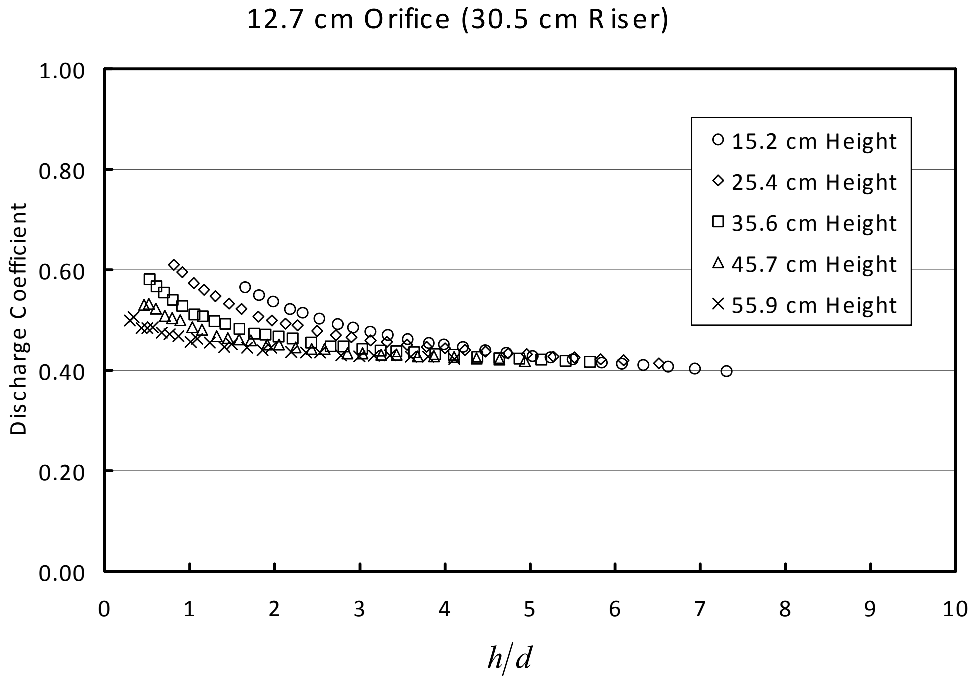

Figure 5.10: 12.7 cm orifice in a 30.5 cm riser

Figures 5.1 through 5.10 show the effect of height above the floor on the discharge coefficient for various size orifices. It is apparent that in most cases as the height from the floor is increased, C_d is decreased until the 45.7 cm height, at which point the discharge coefficients are no longer affected by the tank floor. Further analysis was done in order to determine if the floor height to orifice diameter ratio (h_f/d) plays a role in whether the discharge coefficient will be affected. However, no discernable trends could be found from the limited data of constant floor height to orifice diameter ratio.

Effects of pipe curvature and orifice size

The effects of pipe curvature and orifice size are analyzed in Figures 5.11 – 5.20. Each figure shows the variation of C_d with h/D for all the five d/D ratios and a given size of the rise pipe. In nearly every case, the discharge coefficient decreases as the d/D ratio increases. This confirms the theory from Chapter 2, which hypothesized that as the flow enters the riser from outside the pipe, an increase in d/D would decrease the discharge coefficient due to the flow entering the orifice at increasingly larger angles. This would then increase the contraction of the jet and decrease the discharge coefficient.

For a given d/D ratio, the discharge coefficient is higher for the smaller size riser pipe compared to the larger size riser pipe. That is, for a given d/D ratio, the discharge coefficient increases as the curvature of the riser pipe increases.

