ARCED LABYRINTH WEIR GEOMETRIC DESIGN FOR AUXILIARY SPILLWAY APPLICATIONS IN EXISTING DAM INFRASTRUCTURE

by

Jamie Fitzgerald López-Soto

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Approved by:

Omar I. Molina-Bas, PhD Chairperson, Graduate Committee	Date
Johannes L. Wibowo, PhD Co-Chairperson, Graduate Committee	Date
Ismael Pagán-Trinidad, MSCE Member, Graduate Committee	Date
Victor Huérfano, PhD Representative of Graduate Studies	Date
Ismael Pagán-Trinidad, MSCE Chairperson of the Department	Date

ABSTRACT

A new optimization scheme procedure for arced labyrinth weir design is proposed to be used in a spillway value analysis, for the design of auxiliary spillways. The arced labyrinth spillway geometric design based on an optimization-based program that integrates hydraulic performance from physical models and estimated cost. The optimization procedure compares expected hydraulic conditions and specific site considerations to over 45,000 solutions, and outputs a list of the 10 most economical arced labyrinth weirs. The most promising weirs' geometric parameters, expected hydraulic behavior, and structure construction cost are tabulated, thus giving enough information to the designer about the expected arced labyrinth weir that could sustain the hydraulic conditions under a flood event. High performance designs are then compared to developed full-scale solutions and are compared based on an economic analysis. The geometric parameters are then subject to a sensitivity analysis to analyze a case study thus optimizing the design further for a specific case study discharge. Based on the sensitivity analysis, the trends of the most economic weirs are selected, and a specific set of geometrical parameters is selected as the trending design in which the economic and hydraulic conditions are optimized. Finally, a design optimization ratio was found to be a common denominator in the majority of the designs. The optimization ratio is based on a specific arc radius to the width.

RESUMEN

Se propone un esquema de optimización para el diseño de vertedero laberinto arqueada para ser utilizado en un análisis de valor, para el diseño de aliviaderos auxiliares. El diseño geométrico del aliviadero laberinto arqueada se basa en un programa basado en la optimización que integra el rendimiento hidráulico de los modelos físicos y costos estimados. El procedimiento de optimización compara las condiciones hidráulicas esperadas y consideraciones específicas del lugar para más de 45.000 soluciones, y emite una lista de los 10 vertedores de laberinto arqueado más económicos. Los parámetros geométricos de los vertederos más prometedores, el comportamiento hidráulico esperado, y el costo de construcción de la estructura se tabulan, dando así suficiente información al diseñador sobre los vertedores de laberinto arqueada que podrían sustentar las condiciones hidráulicas en virtud de un evento de inundación. Diseños de alto rendimiento se comparan mediante un análisis económico, con vertedores de laberinto a gran escala. Los parámetros geométricos se someten a un análisis de sensibilidad para analizar un caso de estudio de este modo optimizar el diseño para un caudal específico. Mediante el análisis de sensibilidad, se seleccionan las tendencias de los vertederos más económicos, y se selecciona un conjunto específico de parámetros geométricos como el diseño de tendencia en la que se optimizan las condiciones económicas e hidráulicas. Finalmente se encontró una relación de optimización del diseño que era un denominador común en la mayoría de los diseños. La relación de optimización se basa en un radio de arco específico al ancho de abertura del canal.

To my parents

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I would first thank God for guiding the steps in which the research was developed. Thank you.

I would like to thank my parents for their unconditional support, for understanding the priorities I have traced, and for encouraging me every day to become better. It is your sweet words that I recite day by day.

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GLOSSARY OF TERMS

A	Inside apex width
α	Sidewall angle
α'	Upstream labyrinth weir sidewall angle
B	Length of labyrinth weir (apron) in flow direction
C_d	Discharge coefficient, data from current studies
$C_{d\text{-}res}$	Discharge coefficient for a labyrinth weir spillway located in a reservoir
ε'	Cycle efficiency
G	Acceleration constant of gravity
H	Design flow water surface elevation
h	Depth of flow over the weir crest
H_T	Unsubmerged total upstream head on weir
H_T/P	Headwater ratio
Lc	Centerline length of weir sidewall
L_c	Total centerline length of labyrinth weir
$L_{c\text{-}cycle}$	Centerline length for a single labyrinth weir cycle
N	Number of labyrinth weir cycles
P	Weir height
Q	Discharge over weir
R	Arc center to channel width midpoint distance for an arced labyrinth weir
r'	Segment height for an arced labyrinth weir
R	Arc radius for an arced labyrinth weir
θ	Cycle arc angle for an arced labyrinth weir
Θ	Central weir arc angle for an arced labyrinth weir
t_w	Thickness of weir wall
V_{up}	Approach velocity
w	Width of a single labyrinth weir cycle
w'	Cycle width for the arced labyrinth weir spillway
W	Width of channel; width of labyrinth entrance (normal to flow)
W'	Width of the arced labyrinth weir spillway

1 CHAPTER - INTRODUCTION

1.1 Problem Statement

“The average age of our nation’s dams is 52 years. By the year 2020, 70% of the total dams in the United States will be over 50 years old. Fifty years ago, dams were built with the best engineering and construction standards of the time. However, as scientific and engineering data have improved, many dams are not expected to safely withstand current predictions regarding large floods and earthquakes. In addition, many of these dams were initially constructed using less-stringent design criteria for low-hazard dams due to the lack of development below the dam (ASCE 2014).

To address the need for safer infrastructure, it is necessary to implement solutions with currently available methods and information. The hazards of dam failure from overtopping must be considered with a serious design approach procedure. One problem that leads to dam’s overtopping is the limitation of the spillway outflow capacity during an extreme flood event.

Overtopping occurs when the water inflow is higher than the discharge capacity of a dam structure. As described by Redlinger et al. [1975], Lake Barcroft Dam, located in Alexandria, Virginia, was hit by a tropical storm in June 21, 1972 , resulting in a breach of the dam by overtopping. The dam, a 69-ft-high and 2,530 acre-feet (ac-ft) reservoir, had an estimated uncontrolled discharge of 14,500 cubic feet per second (cfs) due to this event

(Redlinger et al. 1975). Dam overtopping and subsequent water discharge caused severe erosion of the right abutment that measured 36 ft below the normal pool elevation. Eventually, this dam had to undergo extensive repairs.

Dam spillways are flow-control structures that are designed to control the release of flow discharge of the reservoir into a downstream channel. Spillways are designed to pass water from flood events through the structure without overtopping the dam, thus deviating flow and eliminating excess reservoir water. Dams have outlet works that maintain the pool elevation, thus usage of the spillway indicates that the reservoir inlet flow is higher than the outlet discharge. For reservoir applications, spillway designs include different types of spillways: linear, orifice, shaft, side-channel overflow, and labyrinth spillways.

When dam structures cannot safely pass the excess water, a risk of dam overtopping is imminent, which may result in a breach. A dam breach occurs as water overtops the embankment structure and begins to erode a weak layer in the dam. This erosion then starts to penetrate the weakened layer of soil until the soil ruptures and gives way to the flow passage. As water continues to flow through this passage, erosion begins to widen the structure until a less erodible material is encountered (MacDonald and Langridge - Monopolis 1984). A major dam failure from overtopping in the United States occurred in 1989 in Pennsylvania. The South Fork dam was an earthen-type structure with a 72-ft height and a reservoir volume of 11,500 ac-ft. In the flood event that produced overtopping, there were approximately 20,000 people at risk and 2,209 fatalities. The dam was never rebuilt (Graham 2009). Another risk of high water elevations in the reservoir area is piping.

Piping, also known as backwards erosion, starts at the exit point of the seepage path. In earthen dams, a large pressure due to flow and water elevation can cause internal erosion in the dam, which develops an internal cavity that has a direct connection between the downstream with the upstream water. As direct flow passes through, erosion and increased sediment transportation begin to widen the cavity until the structure on top collapses.

The selection of a spillway is a critical part of structure damage prevention, and its design is ultimately left to the designer due to the countless number of possible design variations. Considerations include an economic analysis of possible solutions for type of control structures, which include flow discharge behavior, spillway efficiency, crest selection, location of spillway (projecting, flushed, in channel, etc.), and maximum expected flow discharge.

Although other purposes of spillways include flow aeration and energy dissipaters' among others, these structures are hydraulically designed to sustain and overpass a design flood that would be specific for the area in which it will be constructed. This design flood is a calculated downpour event that has a low probability of occurrence but is powerful enough to cause the highest potential threat to the dam, land, and human life. These are based on extrapolations of hydraulic data that have been taken throughout several years. This should be taken into account as well as any site specific variables and topography. Another flood estimation method used to approximate the outflow is the Probable Maximum Flood (PMF), which is based on a rainfall-runoff model with the most extreme combinations of basic parameters and no return period is specified (Vischer and Hager 1998).

To increase current spillway capacity, Jansen [1988] recommended the following.

- increase the approach channel efficiency
- reshape the abutment and/or piers to increase the efficiency of the discharge characteristics
- lengthen the spillway crest, and
- reshape the crest to increase the coefficient of discharge

Crookston [2010] investigated physical scale models of relatively new design of labyrinth weirs in an arced configuration, thus the name of Arced Labyrinth Weirs. Hydraulic parameters were extracted from the models as well as specific geometric data. Due to the nature of the design, there exists an infinite number of possible configurations; hence, the design method for arced labyrinth design is an iterative procedure based on the already studied linear labyrinth weirs. Falvey [2003] described the hydraulic considerations that must be taken into account in the design of labyrinth structures. These hydraulic considerations include flow characteristics, discharge coefficient, nape aeration, and crest shape. These discussed approaches are the hydraulic considerations that dominate the behavior of the spillway but discussed methods are imposed in the designs of linear labyrinth weirs, and only when a design is proposed then it is hydraulically analyzed and modeled, thus different configurations must be taken into account before a possible solution can be reached. For arced labyrinth weirs, this trial method of design seems extensive. It has been observed that in some cases arced labyrinth weirs have higher discharge capacities than linear projecting weirs, thus an optimization scheme aids in the development of solutions. The increase in discharge capacity of linear labyrinth weirs is due to its increased linear length of the weir, while the discharge increase in arced labyrinth weirs is based on hydraulic efficiency. This change in efficiency then requires to process the collected data for arced labyrinth weirs from Crookston [2010] and Christensen [2012] and use it to (Crookston & Tullis 2013) design different arced configurations until a set of possible solutions are reached. Since the designer has the judgment of what ultimately is the best solution for any specific situation, the design of arced labyrinth weirs should be based on available space, expected flow conditions, and economic analysis.

1.2 Purpose of the Research

To satisfy the outflow conditions experienced by an existing dam structure, there is a need for guidance of the geometric design of arced labyrinth weir structures along with a construction cost estimate as part of the economic analysis and use this information for the construction of an auxiliary or secondary spillway. For existing spillways through which expected flood conditions cannot be passed through the current design, recommendations for possible solutions are based on arced labyrinth weirs. These structures increase the linear length of a spillway, are thus maximizing the space available to accommodate a larger outflow than current linear weirs in the same linear length than linear spillways.

The author has no known information of any design procedure for arced labyrinth spillways that incorporates geometric, hydrological, and economic considerations. The lack of design procedures is due to the limited amount of hydraulic data and infinite number of possible configurations; thus, a new design procedure needs to be developed and evaluated in economic terms for design feasibility. This procedure should be able to take into account the site specific criteria, such as width of the channel and outflow conditions, to design a new spillway. Considerations in terms of biological or ecological impact are not taken into consideration.