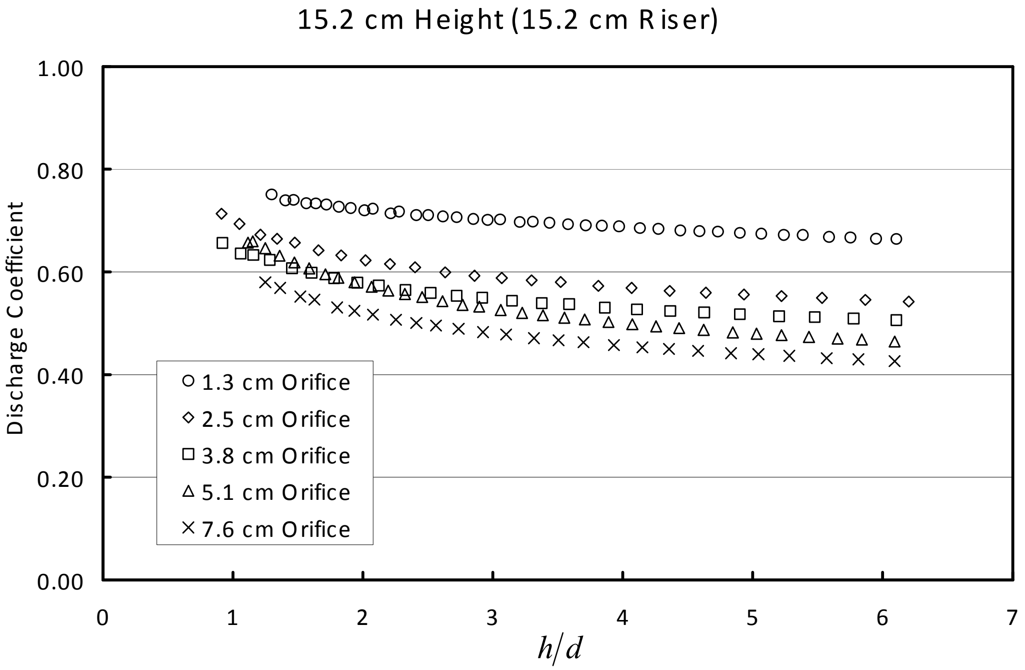

Figure 5.11: 15.2 cm orifice height for 15.2 cm riser

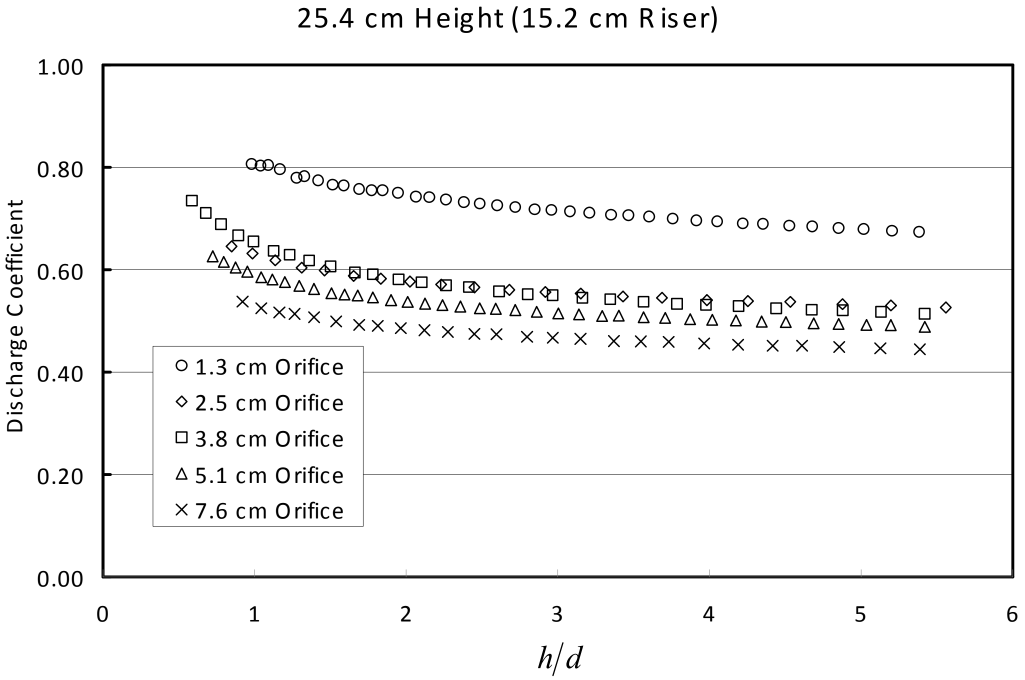

Figure 5.12: 25.4 cm orifice height for 15.2 cm riser

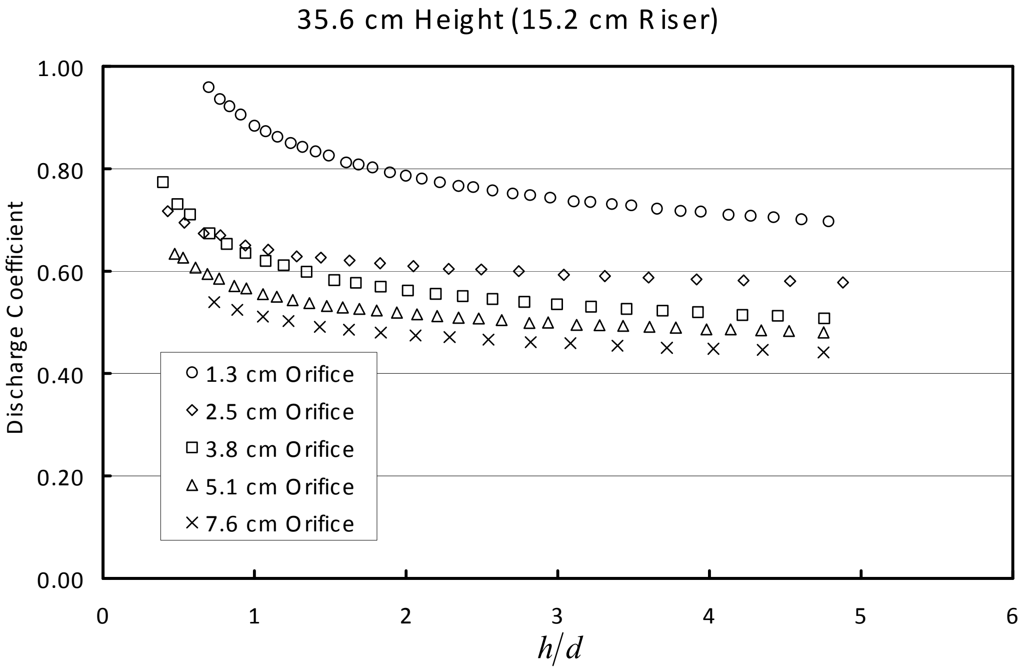

Figure 5.13: 35.6 cm orifice height for 15.2 cm riser

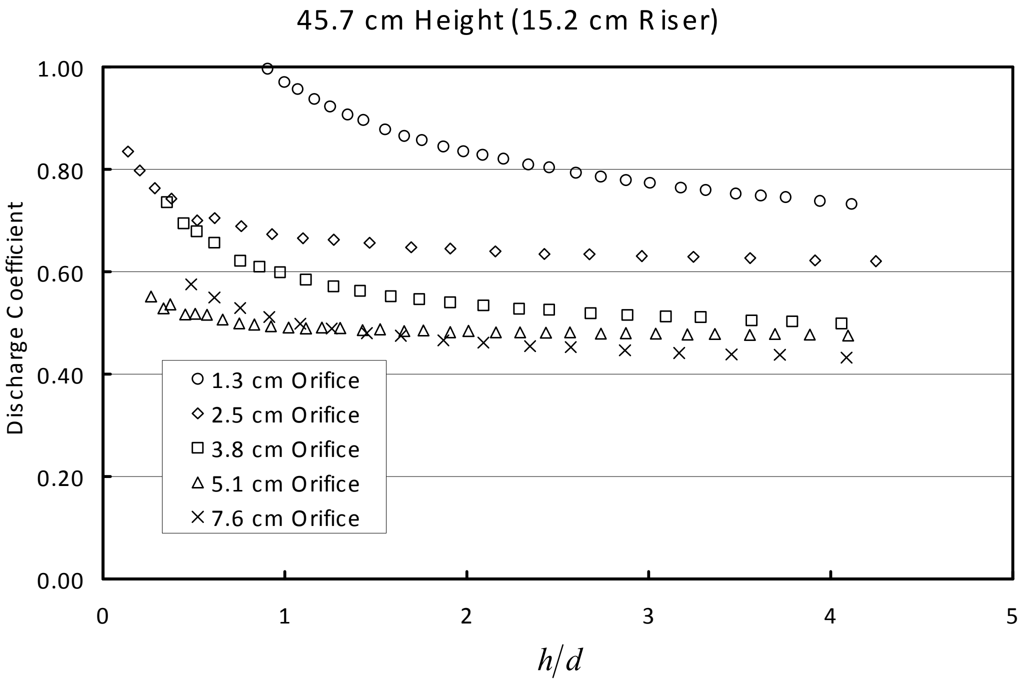

Figure 5.14: 45.7 cm orifice height for 15.2 cm riser

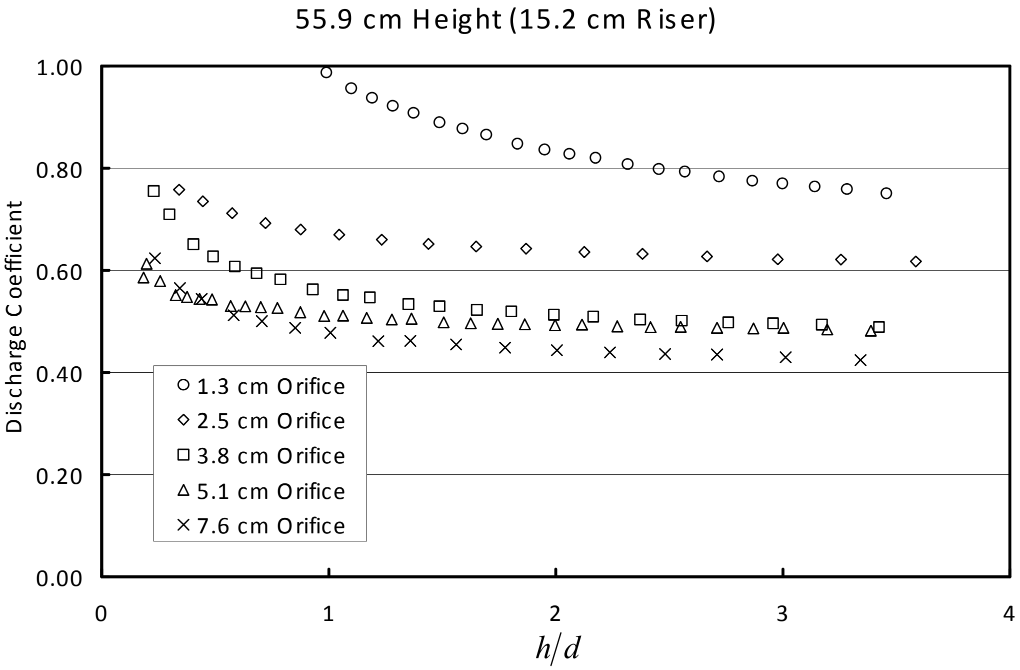

Figure 5.15: 55.9 cm orifice height for 15.2 cm riser

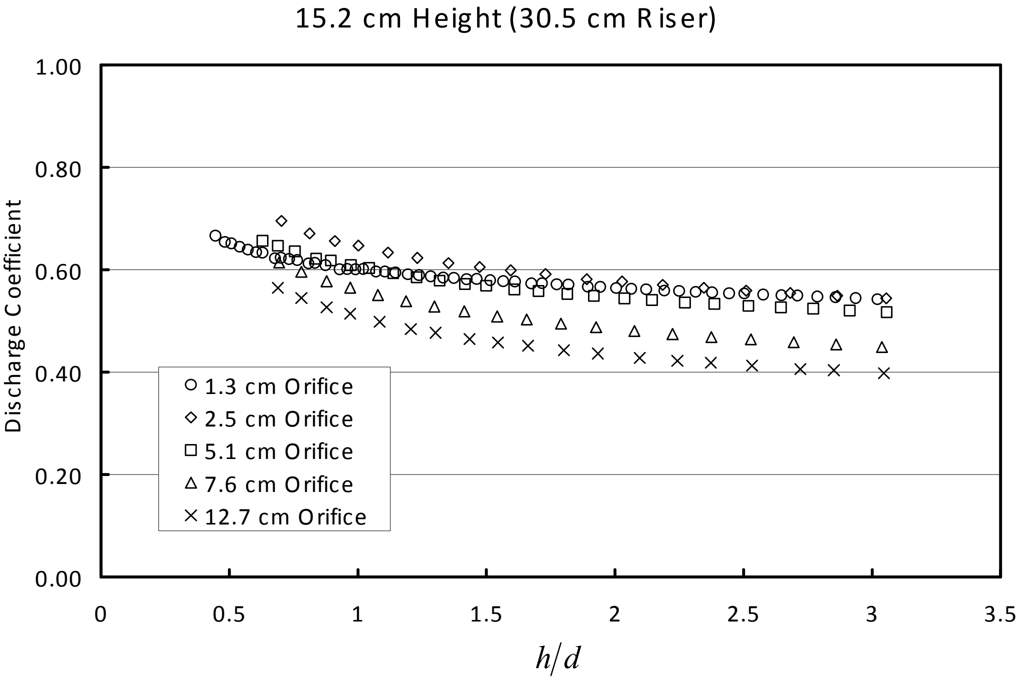

Figure 5.16: 15.2 cm orifice height for 30.5 cm riser

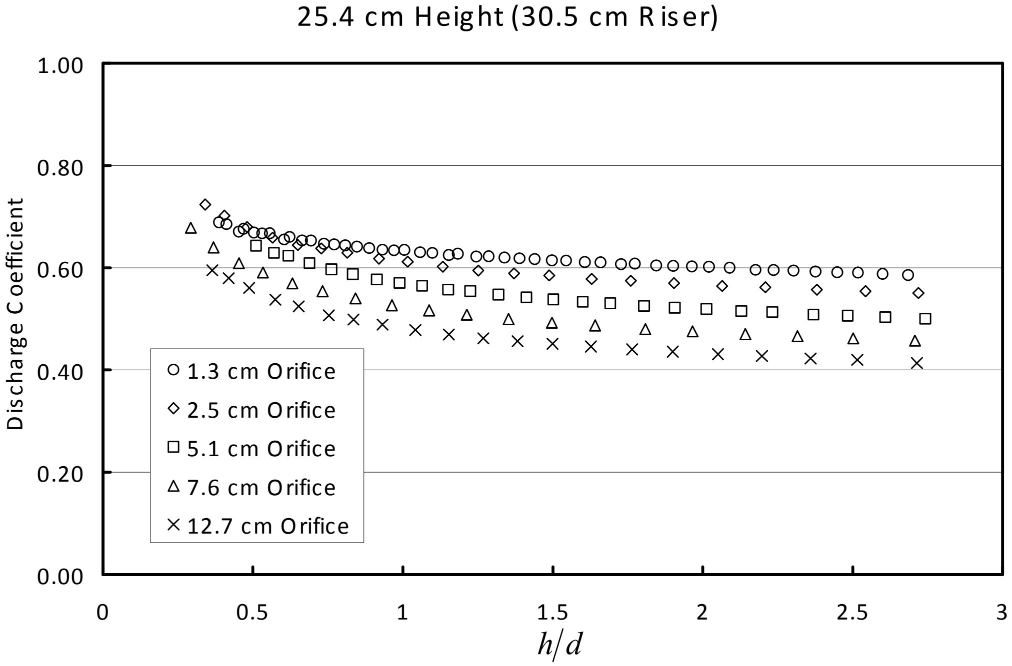

Figure 5.17: 25.4 cm orifice height for 30.5 cm riser

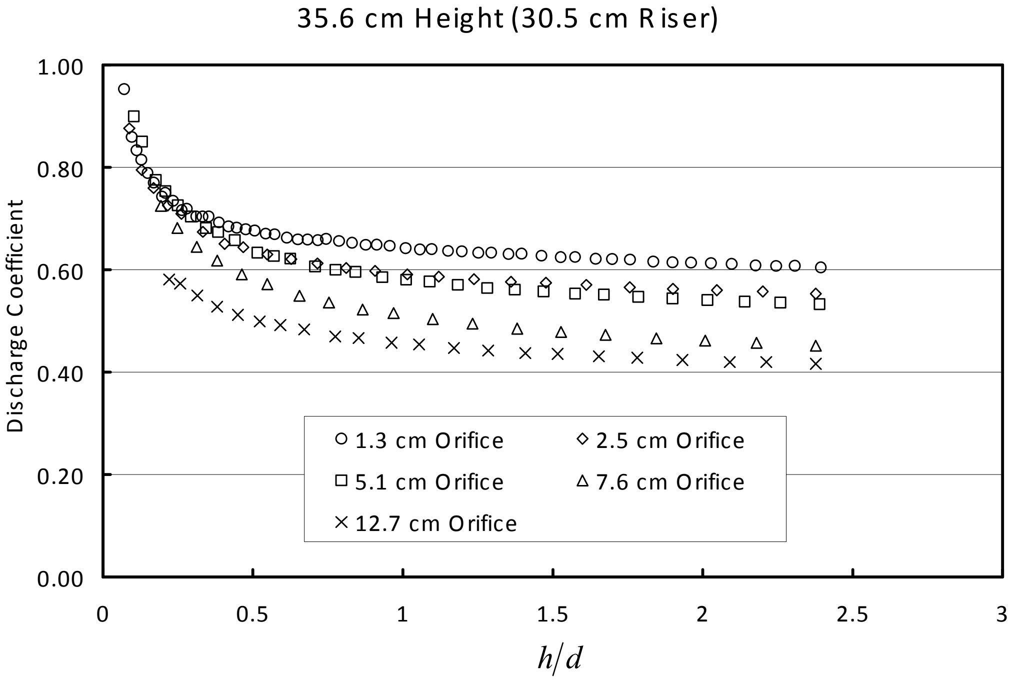

Figure 5.18: 35.6 cm orifice height for 30.5 cm riser

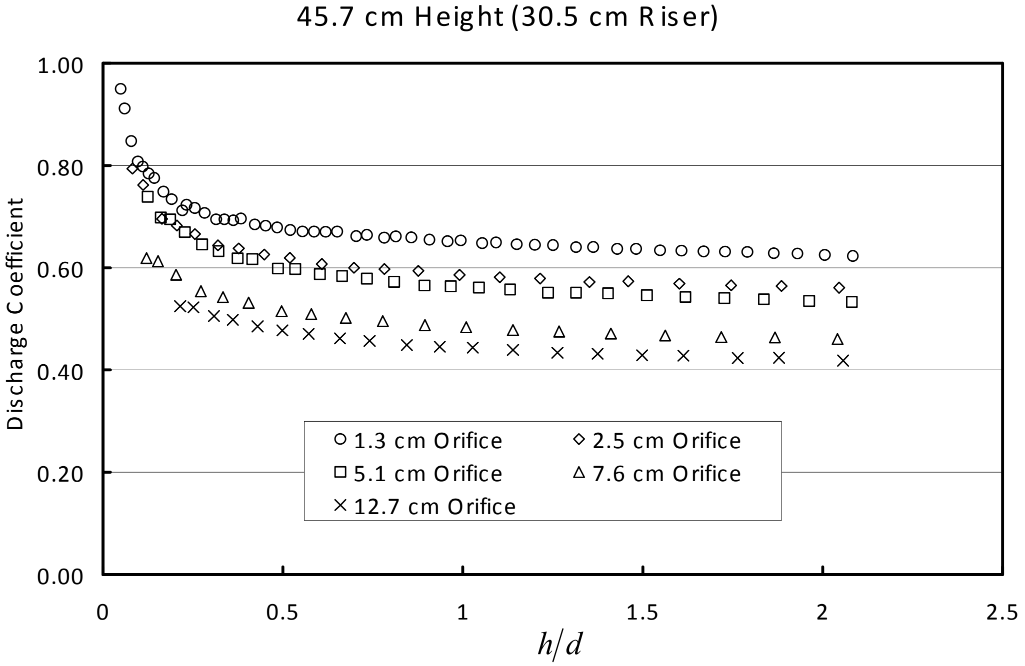

Figure 5.19: 45.7 cm orifice height for 30.5 cm riser

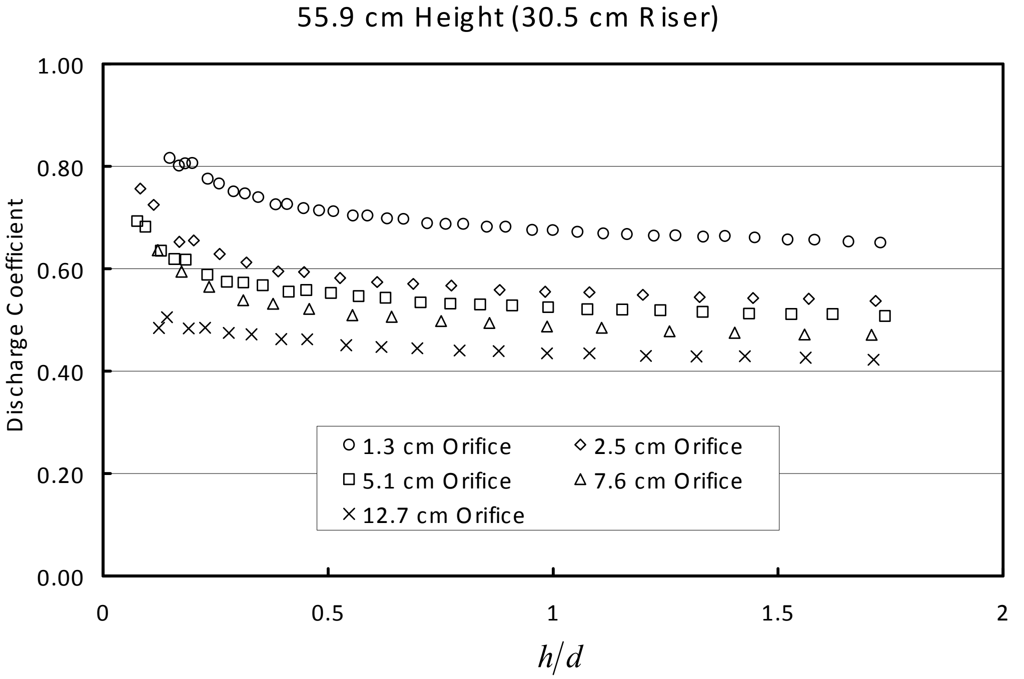

Figure 5.20: 55.9 cm orifice height for 30.5 cm riser

Combination of height-independent data

Noting that the first analysis of the test results showed that the two upper-most orifice heights (45.7 cm and 55.9 cm) yielded discharge coefficients that were independent of the height of the orifice above the floor, data for these orifice heights were seperated for each orifice size and further analyzed. First, trendlines were developed for all orifice sizes. Figures 5.21 and 5.22 show these results for the 15.2 cm riser and the 30.5 cm riser, respectively. The trend lines shown in Figures 5.21 and 5.22 were of the form shown below:

$$C_d = a + \frac{b}{\sqrt{h/d}} \tag{5.1}$$

This form of the power equation was chosen because it had high correlation values with the data. Also the general trend of the data is similar to a plot of $y = 1/\sqrt{x}$. Table 5.1 presents values of a and b for both riser diameters and all orifice sizes. Figure 5.23 shows the parameter a plotted versus d/D ratio. This plot shows how the asymptotic value for each trend line varies with pipe curvature. The parameter, a, tends to decrese with increasing d/D ratio.

After compiling the data in this fashion, it became apparent that for design purposes more general equations would be required. To achieve this, an h/d value of 20 was chosen, and the discharge coefficient for each orifice at $h/d = 20$ was found, denoted here as C_o. The discharge coefficient values for each orifice were then divided by their respective C_o, and plotted against h/d. Figures 5.24 and 5.25 show the compiled data for each riser size.

The data for 1.3 cm orifice in the 15.2 cm riser was discarded from this analysis as it did not fit the general trend of the rest of the data, as seen in Figure 5.21.

Figures 5.26 and 5.27 were created to be used in conjunction with Figures 5.24 and 5.25. They are first used to determine C_o for a given d/D ratio. Once C_o has been determined, Figures 5.24 and 5.25 can be used to find the discharge coefficient at any particular h/d value. Note that Figure 5.26 corresponds to the data from Figure 5.24, and Figure 5.27 corresponds to the data from Figure 5.25.

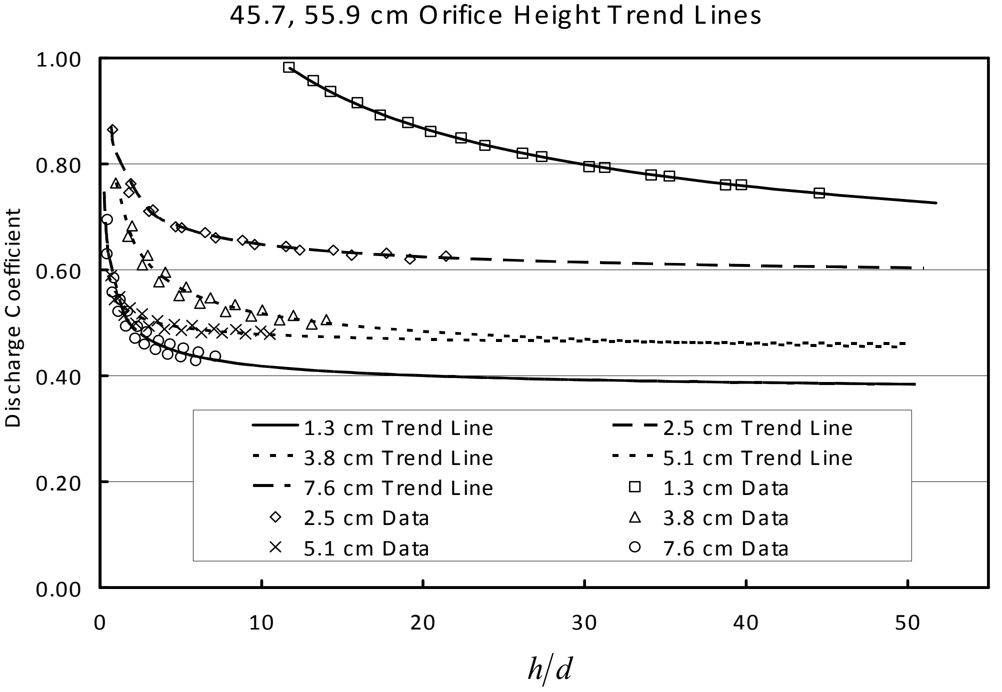

Figure 5.21: 15.2 cm riser upper orifice data and trend lines

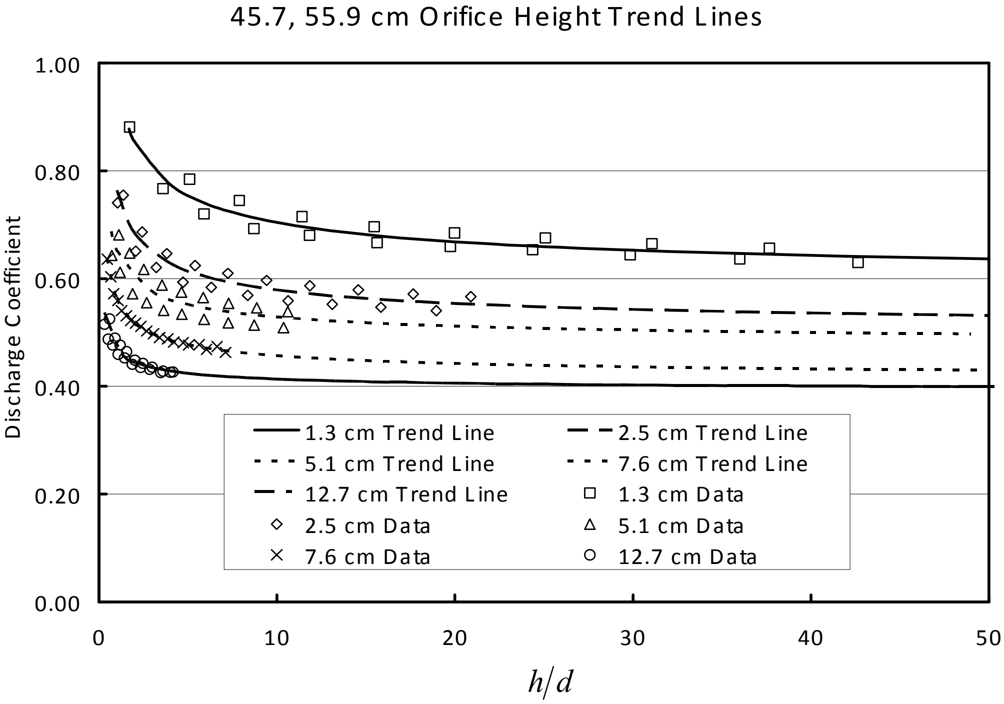

Figure 5.22: 30.5 cm riser upper orifice data and trend lines

Riser Size (cm)	Orifice Size (cm)	*a*	*b*
15.2	1.3	0.49432	1.66746
	2.5	0.56800	0.25345
	3.8	0.40287	0.36200
	5.1	0.44638	0.10101
	7.6	0.35651	0.19540
30.5	1.3	0.28228	0.38494
	2.5	0.49363	0.27006
	5.1	0.47162	0.18074
	7.6	0.40808	0.15490
	12.7	0.38780	0.08191