Since an infinite numbers of solutions can be developed for a specific case, it is important to take into consideration spillways with high value coefficients that would satisfy the expected hydraulic and geometric boundary conditions. The developed design procedure is expected to be incorporated in a computer program due to the large numbers of iterations needed to obtain the optimum values of the design. The optimum designs will be based on the optimization of weir flow capacity while reducing the construction cost of the structure. The output solutions will be compared with each other, and only the 10 most economic weirs that satisfy the expected outflow conditions will be analyzed; thus these spillways can be later analyzed in terms of their value. Cost analysis of the design will be done in the spreadsheet. The approach is a systematic method in which the safety, function, and service of the structure, in this case arced labyrinth weirs, are not compromised. It is important that the approach focuses on cost reduction procedures that directly affect the construction costs of the spillway and not in material substitution. The design process of the structure is handled in a macro scale while subsequent value engineering approaches at the micro scale are encouraged by individuals for specific local events. The purpose of this approach is to maximize the performance (outflow capacity) of the structure and to minimize construction costs without creating an impact in the quality (material selection, higher risk structures) of the end product, thus maximizing the spillway value.

The need to identify trends of the most economic design aids in the selection of a starting point for a weir. The behavior of cost trends identifies optimum geometric parameters for hydraulic efficiency and relates these parameters to the cost; thus the cost becomes the optimization selection criteria in the determination of the geometric design while the hydraulic characteristics become the constraint criteria of the design.

A preliminary structure cost analysis has been mentioned in literature in which it is said to be possible by varying certain parameters (Tullis et al. 1995). Although this is true, the approach into the study of the weirs has been based on the hydraulic parameters as the main design criteria, that is, as long as the weir can sustain the expected hydraulic conditions and can be built in the project site; it is up to the engineer's judgment to develop an in-depth solution, which includes concrete strength, reinforcing steel, specific wall configuration as well as specific geometric criteria. Solutions for arced labyrinth weirs are infinite, and to approximate the optimum weir based on cost and expected hydraulic conditions based on previous design methods is a huge endeavor, since current methods are based on trial and error.

2 RESEARCH OBJECTIVES

2.1 General Objective

To define the process of an arced labyrinth weir geometric design procedure for implementation in existing dam infrastructure.

2.2 Specific Objectives

The objectives of this research are the following:

- develop a spreadsheet-based optimization program that aids in the design of a reservoir, projecting, half-round crest, arced labyrinth spillways for secondary or auxiliary spillway applications,
- expand the knowledge of the design of arced labyrinth spillways in aims of consideration of aced labyrinth spillway arrangement as a possible solution for dam rehabilitation,
- determine the value coefficient of arced labyrinth spillways based on spillway structural cost and functionality,
- establish the feasibility of arced labyrinth weirs compared with linear labyrinth weirs based from an economic standpoint,
- provide the geometric design equations for arced labyrinth weirs based on a minimum quantity of parameters, thus obtaining a wide range of solutions in which it is possible to analyze the cost of each solution,

- present hydraulic characteristic data for designs based on previous physical model studies data,
- identify design trends for optimum economic designs,
- determine cycle efficiency for the top ten most economic weirs, and
- develop a geometry optimization parameter based on a case study.

2.3 Contributions of the Research

Contributions of this research are described based on the reduction of time-consuming calculations while increasing the number of iterations to obtain an adequate optimum solution in the design of arced labyrinth weirs based on economic concerns. A systematic approach is used to ensure all possible solutions, to which data are available, are presented, and the most economic and hydraulic efficient weir is chosen.

1. *Design optimization procedure of arced labyrinth weirs for auxiliary spillway applications that includes approach method and equations.* A design methodology for linear labyrinth weirs was studied and recommended by Crookston [2010], Lux [1989], and Tullis et al. [1995]. Although a design method was not developed for arced labyrinth weirs, Crookston [2010] attempted to implement the same design procedure as for the linear labyrinth weirs. Although successful, the amount of consecutive iterations to converge to an optimum solution can be exhausting for hand calculations and extensive for single computational iterations. This research developed a procedure that consists of selecting the minimal number of geometric parameters and using a programmed methodology to find the most economic

spillways that can satisfy the weir design flow capacity, given site-specific data. The design procedure is based on a radius change approach instead of procedures that constrained certain geometric parameters to which only one solution was available. The number of cycles is treated as a range instead of a single fixed parameter thus allowing angle-based iterations to obtain the large sampling size for possible solutions. The calculations are sequentially dependent, thus equations need to be solved in a specific order to obtain the set of possible solutions. The design uses a minimum amount of the dam's hydraulic information as an input criteria to confidently develop site specific weir solutions.

2. *Batch presentation of data.* The approach of the proposed procedure allows for a great amount of data to be calculated in a small amount of time, to which a great deal of information is available to the user. The output is presented as a series of weirs instead of like past methods, where a single weir was presented to which there was no information about the economic factors, hydraulic capacity, or even if the hydraulic structure would fit in the space available for site specific cases.

3. *First economic analysis integrating optimization scheme based design.* Most decisions on structure feasibility are based on the economy of the design. The economic analysis is based on a list of the lowest cost weirs that can be used to pass the flow, thus allowing the designer to make a spillway selection based on the highest value solutions. The proposed methodology integrates value engineering principles in terms of calculated spillway value coefficients, similar to the

procedure presented by Li & Liu [2006], thus presenting a comparison between the most economic-functional arced labyrinth weirs which at the same time is compared to a base linear labyrinth weir.

4. *Suggestion of an optimizing ratio based on empirical data*. Throughout solution generation process and data analysis using the proposed design methodology a parameter remained constant throughout design and seemed to be a key parameter in the optimization process. The optimization ratio is based on the top solutions for a case study presented and is based the radius of the arc and channel width. The ratio that optimized the case study, high value, arced labyrinth design based on a given channel width lies between 1.508 and 1.532 with emphasis on the higher end.
5. *Interpolation between three geometric parameters.* The new design approach is based on the assumption that hydraulic data can be interpolated between similar geometric parameters. It has been suggested that this procedure can be done and even extrapolate values. Only interpolation of parametric coefficients will be implemented, something that, although suggested, has not been tried given the complexity of the algorithms. To obtain 3D interpolation parameters, the integration of a new, software based, set of functions was implemented into Excel.

2.4 Scope Limitations

The focus of the project is to create a design procedure for arced labyrinth weirs that can be integrated in an optimization-based program. The research is intended for reservoir arced labyrinth spillway applications in the rehabilitation of dams by creating an auxiliary spillway. The spillway crest is a half-round weir spillway. The designs are based on scale model behaviors that were previously studied and tested by Christensen [2012] and Crookston [2010]. Previous arced labyrinth spillway models have been studied for up to a maximum of ten cycles with sidewall angles (α) varying from 0° to 20° for arced labyrinth weirs and cycle arc angles (θ) from 10° to 30°.

2.5 Thesis Outline

Most of current dams are not designed for expected hydraulic conditions, which are conditions higher than for they were initially designed (ASCE 2014), thus indicating a serious risk to human life. The risk can be mitigated using higher discharge capacity spillways. This thesis approach chosen for this study is first discussing previous methods of design of labyrinth spillways and current methods of selection of an arced labyrinth spillway; this is discussed in chapter 3. Also in this the concept of value engineering is introduced since its concepts are used as a means of analyzing the solutions between each other and at the same time it is acknowledge that arced labyrinth weirs need to be compared to other flow discharge structures. Since an optimization based design for arced labyrinth spillways is not available, a new approach is contained in a computer program is discussed. After explaining how the available information impacts the range of possible solutions, the design procedure is described in chapter 4. To obtain the highest value weir that complies with the user specification, a detailed construction cost estimate of the structure was developed to obtain the cost per cubic yard of Portland cement (Appendix B-Construction Estimate and Crew Composition). The cost estimate is then incorporated into the program to solve for possible alternative solutions for an arced labyrinth weir and a specific linear labyrinth weir, thus comparing the feasibility of the arced labyrinth spillway design as a competitive option, when compared to a linear labyrinth spillway. A sensitivity analysis is then developed to understand the construction trends for arced labyrinth weirs and obtain important information about expected weir geometry, parameters, costs, and hydraulic behavior. The minimum cost spillways are then analyzed in terms of value between each other to determine adequate solutions. An optimization coefficient is investigated in chapter 5, since calculated solution for a case study studied in the same chapter suggested an optimization trend that implies the existence of a radius-to-width relation for optimum designs. Chapter 6 contains the immediate conclusion suggested by the study along with recommendations for further studies as the topic has a great deal of possible research areas.

3 LITERATURE REVIEW

The current state of knowledge of labyrinth weirs, arced labyrinth weirs, and value engineering methodology is presented. The value engineering method is explained as an application for analyzing the value coefficient of various alternatives. Previous studies were focused on the determination of a discharge coefficient that describe the hydraulic behavior of the weir. The discharge coefficient is a factor of a wide range of parameters to which different approaches have been taken in the past to explain the flow discharge capacity of the weirs. The small scale weirs were modeled in small-scale physical models; these spillway prototypes studied by Taylor [1968], Hay and Taylor [1970], Darvas [1971], Mayer [1980], Houston [1983], de Magalhães and Lorena [1989], Lux [1989], Tullis et al. [1995], Crookston [2010] and Christensen [2012]. The small scale experiments were made as an efforts to understand the spillway flow behavior and determine feasible means by which to solve critical hydraulic dam deficiencies.

The approach taken in this analysis is the use of arced labyrinth spillways for projecting arced labyrinth weirs in reservoir applications for dam rehabilitation. Current geometric design methodology for the arced labyrinth weirs are based on a similar design approach as linear labyrinth weirs while the flow characteristics are expressed by the equation for a linear weir.

3.1 Labyrinth Weirs

Labyrinth spillways are hydraulic designed structures whose purpose is to regulate the excess flow of water from the reservoir. The construction of the weir is arranged in an accordion like pattern that increases the crest length for a fixed width approach channel. The addition in length to spillways is proportional to the discharge as will be seen and discussed in one of the equations in the next chapter; (Eq. 4-9). Figure 3-1 illustrates the geometric parameters specific for labyrinth weirs. These geometric parameters may be arranged in an infinite number of possible combinations. The labyrinth combinations must take into account the main purpose of creation of this structure, which is to maximize spillway capacity by increasing the weir length in the configuration chosen. Various physical models have been tested by previously mentioned authors, the tested solutions the author believes would be solutions which had been identified as they could pass the expected outflow conditions. Since a physical model study need to occur would have not been feasible to try all the models that would sustain an expected rainfall event. Thus only specific designs were selected. These solutions are rather selected on expected outflow discharge characteristics and designs can be suggested but physical models are still needed to validate results.

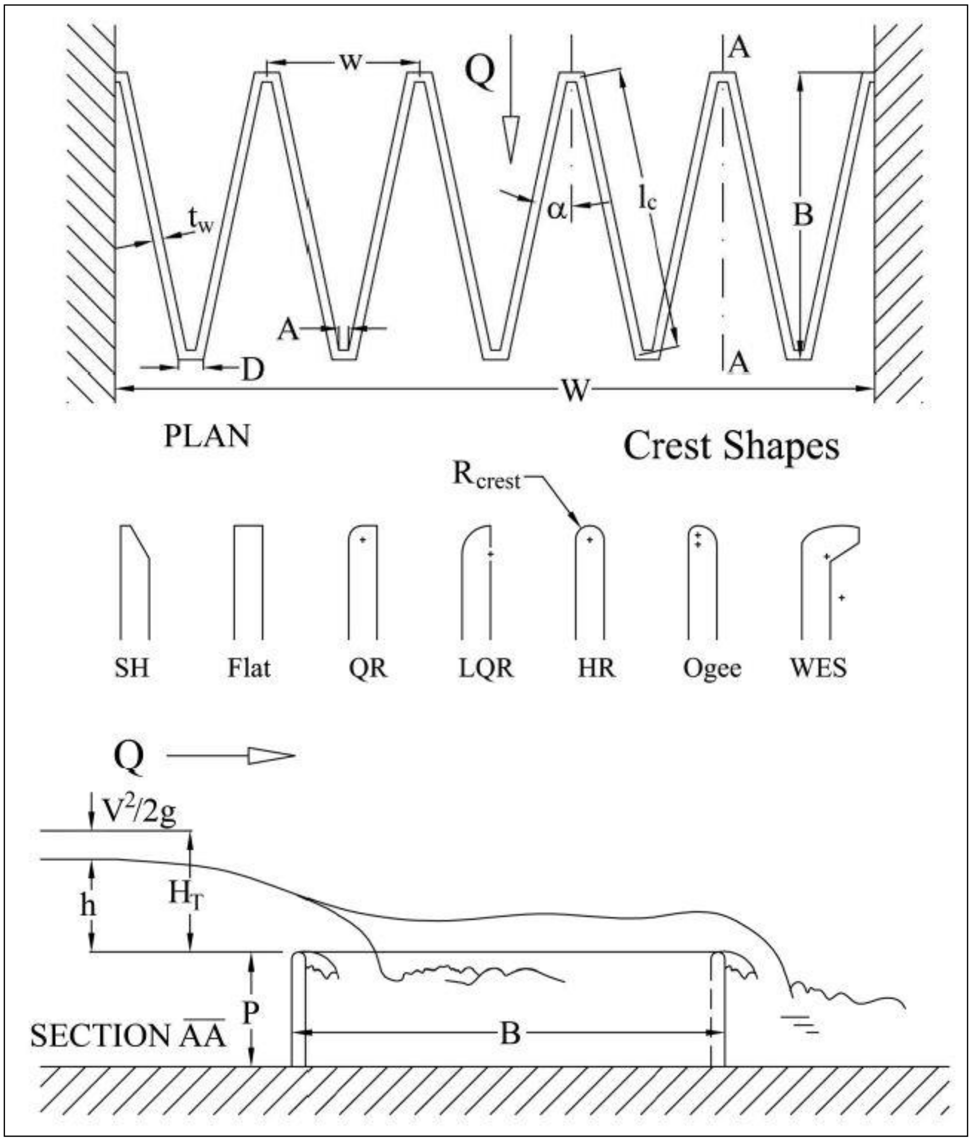

Figure 3-1. Labyrinth weir geometric parameters for a 5-cycle linear labyrinth weir. (Crookston 2010).

A	Apex Center-Line Width
α	Sidewall Angle
B	Length of Labyrinth Weir (Apron) in Flow Direction
D	Outer Apex Width
g	Gravity Constant
h	Depth of Flow Over the Weir Crest

H_T	Unsubmerged Total Upstream Head on Weir
l_c	Centerline Length of Weir Sidewall
P	Weir Crest Height
Q	Outflow Discharge
t_w	Wall Thickness
V	Velocity
$V^2/2g$	Velocity Head
w	Width of a Single Labyrinth Weir Cycle
W	Channel Width
SH	Sharp
Flat	Flat
QR	Quarter Round
LQR	Quarter Wound with Varying Thickness Wall
HR	Half Round
Ogee	OGEE
WES	WES Standard Spillway Shapes (OGEE Crest)

3.1.1 *Previous Design Methods and Models of Labyrinth Weirs*

A large number of linear labyrinth weirs have been tested. Parts of the designs are based on structures that were to be implemented in real life scenarios by studying the behavior in a physical scale model. Other models were made to analyze the flow-weir behavior, thus determining the discharge coefficient for each specific case. Taylor [1968] studied a number of cases for the triangular, sharp crested weirs and presented the data based on a magnification ratio. The magnification ratio was expressed as the ratio of a triangular weir length compared to a linear weir of the same length; this parameter determined the discharge of a weir. Although acceptable this approach would need to account for approach flow conditions in the analysis. Hay and Taylor [1970] developed a simple design method for linear trapezoidal or triangular weirs based on experimental results. Disproval of the use of submerged weirs was suggested by the authors at that time. They encountered that maximum hydraulic efficiency occurred when an air-entrained nape was present, thus discouraging conditions that would negate this effect. During this study, the effect of the velocity in the driving head was not taken into account, causing future designs, based on their procedure, to be under designed. Triangular weirs and high values of α were recommended.

Darvas [1971] introduced an empirical equation that described a discharge coefficient in terms of a discharge flow based on the linear weir equation. The designs using this coefficient were developed for $0.2 \leq H_T/P \leq 0.6$, quarter-round triangular weirs and for a vertical aspect ratio $w/P \geq 2$. Curves were developed for use with the discharge coefficient, the headwater ratio, and cycle efficiency. Houston [1983] and Mayer [1980] developed physical models based on Hay and Taylor [1970], which were found to be under-designed and could not pass the designed flow. The discrepancies were found to be in the definition of the head, which as previously discussed did not take into account the velocity head. de Magalhães and Lorena [1989] developed curves similar to Darvas [1971] for WES crest shapes (Figure 3-1) and based the analysis of a single discharge coefficient that plugs on the linear weir discharge formula.

Lux [1989] suggested a step-by-step procedure for the design of a labyrinth weir that consisted of accounting for the maximum head permitted for each site specific condition. The definition of the maximum allowable head in the weir that would be able to satisfy the dams' limitations would be limited by the expected freeboard conditions or a maximum design water height. The maximum discharge that could pass through the weir should be extrapolated from modeled hydraulic conditions. After this and with the headwater ratio trial value of 0.5, the crest height should be revised to see that it complies with the site limitations. The number of cycle parameters is then chosen at a round, and then calculate the number cycle width and the vertical aspect ratio as a revision of the design. Interpolation in charts and numerically solving the final dimensions are then chosen and sketched to verify if the design would fit into the proposed water channel or dam spillway. This method required extensive hand calculations and chart utilization to eventually find a solution that it would not be clear if it were to be able to be constructed based on the geometrical parameters. No economic analysis was present for this design methodology at the design level, and no optimization of any kind was present for the implementation of this design. The hand calculations were extensive and only developed for linear labyrinth weirs.

The design procedure in a systematic approach was a significant addition to the design process (Figure 3-2) at the time. In the process, it was required to fix the Apex ratio (A/2w) to the values of 0.0765 or less for trapezoidal shape labyrinth weirs. This value corresponds to a fixed sidewall angle for triangular shapes. By fixing this parameter, the geometry is constrained to geometries that will not incur in loss of performance due to nape interference.

This process then fixed the internal sidewall angle to a known value. The process consists of initial trial values to begin the design. Revisions are made to the initial design throughout the process, which although systematic, become a tedious calculation process.

Alterations of the design were made without knowledge of the impact on the hydraulic behavior of the weir or even if the final dimensions would fit in the channel width. Information such as the final spillway width and hydraulic behavior were obtained in the final stages of the calculation procedures. The methodology took into account site specific criteria in terms of expected soil bearing capacity of the site; thus an engineering analysis is implied in the process to understand if the site will support the structure of a certain height. The early consideration of the site and structure interaction is an acceptable starting point for this procedure.

The list of design parameters suggested by Lux [1989] is presented in Figure 3-3. Note that only for this case, W is the width of the cycle while other designs express W as the channel width and w as the cycle width.

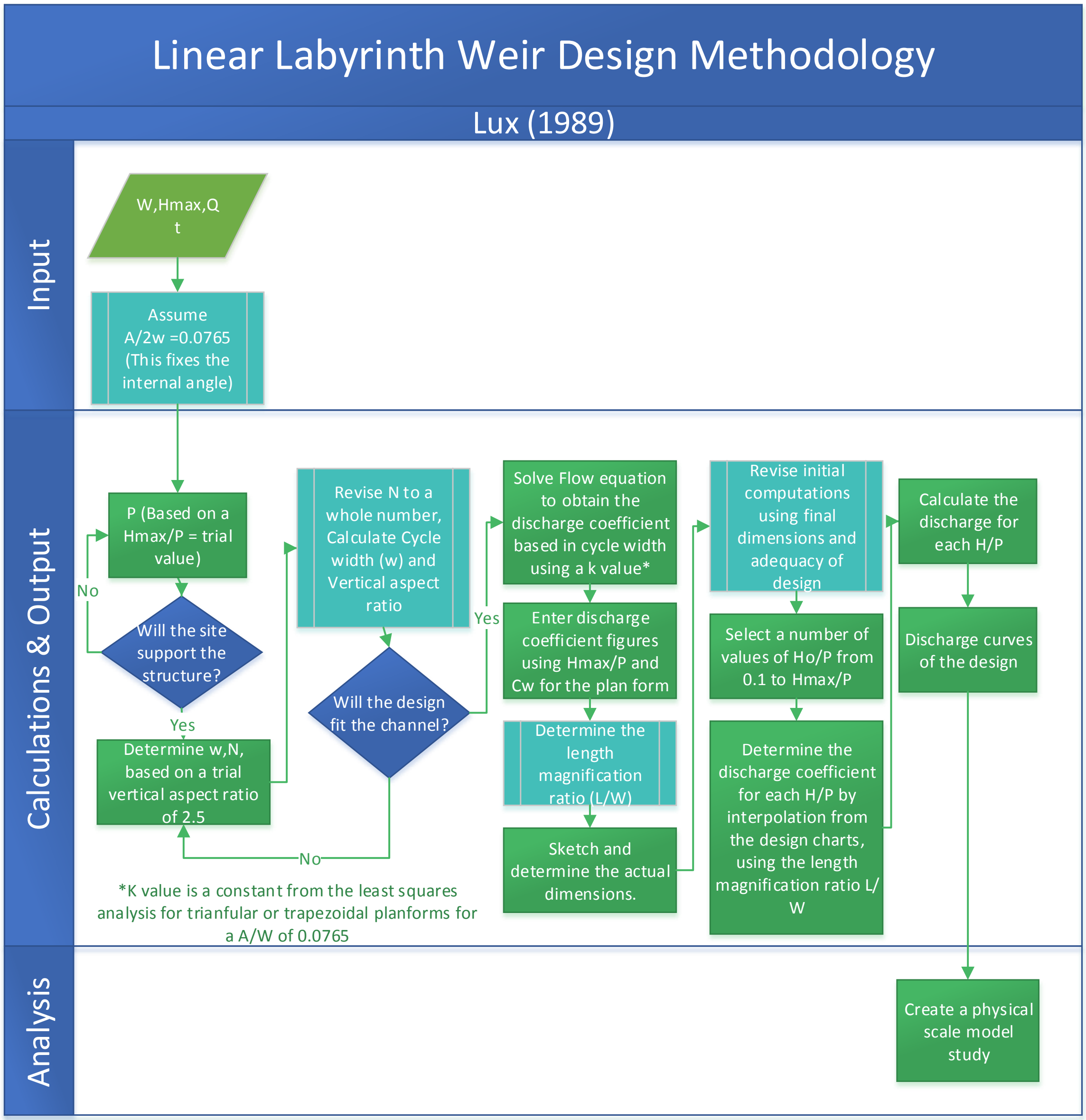

Figure 3-2. Linear labyrinth weir design methodology based on methodology suggested by Lux [1989].

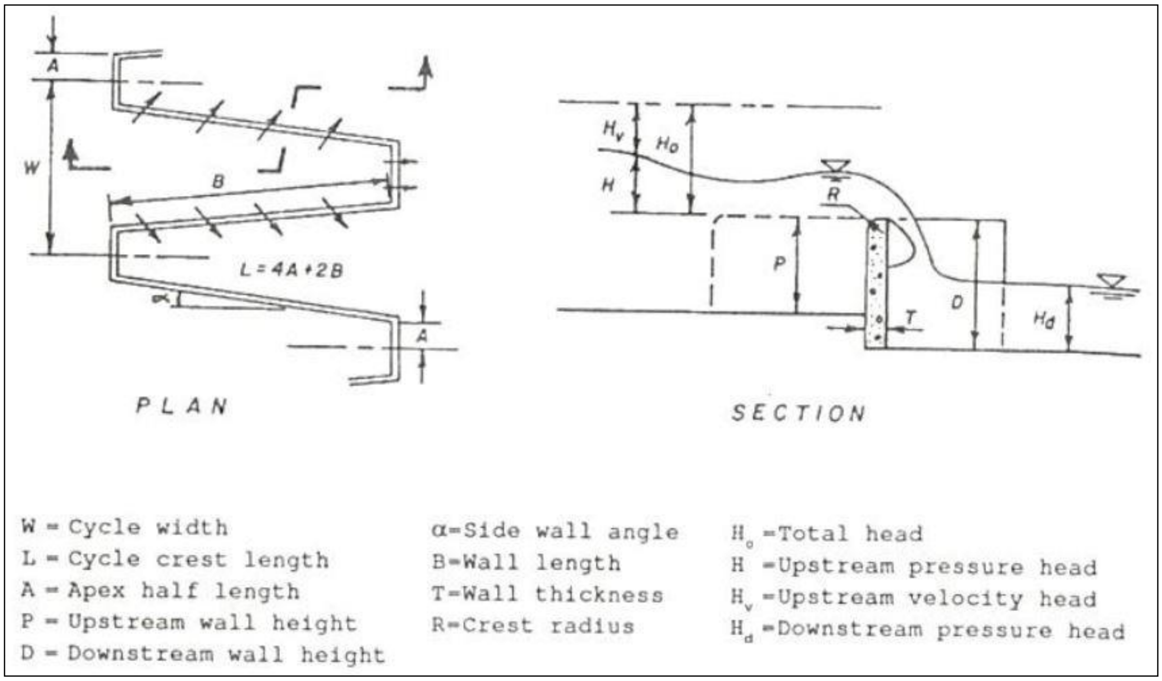

Figure 3-3. Definition of labyrinth parameters by Lux [1989].