Table 5.1: Power function parameters from Figures 5.21 and 5.22

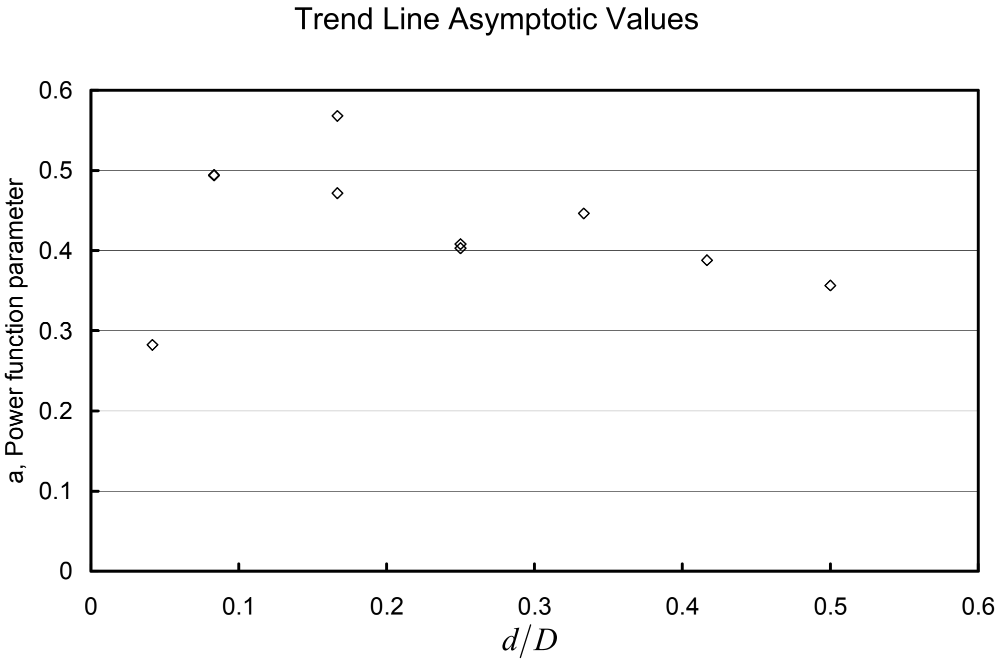

Figure 5.23: Power function parameter, a, versus d/D ratio

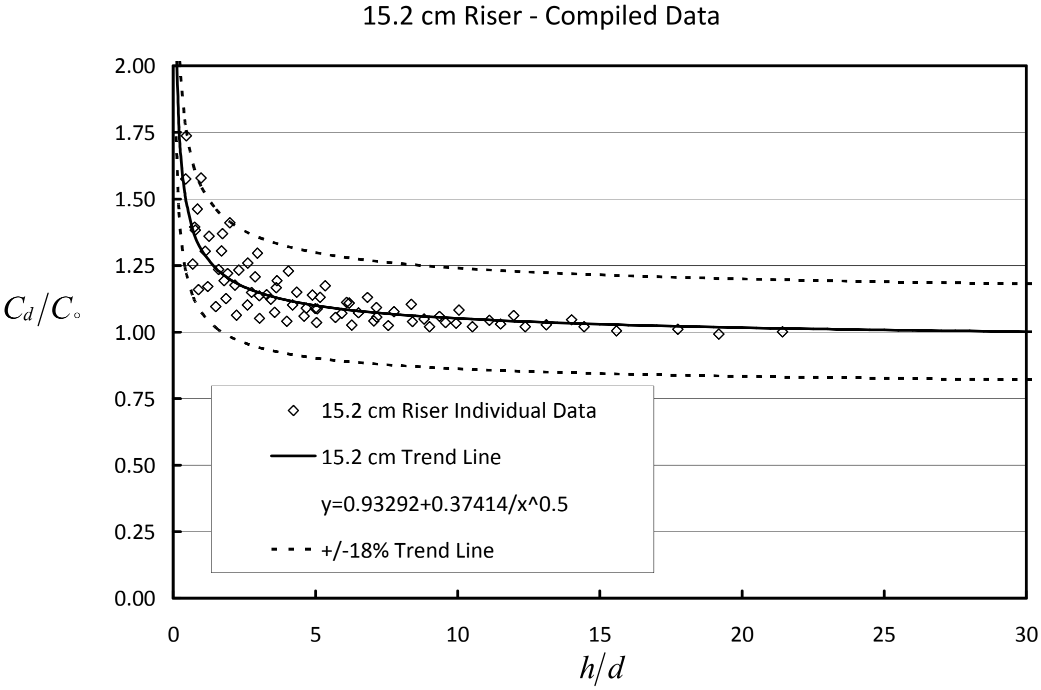

Figure 5.24: 15.2 cm riser compiled data for $h/d=20$

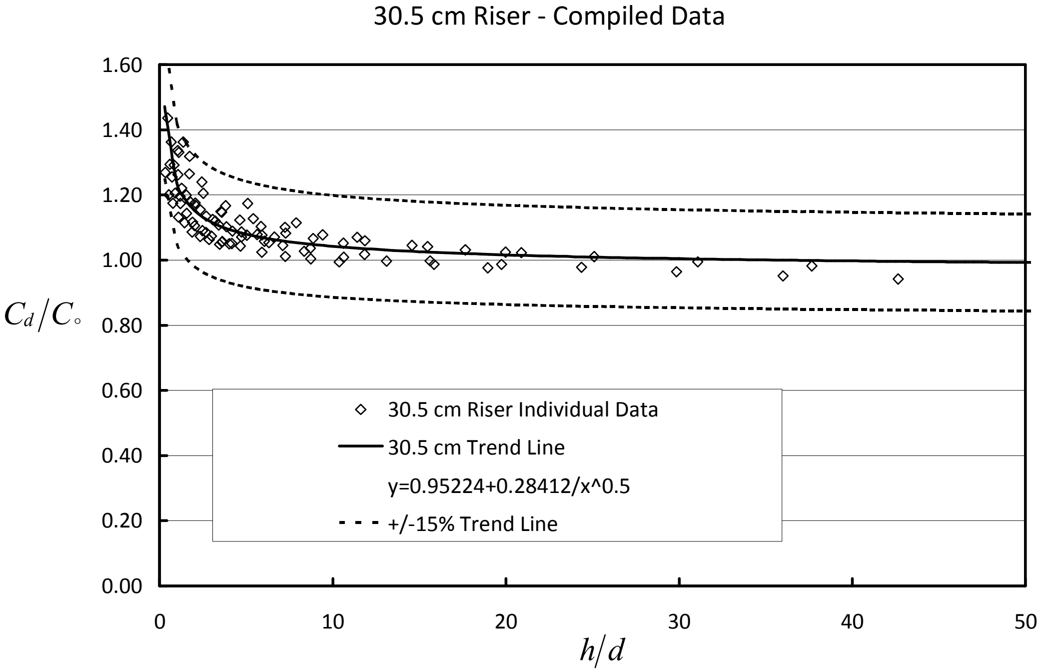

Figure 5.25: 30.5 cm riser compiled data for $h/d=20$

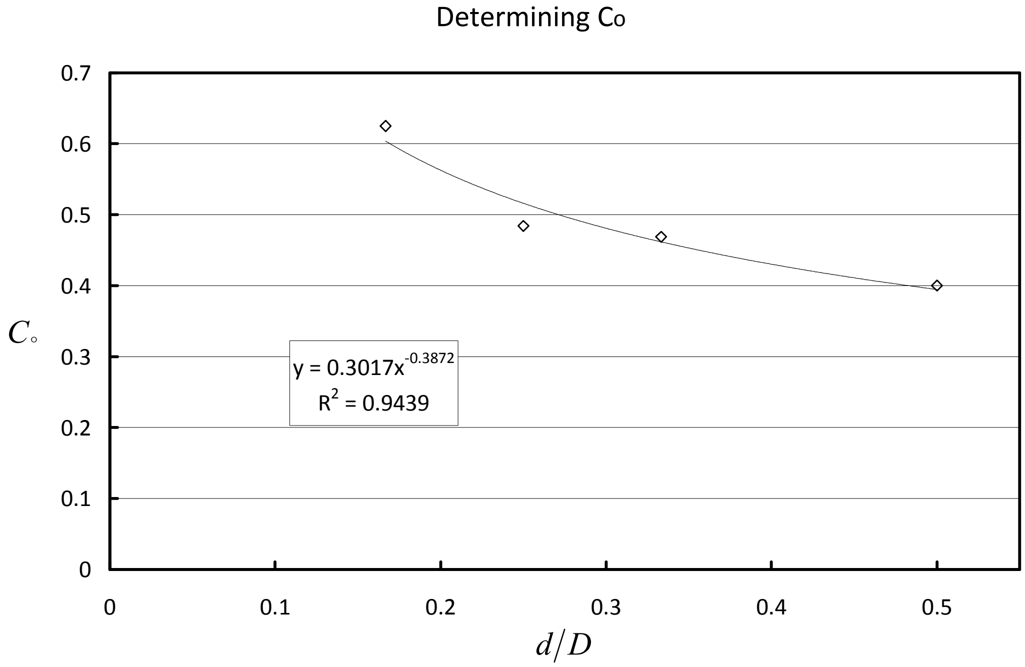

Figure 5.26: Determining C_o for a particular d/D ratio with 15.2 cm riser

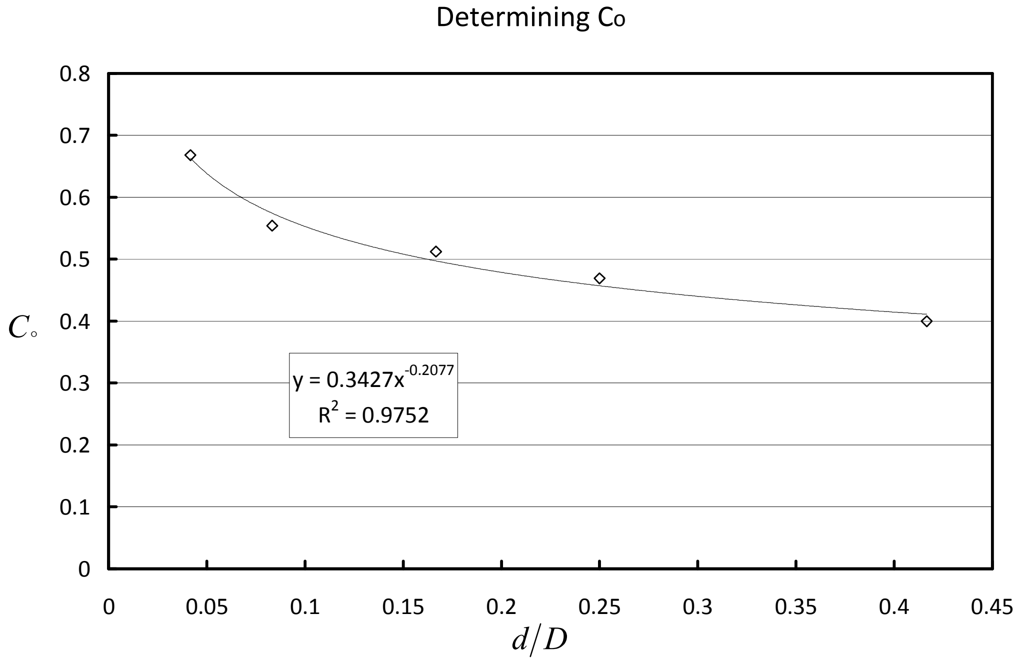

Figure 5.27: Determining C_o for a particular d/D ratio with 30.5 cm Riser

The final step of the analysis combines the normalized data from both the 15.2 cm riser and the 30.5 cm riser. Figure 5.28 combines the data for all the tests in the two riser diamters and can be used to determine C_o for any orifice in any riser pipe size. Figure 5.29, which also combines all the tests in the two risers, is used to find C_d/C_o for any h/d value. The trend line function is also shown in the figure. Once the discharge coefficient ratio (C_d/C_o) and C_o are known, the discharge coefficient for the case in question can then be determined.