Tullis et al. [1995] proposed to use the linear weir equation to explain the behavior of labyrinth weirs, thus the discharge coefficient would take into consideration all the design factors. It was here where a spreadsheet-based tool was first introduced to determine the hydraulic conditions of a weir based on experimental data. The spreadsheet data for the determination of the discharge coefficient was dependent on polynomial fit curves developed by previous studies on labyrinth weirs. The spreadsheet calculated the geometric parameters (Figure 3-4 and Figure 3-5) for a weir; a design flowchart is presented in Figure 3-6. The designer took charge of constraining the number of cycles (N), crest height, and the internal wall angle (α). The inside of the apex (A) was found in a range of two values based on the wall thickness of the weir. The thickness of the wall was calculated based on the height of the weir. There was no economic analysis included during the analysis of the weir design. The number of cycles was found to have a significant effect on the geometric layout, thus affecting the cost and hydraulic efficiency. The variation of number of labyrinth weir cycles (N) was then key in obtaining an optimized weir design geometry. It was recommended that, from a great amount of iterations to where hydraulic conditions were met, the designer could choose a design but insisted that an economic analysis was needed. An economic analysis was implied in the concrete volume calculations where it provides information of the volume of concrete needed for the walls of the weir. The cost of the weir is not calculated during the procedure or used in any other manner during the design. The information on the concrete volume is provided to further analyze in the post processing of the design and aid in the selection of an economic and efficient design. Tullis et al. [1995] suggest that designs should be verified using a model study of the proposed labyrinth. The designs are based on the arbitrary selection of α and N which suggest a weir cost, site specific criteria and limitations, and hydraulic capacity.

Maximum flow	Q_{max}
Maximum reservoir elevation	*res*
Approach channel elevation	—
Crest elevation	el
Total head	H_t

Estimated inlet loss at Q_{max}	Loss
Number of cycles	N
Crest height	P
Angle of side legs	α

Thickness of wall	t
Inside width at apex	A
Outside width of apex	D
Total head/crest height	H_t/P
Crest coefficient	C_d
Effective crest length	L
Length of apron (parallel to flow)	B
Actual length of side leg	L_1
Effective length of side leg	L_2
Total length of walls	L_3
Distance between cycles	w
Width of labyrinth (normal to flow)	W
Length of linear weir for same flow	—
Distance between cycles/crest height	w/P

Figure 3-4. Geometric parameters based on Tullis et al. [1995].

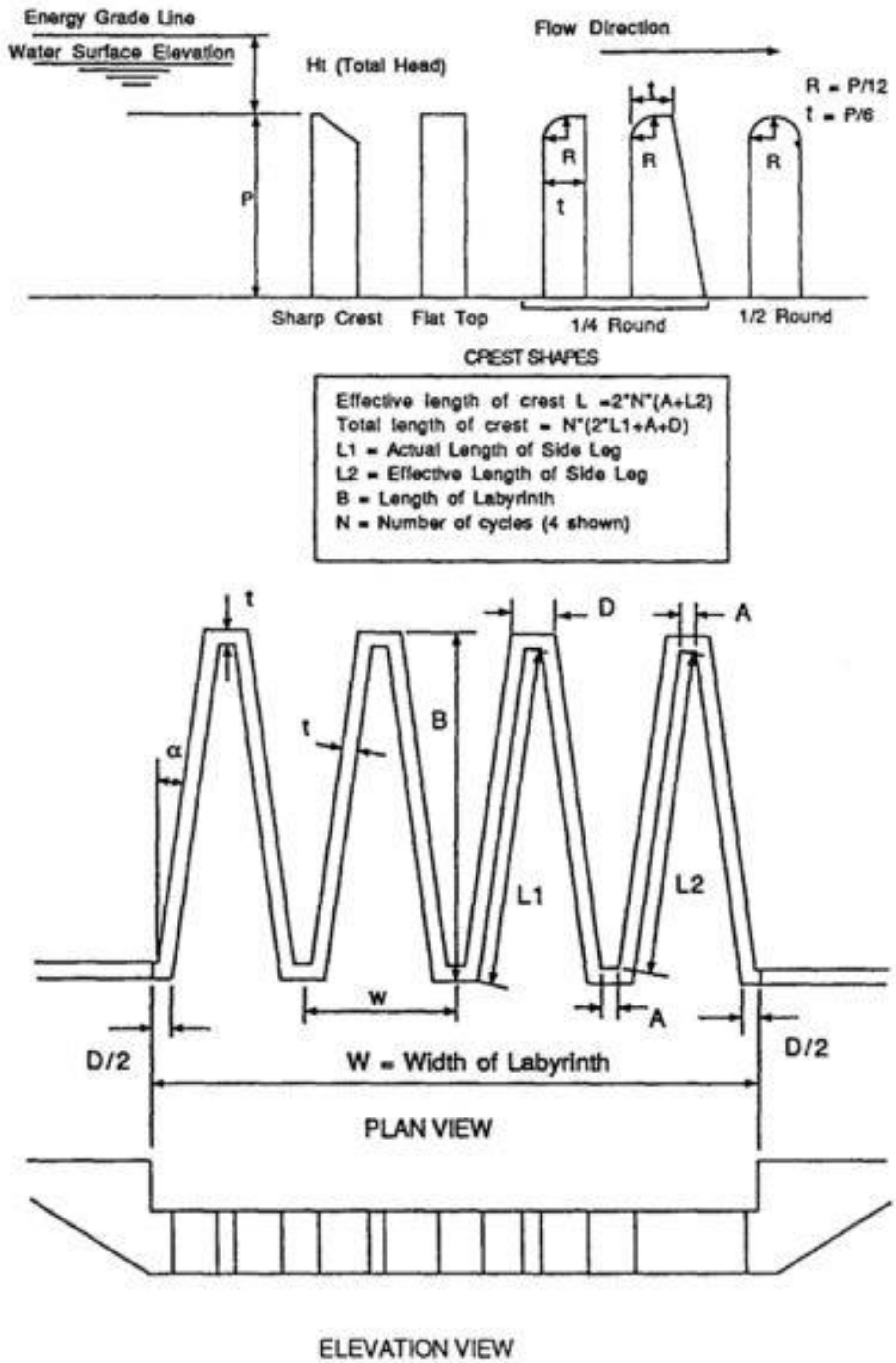

Figure 3-5. Layout and details of a 4 cycle linear labyrinth weir (Tullis et al. 1995).

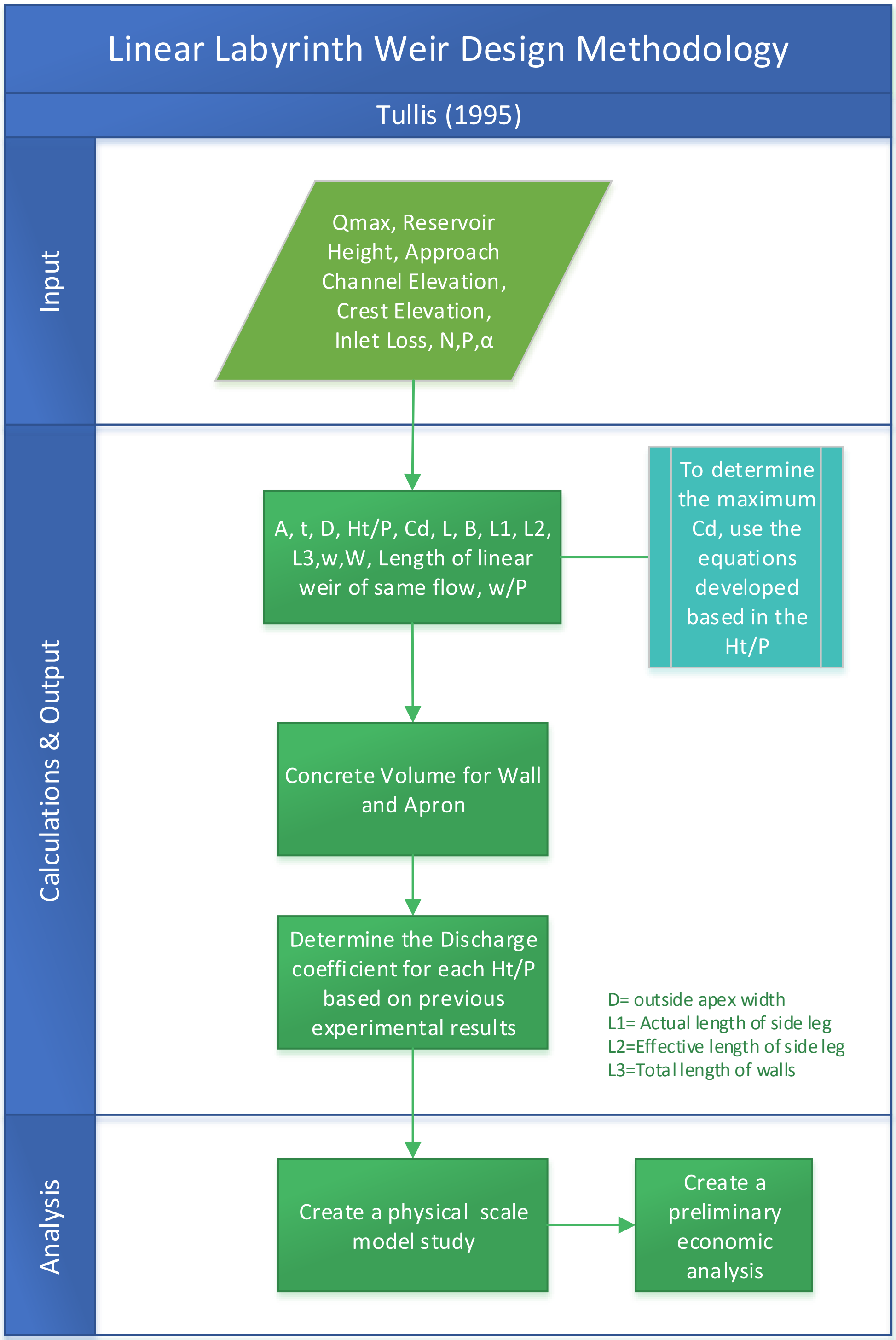

Figure 3-6. Linear labyrinth weir design methodology based on the methodology suggested by Tullis, et al. [1995].

Crookston [2010] further developed the spreadsheet for the design of linear labyrinth weirs suggested by Tullis et al. [1995]. The design implementation is similar to the one presented by Lux [1989] in which an iterative procedure is needed to obtain a design. The usage of the spreadsheet is based on information from Tullis et al. [1995] and data collected by Crookston [2010] during his research. Data included linear weirs and labyrinth weirs with quarter-round and a half-round crests. Crookston [2010] used a polynomial fit to explain the behavior of the discharge coefficient based on the headwater ratio, which was a similar approach to Tullis et al. [1995]. Cycle efficiency and efficacy were used to explain the hydraulic behavior the weirs exhibited during different headwater ratios. The polynomial fit developed by Crookston [2010] was later tested by Crookston et al. [2012], where the trend functions were compared to a numerical simulation for high headwater ratios (up to 2), in which the simulation gave similar results to the ones extrapolated for the function and coefficients developed by Crookston [2010].

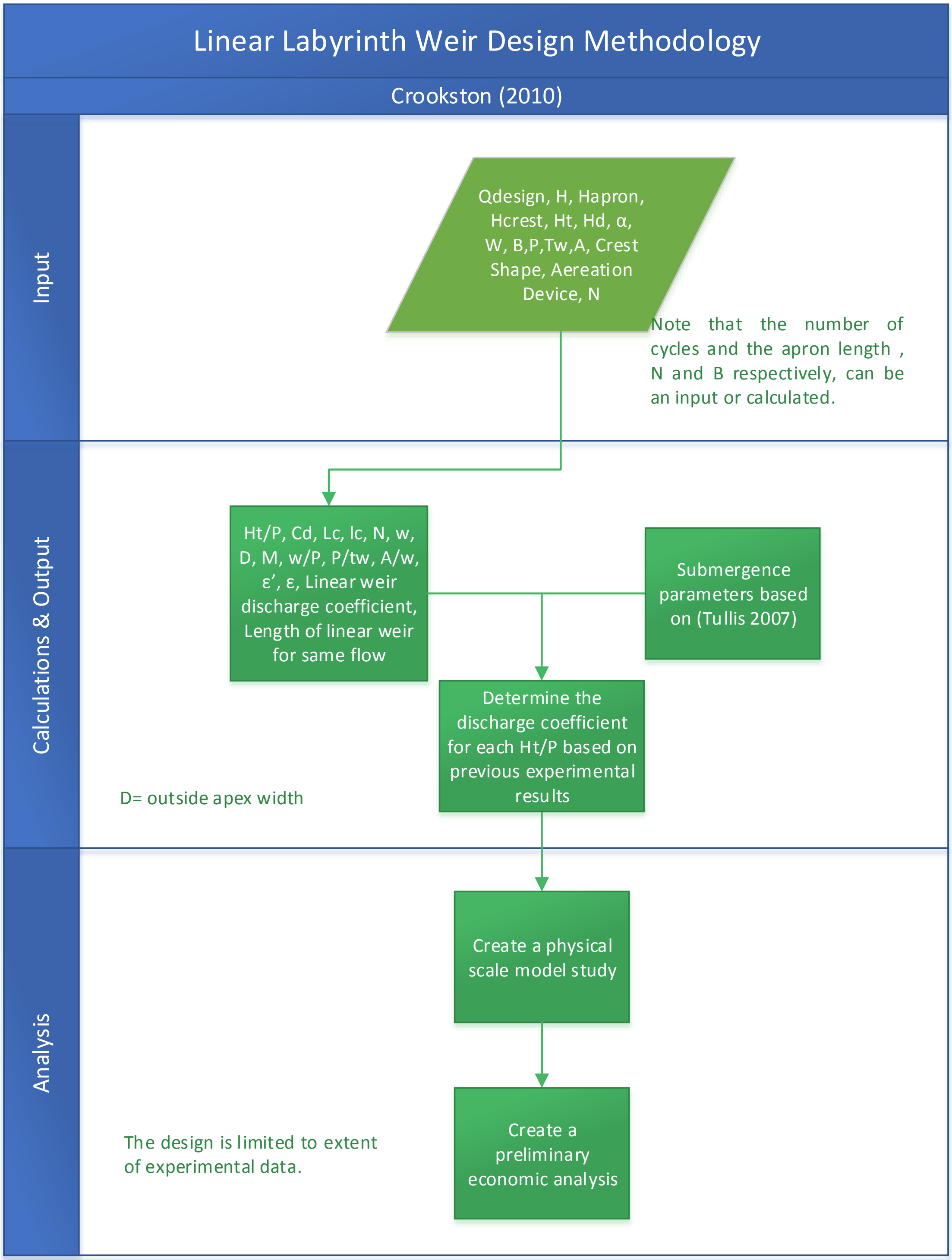

Figure 3-7. Linear labyrinth weir design methodology based on the methodology suggested by Crookston [2010].

3.2 Arced Labyrinth Weirs

Arced labyrinth weirs are labyrinth trapezoidal shape weirs in which the centerlines of the apexes, when viewed from the top, occur around a fixed axis, thus creating an arc (Figure 3-8). This type of design improves the orientation cycle with respect to the approaching flow. The cycle re-orientation increases the efficiency of the discharge capacity of the weir, thus in the same amount of area it is possible to achieve a greater amount of discharge; this effect can be observed in Figure 3-9.

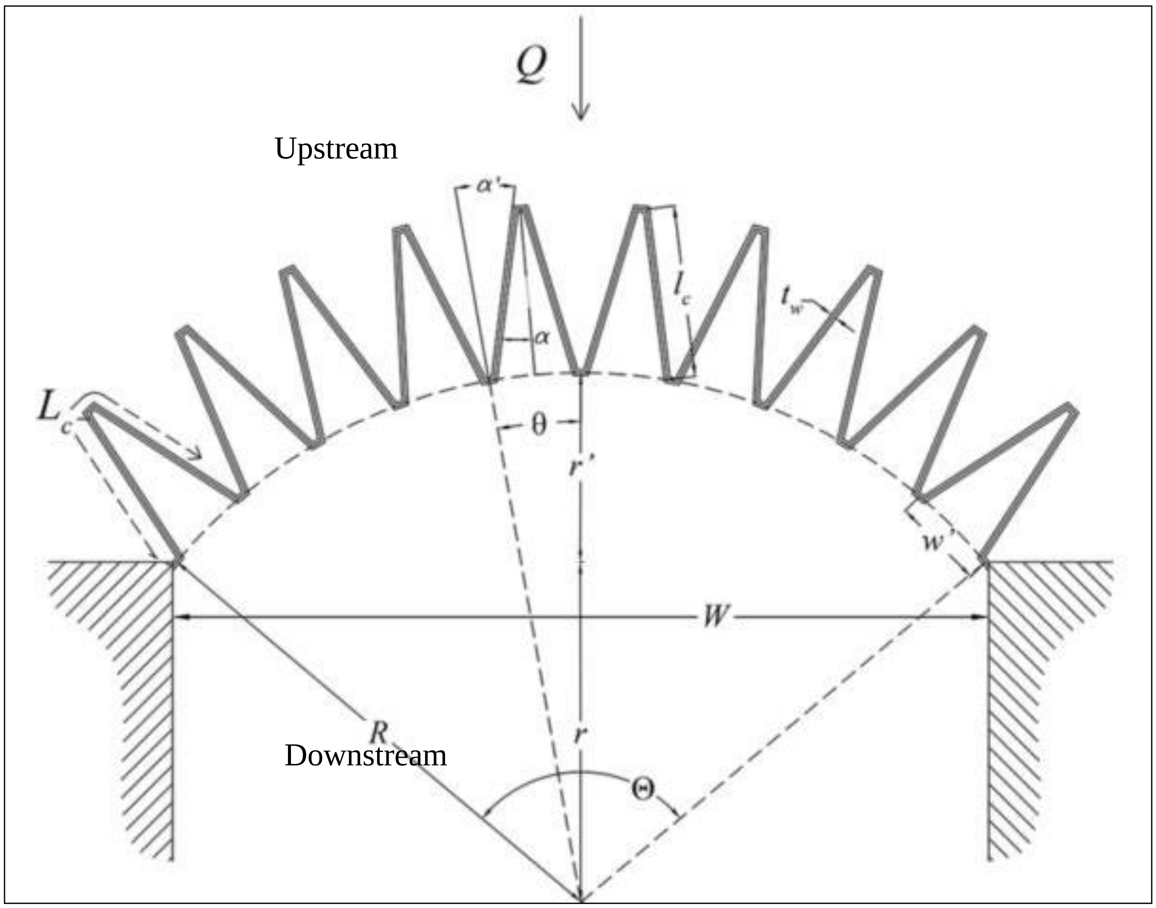

Figure 3-8. 10-cycle arced labyrinth weir configuration (Christensen 2012).

A’ Upstream Labyrinth Weir Sidewall Angle

L_C Total Centerline Length of Labyrinth Weir

R Arc Center to Channel Width Midpoint Distance for an Arced Labyrinth Weir

R’ Segment Height for an Arced Labyrinth Weir

R Arc Radius for an Arced Labyrinth Weir

ϴ Cycle Arc Angle for an Arced Labyrinth Weir

Θ Central Weir Arc Angle for an Arced Labyrinth Weir

W’ Cycle Width for the Arced Labyrinth Weir Spillway

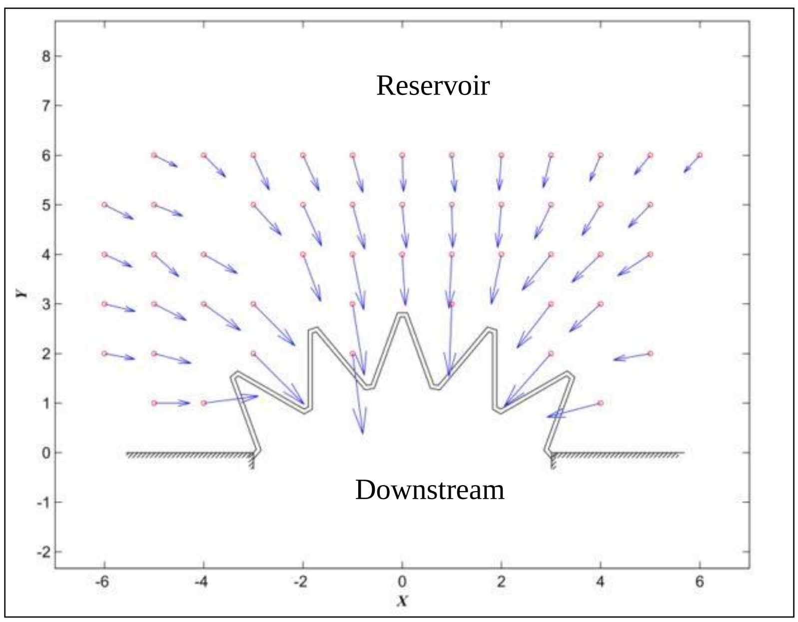

Figure 3-9. Velocity vector plots, grid of a 5 cycle, α=20°, θ=20° at H_T/P = 0.6 as presented by Christensen [2012].

The proposed designs for this study of arced labyrinth weirs are intended for reservoir auxiliary spillway applications. The implications for in-reservoirs applications are that the flow is directed to the spillway from multiple directions from which the arced labyrinth spillways benefit. Copeland and Fletcher [2000], based on a numerical model for the Prado reservoir in California, determined that the linear labyrinth weirs' discharge capacities are very sensitive the approach channel conditions. In the same study, it was determined that there is no significant influence in any changes in the abutment of the spillway. Crookston [2010], when studying arced labyrinth weirs, also determined that the discharge efficiency improves with cycle orientation to the approach flow, and that during high discharges flow separation affects the efficiency of the spillway.

The discharge efficiency is determined from empirical models of the arced labyrinth weirs. A series of arced labyrinth weirs were tested, and the discharge coefficient was determined based in its headwater ratio, similar to the linear weirs studied.

These types of structures are implemented to increase the capacity of existing drainage features and can be used in conjunction with an existing spillway thus creating a new auxiliary or emergency spillway structure. The analysis of different outflow structures is important in terms of the implementation of cost-effective solutions, thus this writing intends to expand the knowledge of the design of arced labyrinth spillways in aims of consideration of this spillway arrangement in a value engineering analysis as a possible solution. An example of the use of a labyrinth support structure is the proposed spillway design for a dam in California where a new proposed project includes the construction of an emergency spillway to support the dam structure during flood events as shown Figure 3-10. The recommendations for new spillways or other flow control structures are due to an assessment of dam conditions. When conditions of under-capacity spillways are of concern, arced labyrinth are a feasible solution compared to linear weirs, due to their increase in spillway length and hydraulic efficiency.