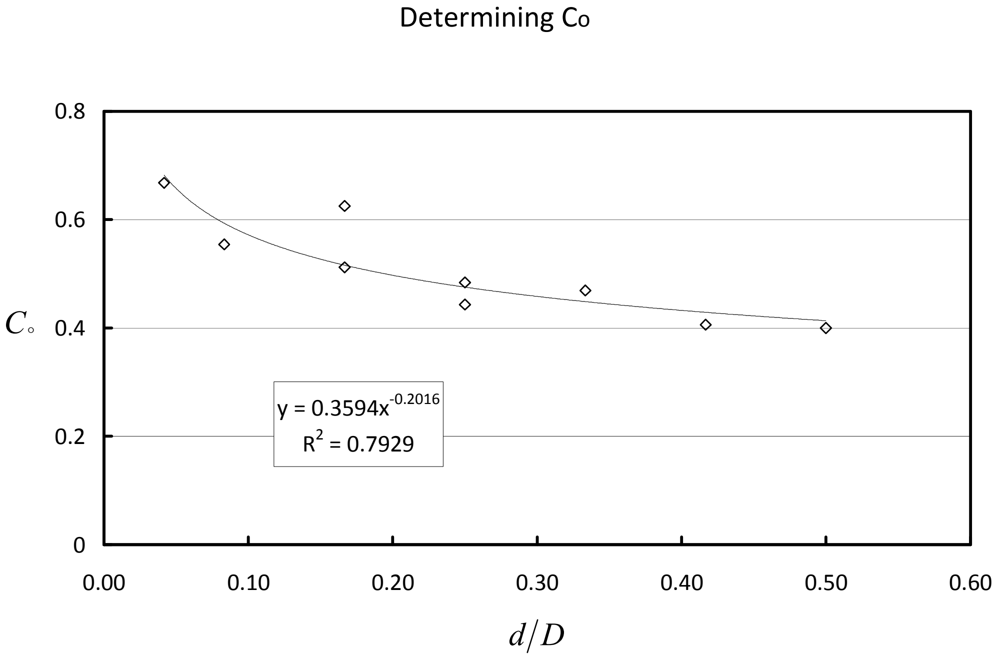

Figure 5.28: C_o for any orifice size and any riser pipe diameter ($d/D \leq 0.5$)

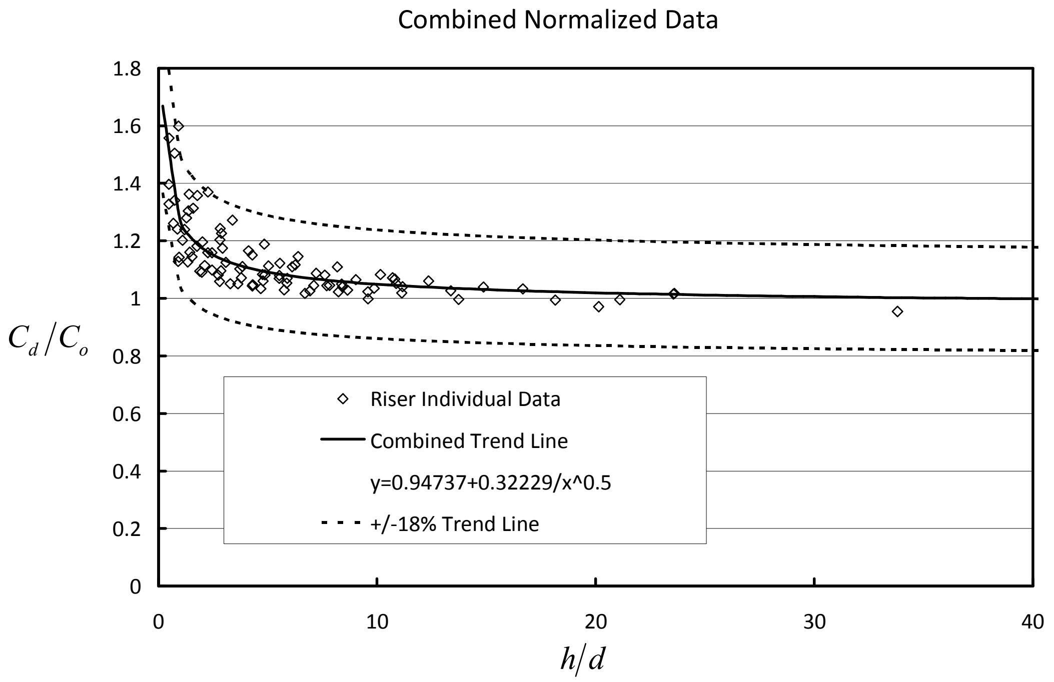

Figure 5.29: Determining C_d/C_o for any d/D ratio with any riser pipe size

In order to determine the relative error involved in this analysis, a theoretical discharge coefficient curve was plotted versus h/d and against the actual data for each d/D ratio investigated. As the 1.3 cm orifice in the 15.2 cm riser data was omitted in developing the curves in Figures 5.28 and 5.29, the data was not included in this analysis. See Figures 5.30 – 5.36 below for the results of this error analysis.