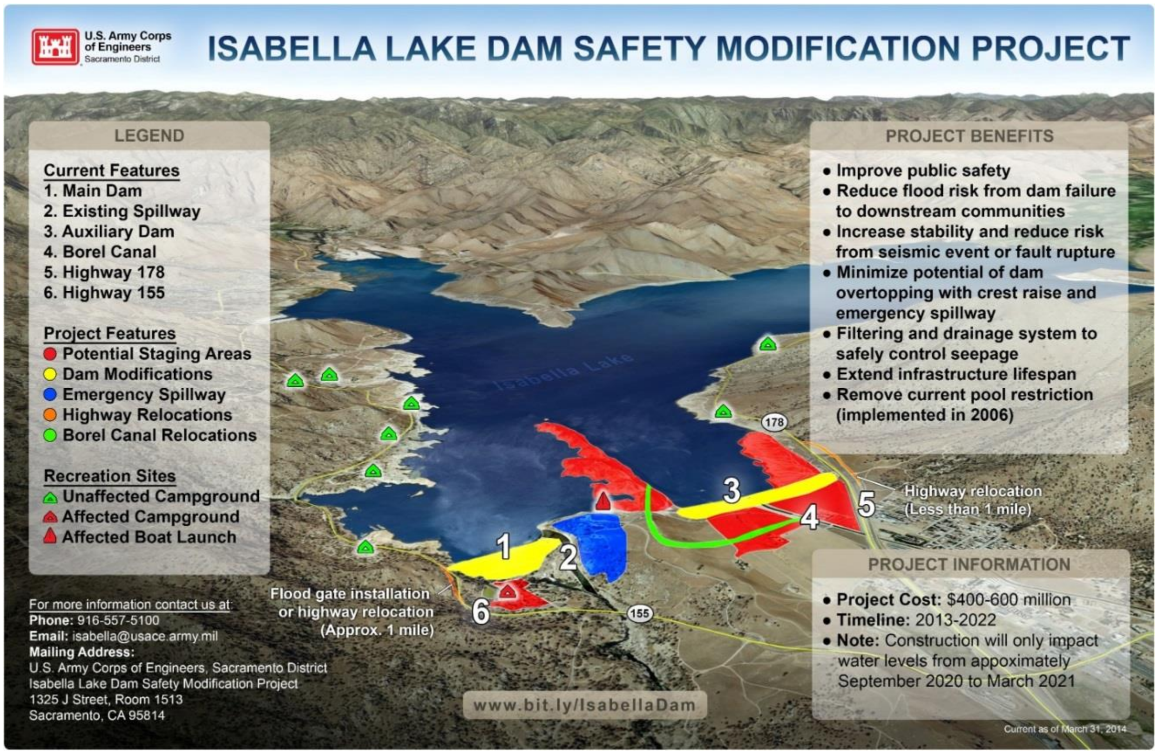

Figure 3-10. Isabella Lake dam safety modification project (U.S. Army Corps of Engineers 2014).

3.2.1 *Models for Arced Labyrinth Weirs and Previous Design Methods*

Crookston [2010] tested various five-cycle arced labyrinth weir models at different headwater ratios; Table 3-1 and

Table 3-2 present the weirs considered by the study. The determination of the discharge coefficient at different headwater ratios allowed plotted data to be fitted with a polynomial trend. This trend curve is defined by four parameters that describe the curve in terms of the headwater ratio for different arced weir geometries. The arced labyrinth flow discharge was then compared to the discharge of an arced weir at different headwater ratios in which it was found that the discharge ranged from 381% to 182% more for arced labyrinth weirs. The study found that it is possible to overdesign the spillway in which the control shifts to the downstream area. This has to be verified for each site-specific model designed.

Table 3-1. Tested arced weirs and trend line coefficients for half-round trapezoidal labyrinth weirs, valid $0.05 \leq H_T/P \leq 0.2$ (Crookston 2010).

α (°)		Orientation	Coefficients			
			A	*B*	*C*	*D*
6	Arced	Projecting, θ = 30°	-10.072	-13.85	3.4033	0.5238
		Projecting, θ = 20°	-15.86	-6.7336	2.1836	0.5647
		Projecting, θ = 10°	25.031	-22.061	3.8631	0.488
	Linear	Projecting, θ = 0°	98.599	-47.272	6.0173	0.3819
		Flush	166.004	-68.1254	7.4922	0.3373
		Rounded Inlet	112.61	-47.638	5.2119	0.441
12	Arced	Projecting, θ = 30°	89.891	-44.348	6.9154	0.4284
		Projecting, θ = 20°	31.087	-20.732	3.8441	0.546
		Projecting, θ = 10°	35.244	-21.308	3.4392	0.5719
	Linear	Projecting, θ = 0°	8.8398	-10.593	1.8034	0.6258
		Flush	83.586	-41.581	5.5661	0.4719
		Rounded Inlet	79.276	-37.17	4.8114	0.5168

Table 3-2. Tested arced weirs and trend line coefficients for half-round trapezoidal labyrinth weirs, valid $0.05 \leq H_T/P \leq 0.2$ (Crookston 2010).

α (°)		Orientation	Coefficients A	B	C	D
6	Arced	Projecting, θ = 30°	-4.1930	7.3673	-4.6092	1.2327
		Projecting, θ = 20°	-3.3019	5.9622	-3.9526	1.1798
		Projecting, θ = 10°	-3.2392	5.709	-3.7124	1.1178
	Linear	Projecting, θ = 0°	-1.8936	3.5802	-2.5204	0.8605
		Flush	-1.8381	3.2521	-2.2005	0.762
		Rounded Inlet	-2.0028	3.5671	-2.4166	0.833
12	Arced	Projecting, θ = 30°	1.5198	-1.3712	-0.5984	0.9124
		Projecting, θ = 20°	1.4404	-1.3929	-0.4088	0.8606
		Projecting, θ = 10°	1.2107	-1.0806	-0.4449	0.8128
	Linear	Projecting, θ = 0°	-0.1153	0.7162	-1.1144	0.8163
		Flush	-0.7374	1.5114	-1.3966	0.8162
		Rounded Inlet	-1.1832	2.1713	-1.7164	0.8916

The corresponding weir orientations identified in Table 3-1 and Table 3-2 are presented in Figure 3-11.

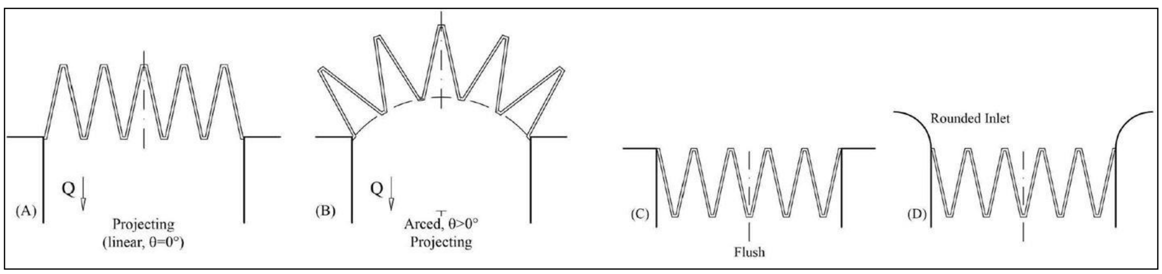

Figure 3-11. Weir orientations by Crookston [2010].

The design method for arced labyrinth weirs presented by Crookston [2010] has the same procedure as a linear weir, in which, a broad range of parameters are selected and then all the geometric parameters are calculated. After calculation and various manual trials, a design is selected. The design iterations are not optimized geometrically or economically, and the selection of the parameters is arbitrary or experience based instead of a systematical approach or parameter variation augmentation percentage. Final geometric and hydraulic designs for Crookston [2010] are based on physical weir modeling in which the hydraulic data were previously obtained. It is assumed that this hydraulic data can be extrapolated for a design for conditions that have not been tested. Later, the suggested geometry is physically modeled in which the weir has to be tested and verified that the expected hydraulic conditions are met. The approach then becomes dependent on physical models that can or cannot behave as expected as with the linear labyrinth weir approach. An economic analysis is suggested by the Crookston [2010], and determination of critical site-specific criteria must be determined and accounted for in the design selection. It is possible to do an economic analysis of a weir once the design is implemented and known that the design does achieve the expected hydraulic efficiency, but the method implies developing individual solutions. The method along with the analysis (hydraulic and economic) is presented in Figure 3-12. It is clear that to optimize the design of an arced labyrinth weir, the economic analysis should be an integrated part of the design procedure instead of an individual task for a single solution. With the perception of an integrated approach instead of single solution with individual tasks, a new geometric design optimization scheme was developed for arced labyrinth weirs.

Figure 3-13 shows a selected example of an arced labyrinth weir that includes the foundation of the structure. As will be discussed later, the foundation of the structure is an important part of the economic analysis and design for an arced labyrinth weir; thus it is essential to maintain this mindset when considering an arced labyrinth weir design.

Note that the design method used by Crookston [2010] fixes the following parameters: internal angle, number of cycles, and the apron length. The purpose of this design approach is to constrain the design to known parameters. The cost of using this type of approach is that it limits the design of the arced weir to previous small-scale studies. A parameter that is known to the designer is the width of the channel where the construction of the weir is to be set. The methodology proposed by Crookston [2010] does not have the ability to set the width of the channel; thus this becomes a dependent variable of the number of cycles selected by the user. It is this author's opinion that it is important to control the channel width parameter and from there begin the plan and design of the geometric layout of the weir.

The geometric design optimization scheme presented herein consist of the utilization of a minimum of hydraulic parameters and, in a computer program, vary key geometric parameters and present the minimum cost solutions that could pass the expected flood event. Contrary to other designs, the approach is self-iterating instead of direct solutions and equations are solved in a specific order. The variation of cycle arc angle, radius, and internal angle seem to be effective when obtaining the widest range of possible solutions for the design. The proposed process flow is described in Figure 3-14. The procedure takes into consideration the width of the channel to incorporate the possible design that will fit this area, thus eliminating the need for a re-design of the geometry and eliminating the need to fix the number of cycles.

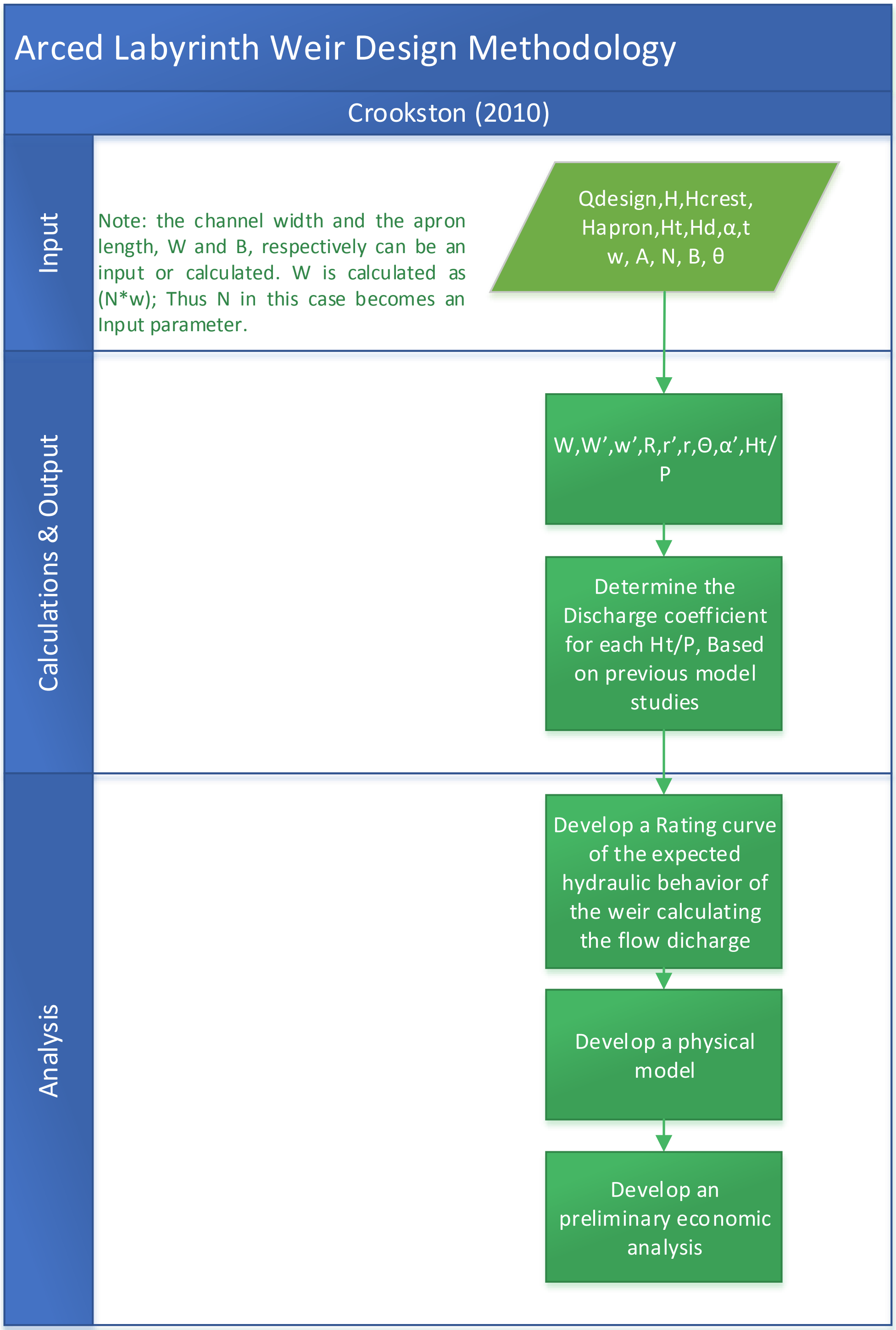

Figure 3-12. Arced labyrinth weir design methodology based on the methodology suggested by Crookston [2010].

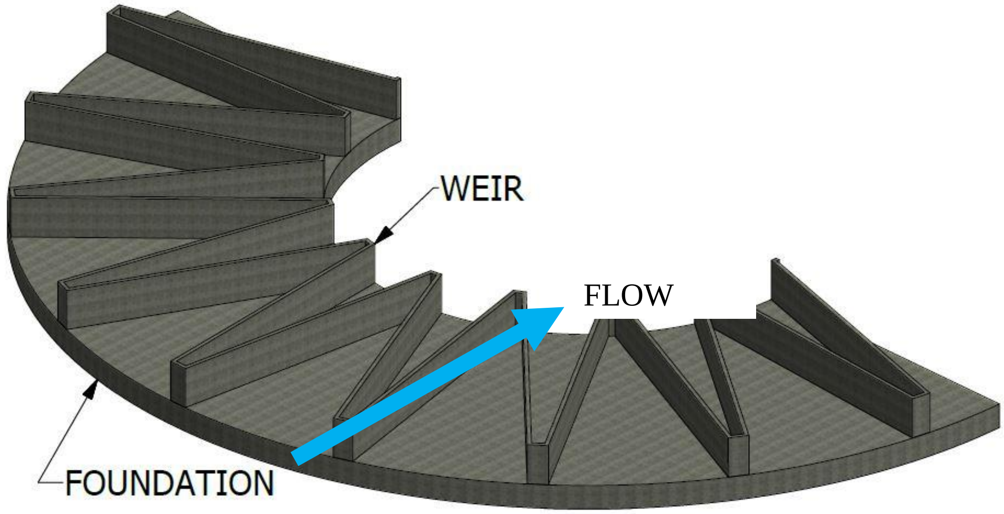

Figure 3-13. Arced labyrinth weir with expected foundation representation.

Contrary to other designs, the approach is self-iterating instead of direct solutions and equations are solved in a specific order. The variation of cycle arc angle, radius, and internal angle seem to be effective when obtaining the widest range of possible solutions for the design. The proposed process flow is described in Figure 3-14. The procedure takes into consideration the width of the channel to incorporate the possible design that will fit this area, thus eliminating the need for a re-design of the geometry and eliminating the need to fix the number of cycles. The program incorporates the general idea suggested by Falvey (2003) and later by Crookston and Tullis (2013) for labyrinth weirs which consists of the interpolation of discharge coefficient curves based on current existing data. Previous to the interpolation of values Tullis et al. (1995) reasoned that since the discharge coefficient for linear labyrinth weirs did not vary significantly for small changes in α the same equations for the discharge coefficient developed empirically could be used. In this case the coefficients for the discharge coefficient curves are interpolated between three non-homogenous variables, namely cycle number (N), internal wall angle (α), and cycle arc angle (θ) to provide an interpolated curve for the discharge coefficients. The workflow integrates a preliminary cost estimate of the structure in the decision of optimum weir geometric design based on economy and hydraulic performance. The integration of a cost analysis during the calculation phase is a key part of the determination of the optimum weir design in which it is possible to determine the value of each geometric design. The design approach can result in an overdesign of a spillway structure, thus sound engineering judgment should be undertaken when considering a solution.

Christensen [2012] further studied the hydraulic behavior and expanded the discharge coefficient curves for the arced labyrinth weirs by studying different geometries (Table 3-3) thus following the work initialized by Crookston [2010]. With the new geometries, a new equation to describe the discharge coefficient was developed for the curves, and new trend line coefficients were introduced. The information, although valuable, is not going to be used as presented by Christensen [2012], and the data were formatted using a polynomial fit as presented by Crookston [2010] and Tullis et al. [1995]. These small scale models presented by Christensen [2012] expand the hydraulic behavior knowledge of arced labyrinth weirs, thus providing valuable information in the study of the behavior of these type of spillway structures.

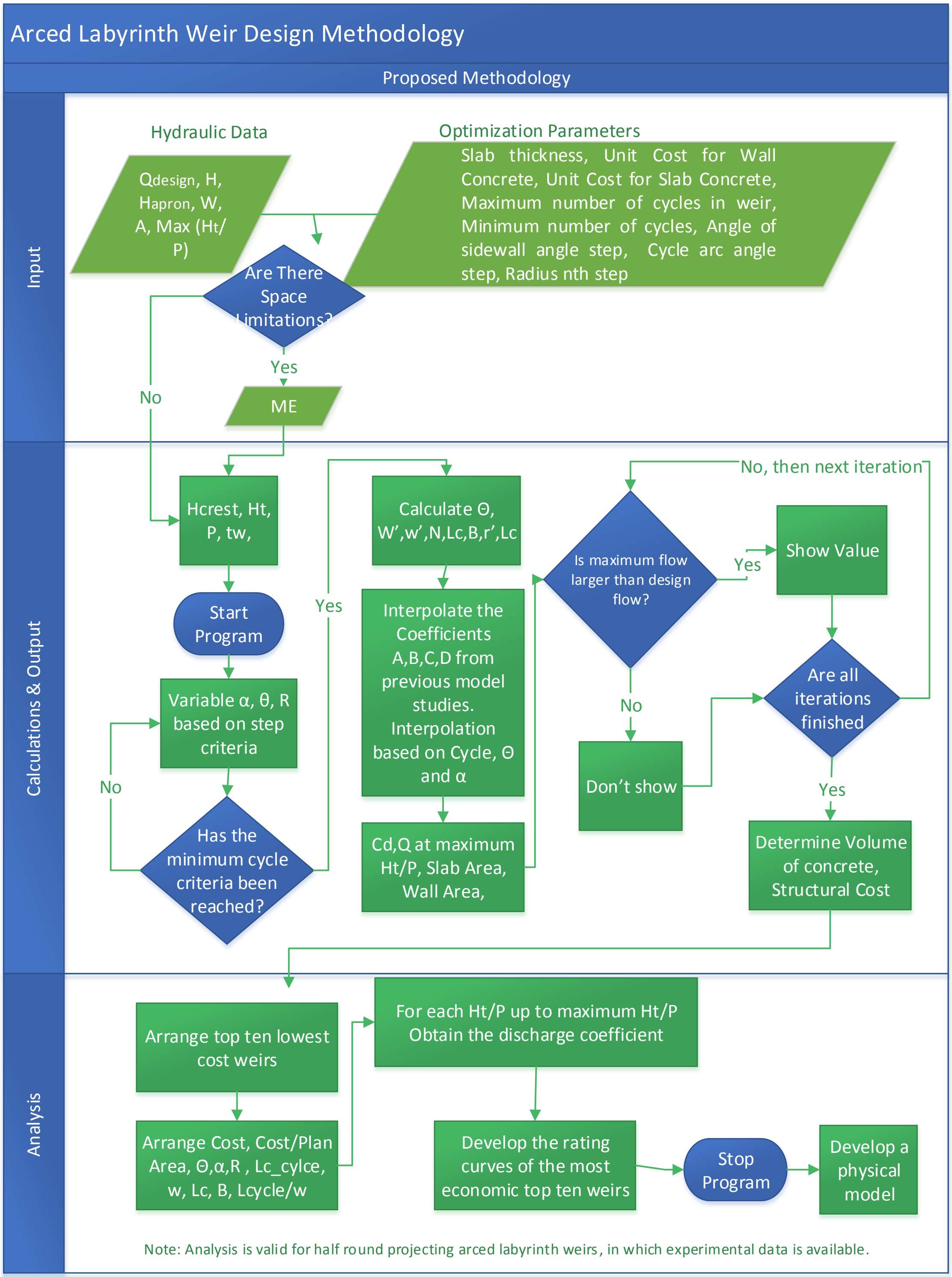

Figure 3-14. Arced labyrinth weir design proposed work flow.

Table 3-3. List of models in US units (*inches*) tested by (Christensen 2012).

Model	α	θ	P	$L_{c\text{-}cycle}$	$L_{c\text{-}cycle}/w$	w/P	N	Orientation
1	12	10	8	63.45	3.951	2.008	10	Arced & Projecting
2	12	10	8	63.45	3.951	2.008	7	Arced & Projecting
3	12	20	8	63.45	3.951	2.008	5	Arced & Projecting
4	12	10	8	63.45	3.951	2.008	5	Arced & Projecting
5	20	10	8	40.41	2.516	2.008	10	Arced & Projecting
6	20	30	8	40.41	2.516	2.008	5	Arced & Projecting
7	20	20	8	40.41	2.516	2.008	5	Arced & Projecting
8	20	10	8	40.41	2.516	2.008	5	Arced & Projecting
9	20	0	8	40.41	2.516	2.008	5	Projecting
10	20	0	8	40.41	2.516	2.008	5	Flush
11	20	0	8	40.41	2.516	2.008	5	Rounded Inlet

Note: N is the number of cycles and $L_{c\text{-}cycle}$ is the centerline length for a single labyrinth weir cycle.

3.3 Value Engineering

3.3.1 *Value Engineering Methodology*

Value engineering (VE) as a concept has its roots in what was initially conceived as Value Analysis (VA). The concept was developed by Lawrence Miles in 1945, and the technique supported cost reduction activities by relating the value of a solution to the cost component of the function contributions [Crow 2002]. The relationship is defined by equation 3-1 :

$$\boldsymbol{Value = \frac{Function}{Cost}} \qquad \textbf{3-1}$$

The relationship described in equation 3-1 is not only about reducing the cost but getting a high level of performance in relation to a low cost; thus the approach itself is not to obtain the analytical minimum of a solution, but which solution performs better given a set of parameters relative to its cost. To obtain a solution in terms of a value index as suggested by equation 3-1, it is necessary to compare a designated range of solutions between each other to obtain the highest value coefficients among the lowest cost solutions. Cariaga et al. [2007] in their approach method for evaluating design alternatives, explain the Data Envelopment Analysis (DEA) process to optimize the owner's decision. This method estimates the efficiency of the value component of equation 3-1 and is only able to assess how an alternative structure performs in comparison to its peers and not against an analytical optimum solution. In a value analysis process is a series of phases that must occur in order to obtain an optimum solution that are presented in Figure 3-15 .