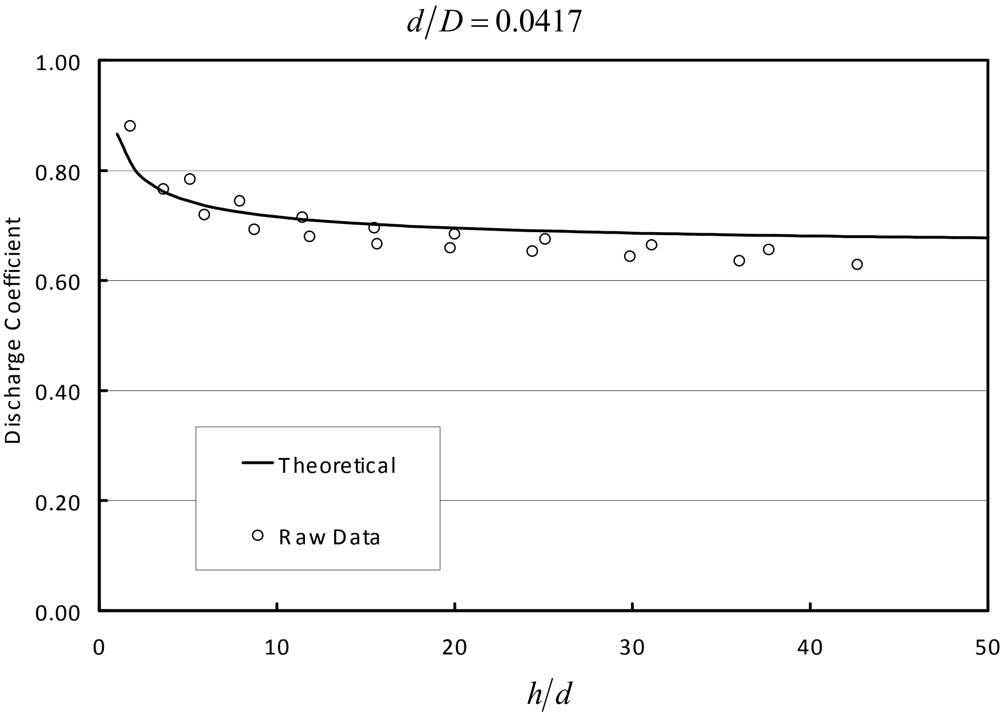

Figure 5.30: Relative error analysis with $d/D = 0.0417$

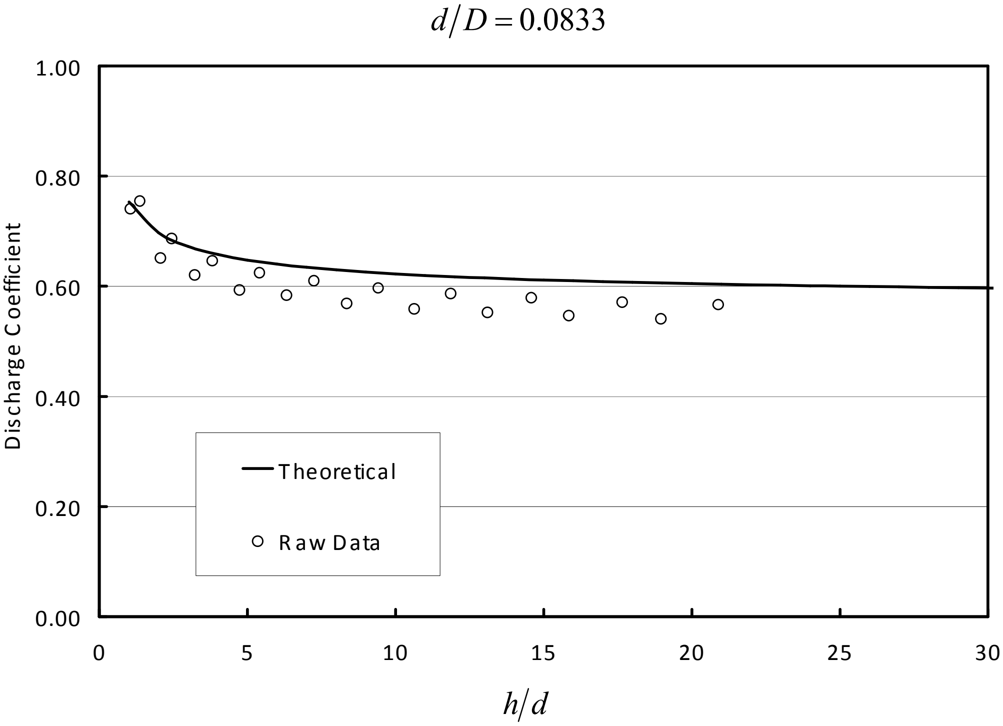

Figure 5.31: Relative error analysis with $d/D = 0.0833$

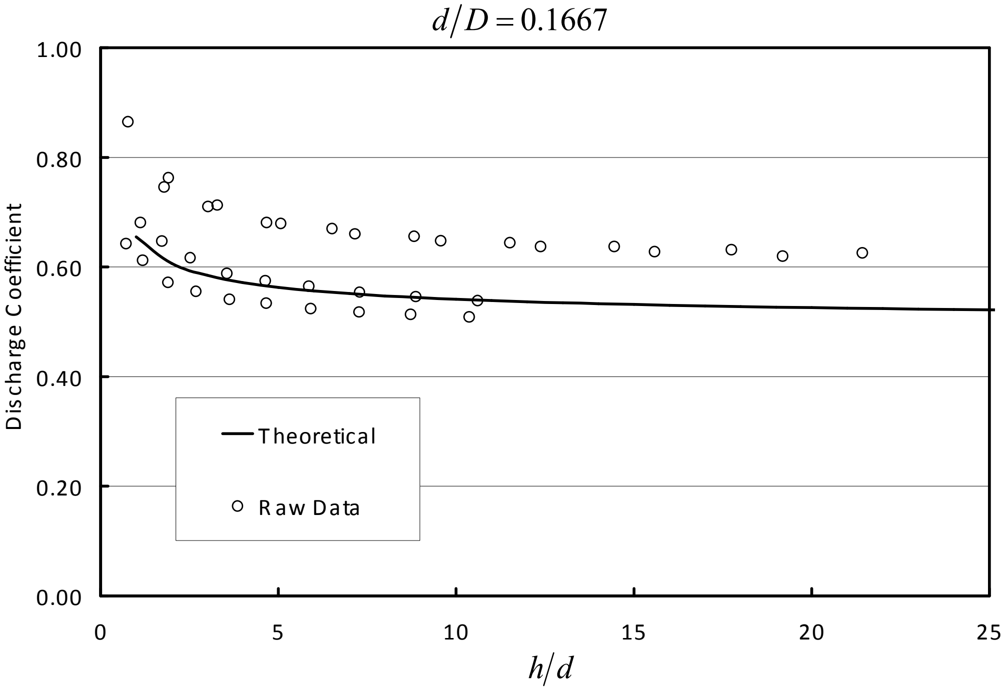

Figure 5.32: Relative error analysis with $d/D = 0.1667$

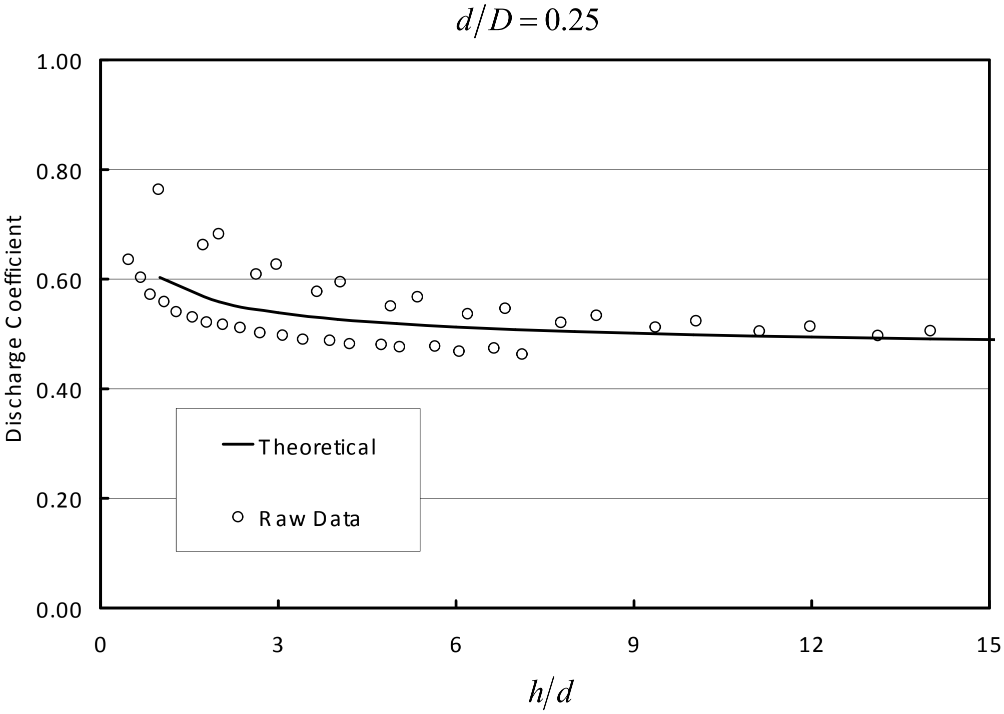

Figure 5.33: Relative error analysis with $d/D = 0.25$

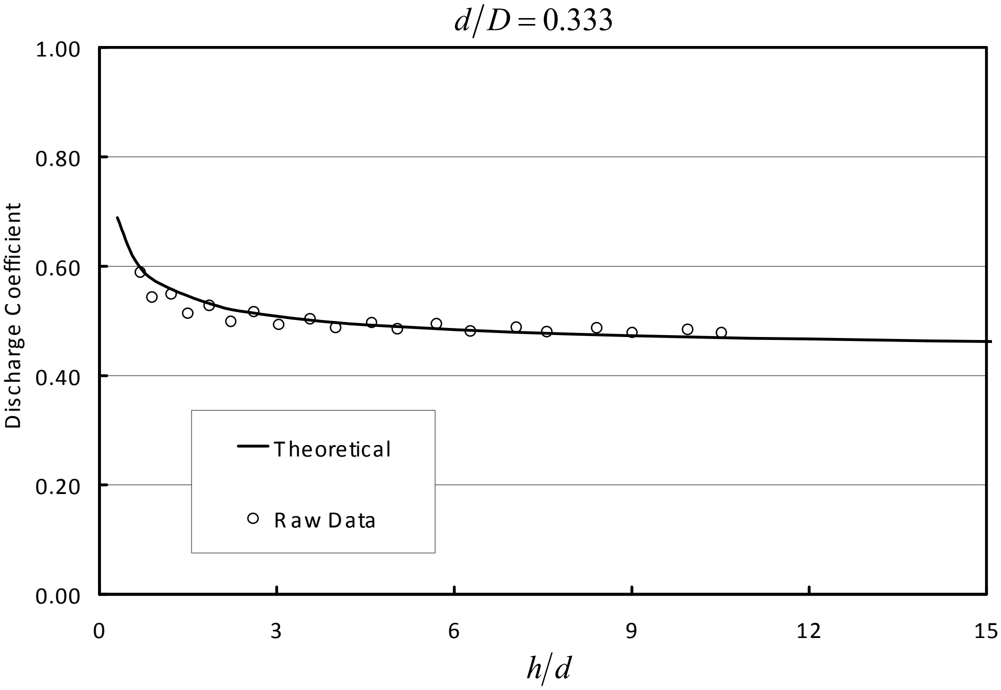

Figure 5.34: Relative error analysis with $d/D = 0.333$

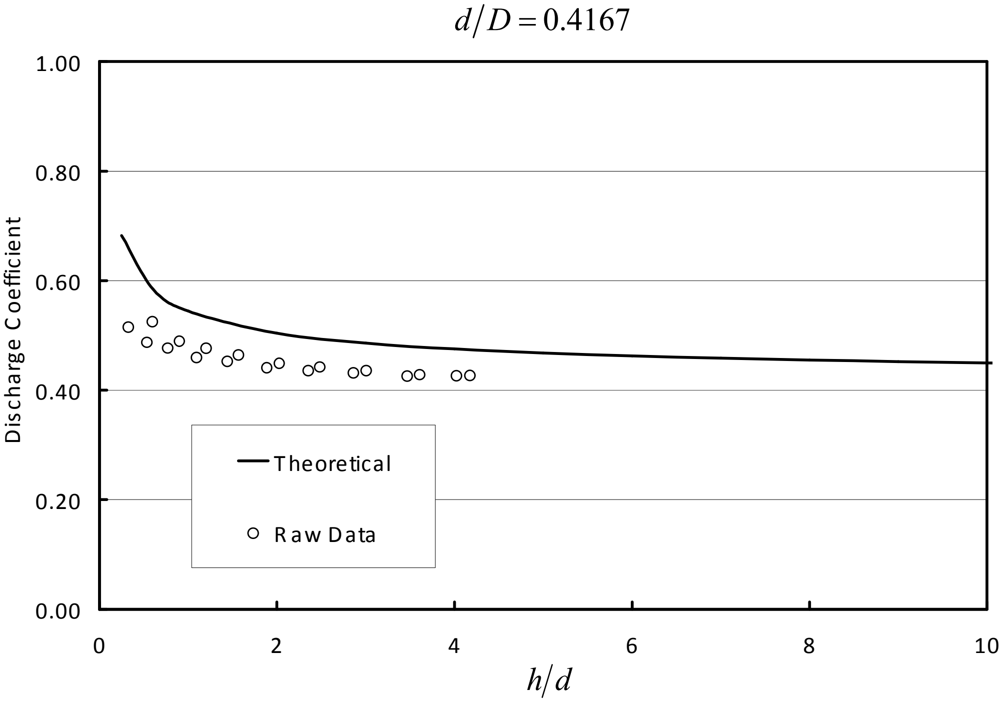

Figure 5.35: Relative error analysis with $d/D = 0.4167$

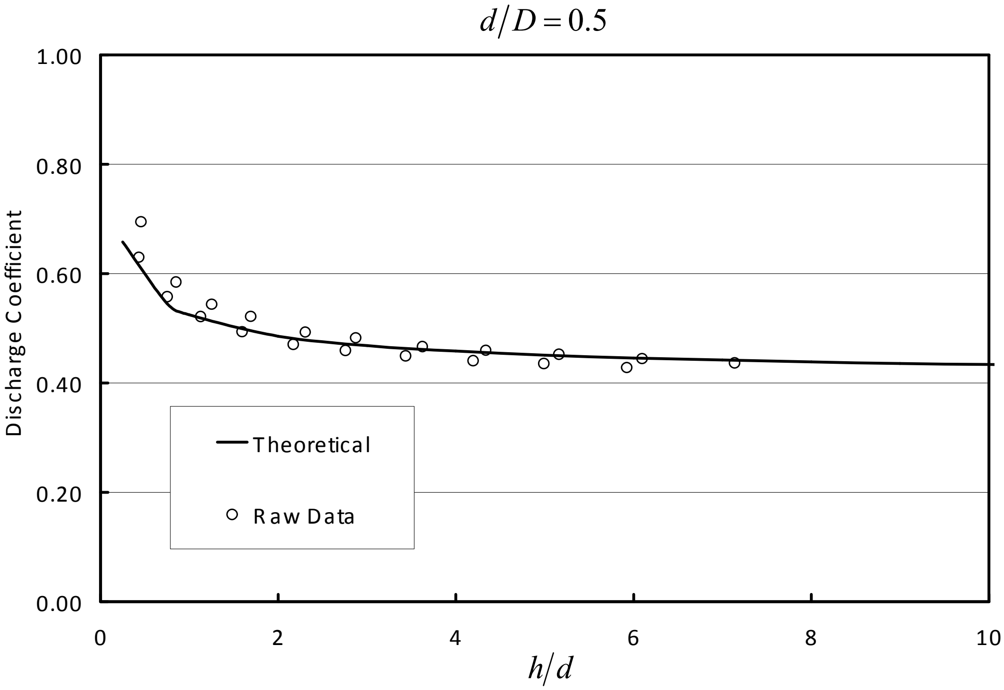

Figure 5.36: Relative error analysis with $d/D = 0.5$

Secondary study: effect of spacing with multiple orifices

A secondary part of this investigation was to determine what effect, if any, there would be on the discharge coefficient when multiple orifices were used in the same riser pipe with different spacing between the orifices. Two orifice diameters (5.1 cm and 7.6 cm) were tested in the 30.5 cm diameter riser pipe at various spacing (multiple of orifice diameter). To analyze the data, the upper and lower orifices were first tested individually to obtain their separate discharge coefficients. These discharge coefficients were used to compare the volume drained versus time data for the two orifices opened simultaneously and for the two orifices acting independently. The volume drained for the two orifices acting independently was obtained using the time versus head data from the test with two orifices opened simultaneously. If the volume drained in the two cases was different, the two orifices were not acting independently. In other words, the two orifices were influencing the flow of each other.

Figures 5.29 – 5.35 below show the volume drained versus time plots for different orifice sizes and spacing. The plots indicate little difference in the theoretical and actual volume drained. This is indicative that the flow fields from all tests, even those from the $2d$ spacing, did not significantly interact with each other. Any interaction between the orifices may have been offset by attracting more flow from the opposite side of the orifice. The results also do not indicate any more or less difference for the greater spacings as compared to the smaller. The 7.6 cm orifice also behaved similarly to the 5.1 cm orifice for the same spacing ratios tested. The maximum water level in the tank prevented the 7.6 cm orifice from being tested at an $8d$ spacing. In general the results show that orifices placed $2d$ or more apart could be treated as independent orifices.

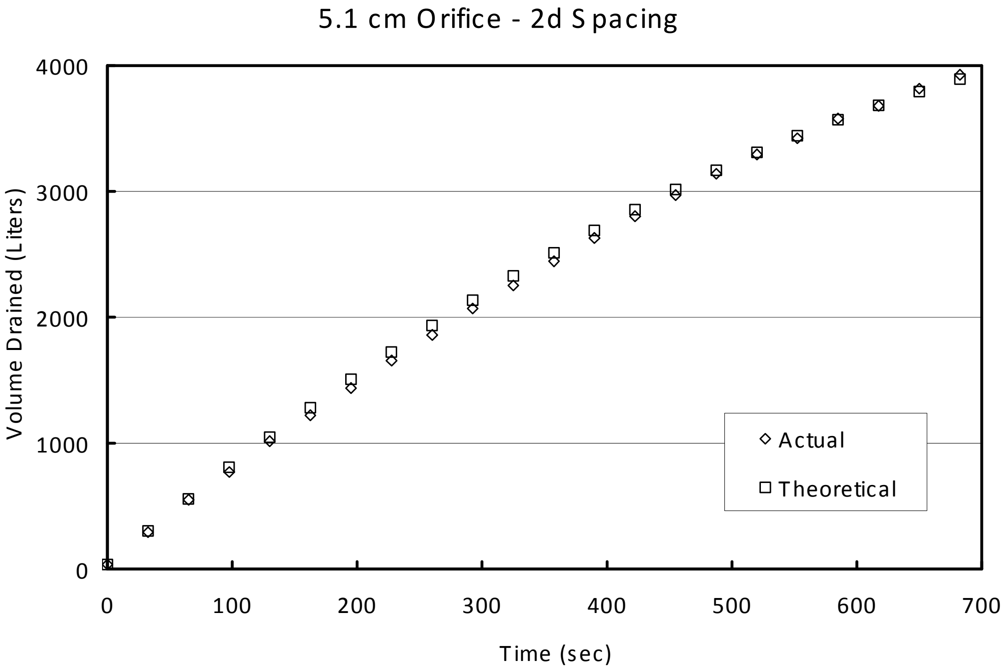

Figure 5.37: 5.1 cm orifice at $2d$ spacing

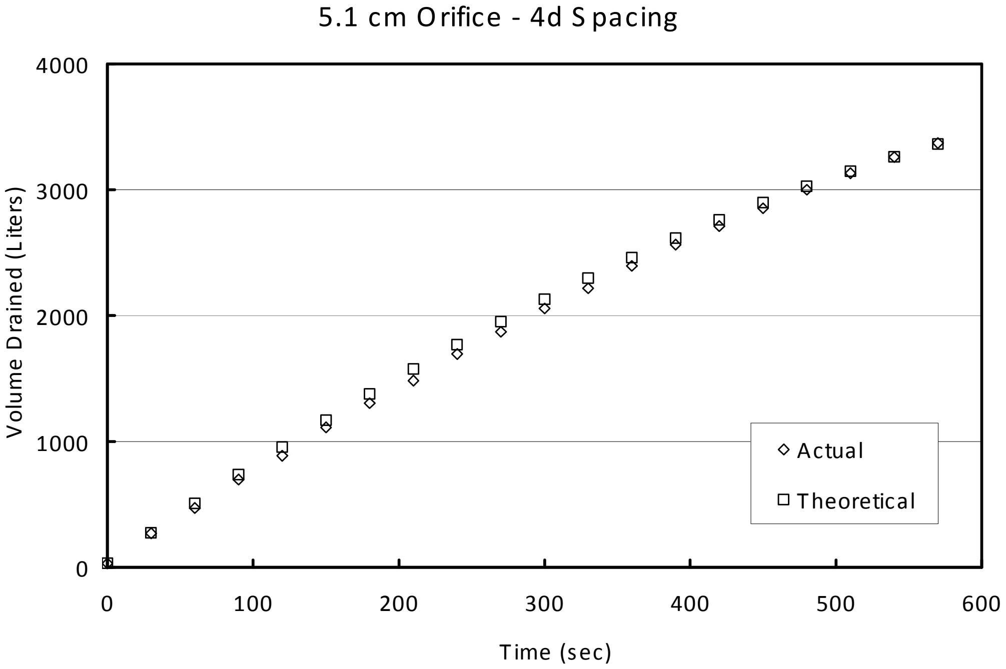

Figure 5.38: 5.1 cm orifice at $4d$ spacing

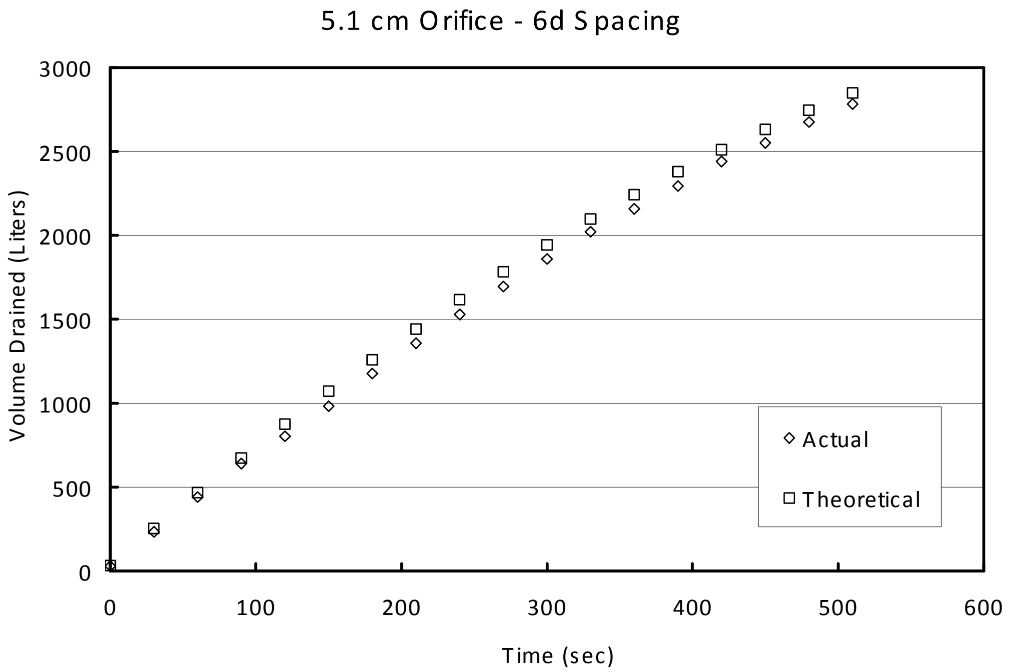

Figure 5.39: 5.1 cm orifice at $6d$ spacing

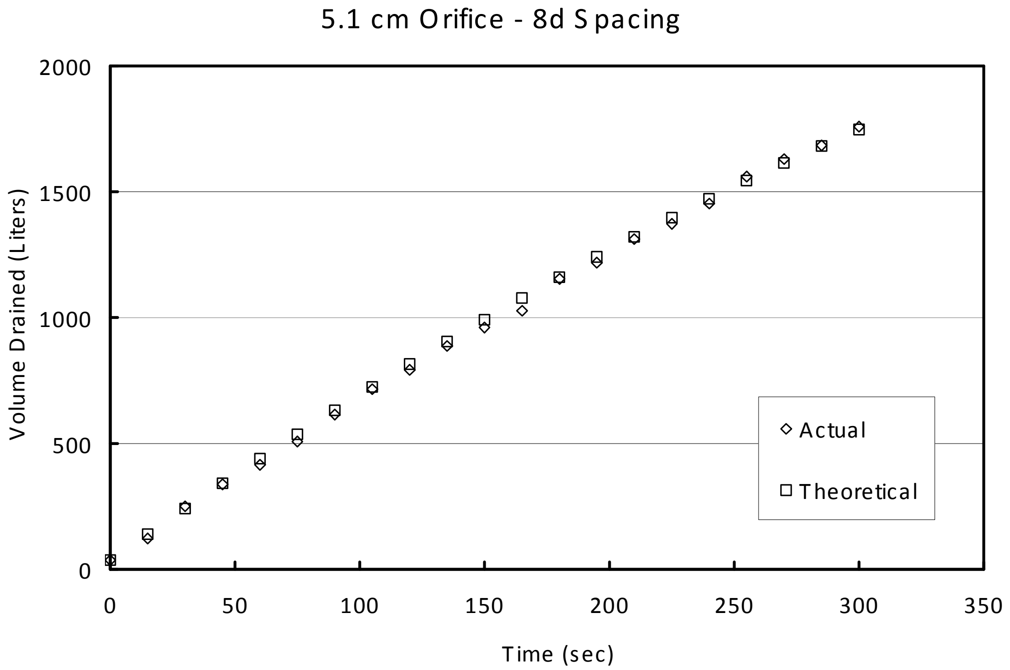

Figure 5.40: 5.1 cm orifice at $8d$ spacing

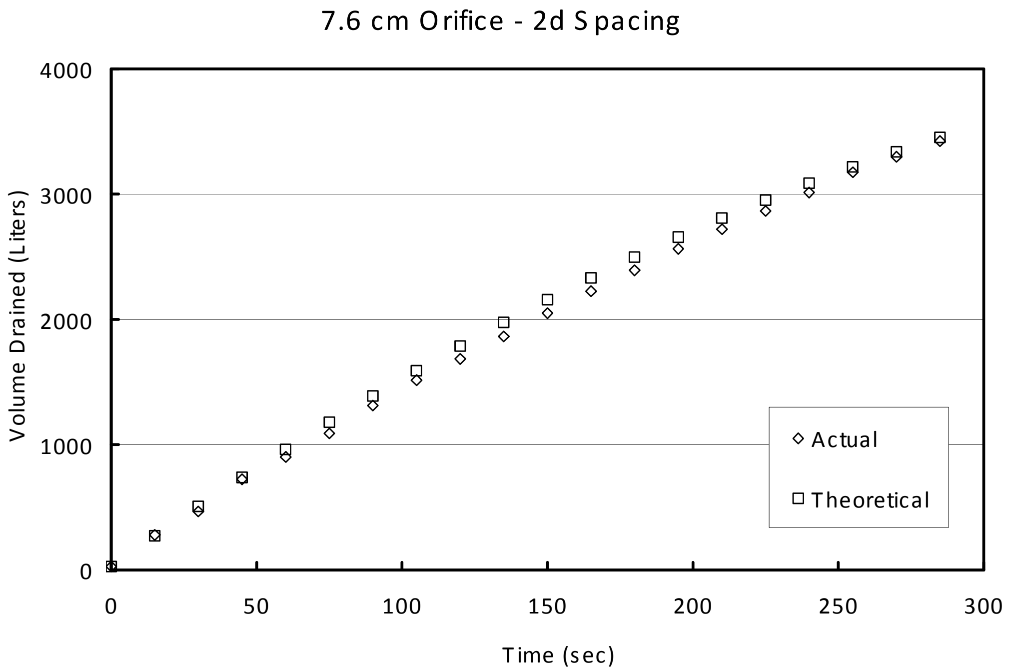

Figure 5.41: 7.6 cm orifice at $2d$ spacing

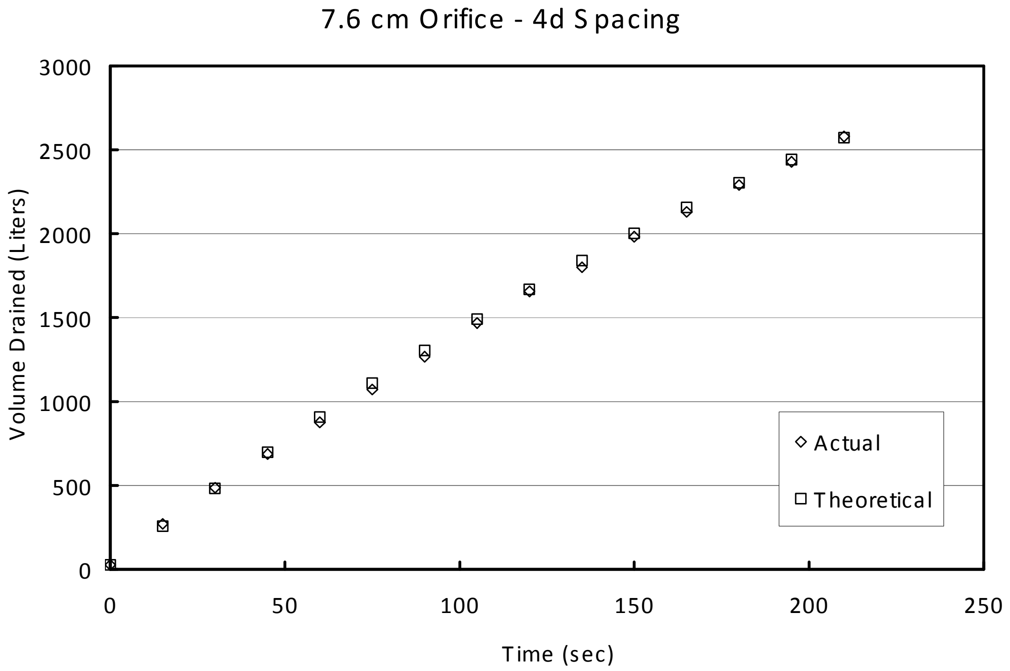

Figure 5.42: 7.6 cm orifice at $4d$ spacing

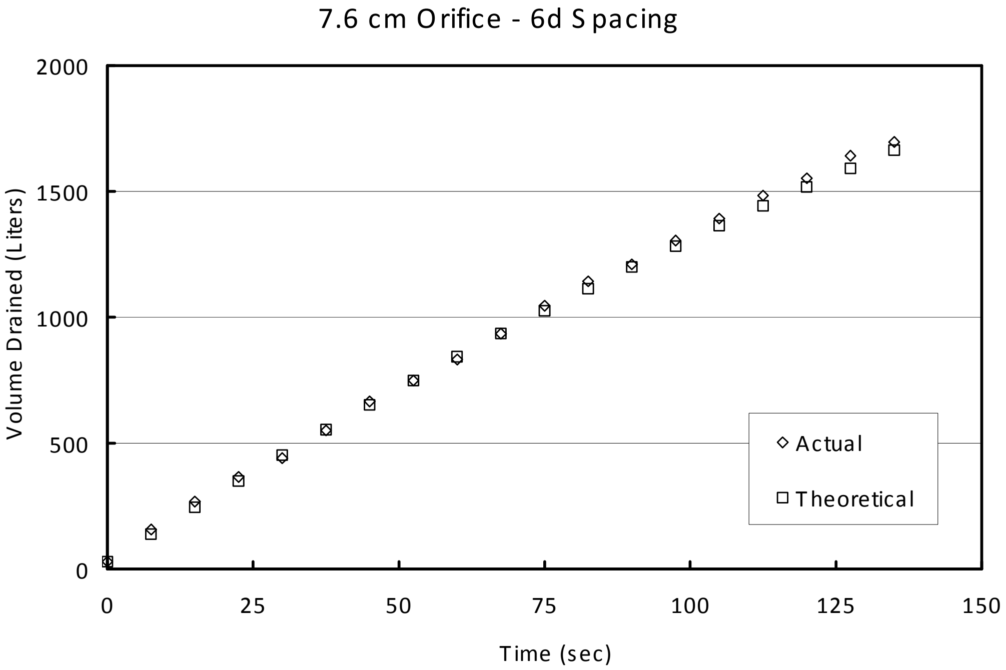

Figure 5.43: 7.6 cm orifice at $6d$ spacing

Potential sources of error

Care was taken at every step of the investigation to use analytical and experimental methods that would reduce the amount of error in the study. However, there is the possibility for uncontrollable error at various points in the experiment. Any slight inconsistency in the cutting of the orifices could change the area of flow and the contraction of the jet exiting the orifice. All orifices were cut with a boring bit (i.e. hole saw), and the exact diameter of each orifice was confirmed with a calibrated set of calipers to be within +/- 0.25 mm. The inner face of each orifice was made to be as smooth as possible, and the edges of each orifice as square as possible. Any slight difference in the roughness of the orifice or an imperfection at the edge could change the nature of the contraction and therefore affect the discharge coefficient. The height of the orifice above the tank floor plays a role in determining the discharge coefficient, and any error in recording the height could affect C_d. The orifice heights were measured before testing, and the exact height of the orifice centerline was used in data analysis.

The pressure transducer used to measure water level also could have been a source of error for the investigation. The accuracy of the transducer as determined by the manufacturer is 0.25% of the full scale. A constant head test showed the readings would oscillate around the true value. However, the data for the tests was large, so any variation would be unnoticeable. Trend line equations were used to determine the height and volume drained, and the fit of the line may have introduced error, but all calibration curves yielded correlation coefficients of 0.999 or greater.

Another possible source of error might be the flanges used to attach the riser pipes to the tank floor. The flanges were approximately 8 mm thick, and the flow field of the lowest orifice height (15.2 cm) might have been affected by the different shape of the vertical plane. Dye tests were performed to rule out any role the flanges might have played in the flow patterns, but it could not be determined with absolute certainty.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

An investigation was performed to determine the discharge coefficient for circular orifices cut into thin-walled (orifice diameter greater than pipe wall thickness) riser pipes that might be used for an outlet control device from a stormwater detention pond. The scenario was unique because the flow entered the riser pipe through the orifice from outside the pipe, presenting a case of flow over a convex, or inward-curved, surface. This study investigated a total of six different orifice sizes, ranging from 1.3 cm (0.5 in) to 12.7 cm (5 in), at five different heights from the tank floor, ranging from 15.2 cm (6 in) to 55.9 cm (22 in). The study also utilized two different riser pipe diameters, 15.2 cm (6 in) and 30.5 cm (12 in).

The study found that for a given orifice size decreasing head values resulted in a gradual increase in the discharge coefficient, with a more drastic increase in C_d as the water level approached the top of the orifice. This was primarily the result of a decrease in the contraction of the jet exiting the orifice, due to the reduced velocity of the flow approaching the orifice. For a given orifice size, the discharge coefficient reached a constant value at high head values.

The study found that for a given orifice size as the orifice height above the tank floor was increased, the discharge coefficient decreased, possibly the result of suppression of the flow entering the orifice at lower heights. It was also determined that at the upper-most heights (45.7 cm and 55.9 cm), C_d was unaffected by the tank floor.

The study found that increasing the d/D ratio resulted in a decrease of the discharge coefficient. This was expected as the greater the curvature effect of the orifice, the more oblique the angles will be at which flow streamlines must enter the orifice. This increased the transverse velocity components of the streamlines and reduces the area of the jet at the vena contracta.

The test results from the two upper orifice heights were successfully normalized and compiled into a single curve, which, along with a curve used to determine a parameter C_o, can be used to find the proper discharge coefficient for any orifice size in any riser pipe diameter at any h/d value.

As a secondary aim of the study, multiple orifices in the same vertical plane were tested at several spacings based on the orifice diameter, d. The study found that the discharge was unaffected for spacing equal or greater than $2d$.

It is recommended that further investigation be undertaken to extend the results presented here. Detailed analysis of orifice flows near a floor should be undertaken. Also work should be undertaken on orifices of non-circular shapes with these same parameters to determine if the discharge coefficients vary in the same fashion. Also, a more in-depth analysis of the interaction of multiple orifices should evaluate the changes in discharge with orifices spaced closer together than this investigation performed, more than two orifices, and orifices in the same horizontal plane. Finally, investigation should be undertaken to determine the discharge coefficient for orifices lying in a horizontal plane, which may act similar to a weir under low heads.

REFERENCES

Akan, A. O. and Houghtalen, R. J. (2003). *Urban Hydrology, Hydraulics, and Stormwater Quality*. John Wiley & Sons, Hoboken, N. J., pp 373.

Brater, E. F., King, H. W., Lindell, J. E., and Wei, C.Y. (1996). *Handbook of Hydraulics*. McGraw-Hill, New York, N. Y.

Bryant, D. B., Khan, A. A., and Aziz, N. M. (2008). "Investigation of Flow Upstream of Orifices." *Journal of Hydraulic Engineering*, ASCE, 134(1), 98 – 104.

Gregg, W. B., Werth, D. E., and Frizzell, C. (2003). "Determination of discharge coefficients for hydraulic sparger design." *Journal of Pressure Vessel Technology*, ASME, 126(3), 354 – 359.

Gupta, R. S. (2008). *Hydrology and Hydraulic Systems*. Waveland Press, Long Grove, Illinois., pp 896.

Jarrett, A. R. (1993). "Design of Perforated Risers to Control Dewatering of Sedimentation Basins." *Applied Engineering in Agriculture*, ASAE, 9(1), 37 – 42.

Millen, J. A., Jarrett, A. R., and Faircloth, J. W. (1997). "Experimental Evaluation of Sedimentation Basin Performance for Alternative Dewatering Systems." *Transactions of the ASAE*, ASAE, 40(4), 1087 – 1095.

Smith, D., and Walker, W. J. (1923). "Orifice Flow." *Institution of Mechanical Engineers – Proceedings*, 1, 23 – 36.

Smith, Hamilton, Jr. (1886). *Hydraulics*. John Wiley & Sons, New York, N. Y., pp 421.

Tsihrintzis, V. A., and Hamid, R. (1997). "Modeling and Management of Urban Stormwater Runoff Quality: A Review." *Water Resources Management*, 11(2), 137 – 164.

Werth, D. E., Khan, A. A., and Gregg, W. B. (2005). "Experimental study of wall curvature and bypass flow effects on orifice discharge coefficients." *Experiments in Fluids*, 39, 485 – 491.