From Figure 3-15 and further explained by Crow [2002], it is certain that the first step of a value engineering process is to define the problem and its scope. After this, the function of the products components are appointed. A cost function matrix is created, and the components are rated in terms of the cost provided by its function. This type of approach is done to focus the analyst on the contribution in function of each component.

The Function Analysis System Technique (FAST), developed by Charles W. Bytheway in 1964, is a process that allows individuals from diverse backgrounds to analyze the problem and obtain a solution based on a group-type approach. It is used to decompose a basic function and organize it into a logic diagram called the FAST model.

PRE STUDY
User/Customer Attitudes Complete Data File Evaluation Factors Study Scope Data Models
VALUE STUDY
Information Phase Complete Data Package Finalize Scope ***Function Analysis Phase*** Identify Functions Classify Functions Function Models Establish Function Worth Cost Functions Establish Value Index Select Functions for Study ***Creative Phase*** Create Quantity of Ideas by Functions ***Evaluation Phase*** Rank and Rate Alternative Ideas Select Ideas for Development ***Development Phase*** Benefit Analysis Technical Data Package Implementation Plan Final Proposals ***Presentation Phase*** Oral Presentation Written Report Obtain Commitments for Implementation
POST-STUDY
Complete Changes Implement Changes Monitor Status

Figure 3-15. Value methodology Job Plan as presented by Wixson [1999].

One important contribution of FAST is its synergistic way of developing, decomposing, and analyzing the functions of any component [Wixson 1999].

The process as a whole for a VE workshop includes the following steps [Cullen 2010].

- Information
- Speculation
- Analysis

- Development
- Presentation Phases

The information phase gives the background information about the owner's definition of value, the end product, and the decisions that have influenced the current design. During the speculation phase, the team brainstorms possible ideas to provide the necessary function. All possible design alternatives have an equal chance of being pursued at this time. In the evaluation phase, the VE team, client, and others define the criteria for the evaluation of each possible solution, and ideas that seem impractical are discarded. It is in the development phase that the ideas are worked into feasible solutions; this is done by describing any change in design and evaluating advantages and concerns about the projected design alterations. The outcome of the workshop is compiled as a written report and is presented to the owner or client. The report gathers the ideas and reasoning that influenced the decision.

3.3.2 *Value Engineering in the Construction Industry*

Part of value engineering involvement in the construction industry is based on the design or redesign phase. In the design phase, a VA can be done when the design is at least a schematic drawing; most government agencies require at least one version of value engineering session on projects over a certain amount [Cullen 2010]. The U.S. Army Corps of Engineers [2005] states in its guidelines that it is required that this agency uses a VE management tool and applications to reduce acquisition costs on projects over $1,000,000. For civil works projects like the one proposed in this document, the development or arced labyrinth weirs, "*VE studies shall not be waived for any project over $10,000,000 construction cost*" [U.S. Army Corps of Engineers 2005]. In this case, the agency conducts a workshop or study that follows the VE Job plan format as describes by ASTM and the Society of American Value Engineers (SAVE) International standards.

It is the construction sector that the applications of VE principles is an area of opportunity since designers spend years developing designs and drawings without fully understanding the construction methods, or following out-of-date codes and not utilizing the computational capacity at his or her disposal and can submit designs with embellished factors of safety. On the other side, the contractors builds without taking into account the design principles involved (Papazian Bedian 2002).

In the construction industry, the VE principles have been used for the solution of design problems. Papazian Bedian [2002] used value engineering principles to solve problems in the geotechnical area. For that case, the original design required shafts to get to a sound rock; instead of drilling, she proposed that the material had enough side friction and end-bearing resistance to support the structure. The principles have also been applied to the analysis of low-volume road bridge selection and was studied by GangaRao et al. [1989]. Different scenarios were identified and evaluated using VE principles. The method included a systematic investigation of all the bridge components and followed the described VE job plan. Bridge systems were evaluated in Egypt by Basha and Gab-Allah[1991]. During the evaluation phase, the team developed an evaluation criteria and ranked the structures, thus following the VE approach methodology. The solutions were applied to a bridge at the airport of Cairo. For marine construction, Tang and Bittner [2014] developed a seven (7) step method in which they take into account the VE principles. The method is used to identify solutions and satisfy the needs for construction cost reduction. Marine construction has unique challenges that are not targeted directly, and solutions require a wide range of technical knowledge as well as creativity. The methodology defines how to measure the performance of a solution and the restrictions that will be fulfilled by applying the solution. The methodology is divided into the following steps.

1. Gather information
2. Analyze functions
3. Generate solutions
4. Evaluate solutions
5. Select and prepare solutions
6. Present solutions
7. Monitor the solution-execution process

In the hydraulic industry, the value engineering principles have been applied to water distribution systems by Li & Liu [2006]. It is in this case study that the authors developed a quantitative model to evaluate the water distribution system similar to equation 3-1. The difference in the method is that the value of the solution is calculated based on the sum of the functions and costs thus normalizing the function and cost parameters. This is done since the function of the networks is a function of four (4) variables that have a linear relationship. The method was used in Suzhou, China and it is the proposed method of VE analysis of this author.

In all discussed projects, the common denominator is a sound knowledge of engineering principles with an open reasoning method that ends up saving the owner money.

4 METHODOLOGY

The geometric design procedure presented in this thesis has been developed to include a minimum set of parametric constraints into the problem formulation. It was developed with a dam rehabilitation mindset, in which the expected hydraulic conditions are maintained constant. The procedure is based on current physical model studies which analyze the hydraulic behavior of arced labyrinth weirs. The final results presented by the optimization scheme will be based on the expected reservoir hydraulic conditions that will cause the highest pool levels and not for the normal or daily interaction between reservoir and the arced labyrinth weir spillway. Finally to pass the expected dam outflow conditions the construction of an arced labyrinth emergency or secondary spillway needs to be analyzed in terms of cost efficiency.

The calculations of the minimum cost of all possible solutions will be performed using a Monte Carlo simulation procedure. This type of approach is used to estimate a solution based on the input of random variables. The constraints-based optimization problems are described by eight different independent variables that affect the cost directly and by one constraint that affects the performance and from these eight, seven can be used for this procedure as independent variables, but only five will be varied for this proposed method. In total the three variables that will not be changed are the wall thickness, slab thickness and apex width. A successful solution is one that can be found in the domain where the constraint inequality is satisfied. This inequality is in the form of equation 4-1, where Q_{max}

is the maximum flow expected and $Q_{Ht/p}$ is the expected flow of a weir from a specific design or in terms of this VE approach denominated the function from equation 3-1.

$$Q_{Ht/_P} \geq Q_{max} \quad \textbf{4-1}$$

where:

$$\boldsymbol{Q_{Ht/_P} = Function} = \left(\frac{Ht}{P}, w, R, A, \alpha, \theta\right) \quad \textbf{4-2}$$

The arced labyrinth weir is conditioned to the following constraints:

Table 4-1 Contraints of the hydraulic behavior for an arced lbyrinth weir

Variable	Range
$\frac{H_t}{P}$	0 - 0.5
W	Based on location
R	W/2
A	2 ft – 4 ft
α	6°-32°
θ	10° or 20° or 30°

The proposed methodology cost analysis will be based on a similar procedure developed by Li & Liu [2006] in which they used the VE principles to analyze the cost and function of their solutions. To develop the subject so that a VE job plan can be conducted while taking into consideration the arced labyrinth weir design the author will focus on the initial phases of the VE methodology up to the analysis phase of the solution. Only when all solutions are accounted for then and only then should a team evaluate possible solutions with a unique fully developed rating system. Further steps above the analysis phase cannot be continued since the author recognizes that a multi-discipline approach is needed to evaluate specific cases. Specific case solutions are dependent on location, availability of materials, risk of dam failure, and specific rating curve and dam criteria, which should be evaluated in a VE workshop. The purpose is to determine the value of arced labyrinth weirs so they can be compared to other wider known solutions. A final selection of one specific weir structure will not be done; thus a life cost analysis of the weir can be done analytically but is not part of the VE process in which this analysis will focus, since it includes a selection of specific weir for a specific case.

The procedure will focus on the following aspects.

1. Informing about the possibility of using arced labyrinth weirs
2. Speculation: In this phase all the solutions for arced labyrinth weirs will be analyzed each with an equal opportunity of being selected
3. Analysis: The phase of analysis is where the value engineering process will incorporate a procedure similar to Li & Liu [2006] in which the value of the solution is measured by equation 3-1.

Developing a solution for a VE analysis phase occurs in the speculation phase, which using current design methodologies would be extensive and that is why a new geometric optimization scheme is needed to be implemented. After the implementation of the design scheme approach, a detailed cost estimate will evaluate the cost of each solution, while the performance is evaluated by the expected outflow. The process of obtaining solutions is an iterative procedure, thus the VE approach of data envelopment analysis (DEA) is used to find an acceptable solution. The limitations of DEA is that it is a nonparametric linear programming framework (Cariaga et al. 2007). By understanding that the behavior of the objective function is nonlinear, a Monte Carlo simulation methodology needs to be used to solve for solutions, thus creating a region where solutions exist and where function and cost can be evaluated to obtain the value of the solution. The objective function has the form of

$$\boldsymbol{Cost} = f\left(\frac{Ht}{P}, w, R, A, \alpha, \theta, t_w, Slab_{th}\right) \quad \textbf{4-3}$$

where:

$\frac{Ht}{P}$	Headwater ratio
w	Total centerline length of labyrinth weir
R	Arc radius for an arced labyrinth weir
A	Apex width
α	Arc radius for an arced labyrinth weir
θ	Cycle arc angle for an arced labyrinth weir
t_w	Spillway wall thickness
$Slab_{th}$	Spillway foundation thickness.

The objective function is conditioned to the following constraints:

Table 4-2 Objective function constraints

Variable	Range
$\frac{H_t}{P}$	0 - 0.5
W	Based on location
R	W/2
A	2 ft – 4 ft
α	6°-32°
θ	10° or 20° or 30°
t_w	P/8 or based on location
$Slab_{th}$	Based on location

Variables which are constrained by site specific criteria are independent variables throughout the analysis process. The channel width W can be constrained by the limitations of a previously constructed spillway where because of space limitations the solutions need to be delimited to a certain space. Another space limitations would be were the proposed auxiliary spillway is to be constructed next to a mountainous terrain where cut and fill could be excessive thus for cost considerations area limitations are expected. Slab and wall thickness are considered site specific constraints since soil bearing capacity, overturning, sliding, structural integrity and global stability are need to be addressed as part of the structural and geotechnical assessment of the structure.

A Monte Carlo simulation-based approach supersedes linear programming for this case since the number of variables is excessive and variables behave nonlinearly and discontinuously. Given the complexity of a possible analytical solution, it is possible using a Monte Carlo simulation to estimate a solution using a quantitative approach and later comparing all solutions based not only on performance but also in terms of cost. It is the comparison based on cost that will guarantee a minimum value coefficient thus becoming the key factor in the selection of a solution, if a solution exists. Figure 4-1 presents the flowchart of the proposed approach method for the cost optimization in the cost procedure.

Monte Carlo simulations begin with minimum value α, θ and R. These values are changed throughout the procedure at a discrete increment set by the user, increments would depend on parameters. For example α, θ can be changed at intervals ranging from 1 to 5 degrees while the radius (R) will be a fraction of the channel width. As these geometric parameters are changed each of the dependent variables are calculated to obtain expected hydraulic conditions and estimated spillway structure construction cost. Spillways which do not satisfy expected hydraulic conditions are not included into the analysis, and are filtered during the process, thus only allowing the region where acceptable solution do exist. To control the sensibility of how the simulations were developed, H_T/P ratios as well as the channel width, were not included as continuous changing parameters for this methodology, thus giving a user a better understanding of the behavior and trends during the process of the geometric design of an arced labyrinth weir. These parameters need to be changed manually and the program re-runned in order to have a better control of the output solutions.

The method of applying a Monte Carlo simulation is not new, but, to the author's knowledge, the application of this technique for the selection of a weir has not yet been implemented. It is important to note that, to obtain a solution, an iterative approach has to be developed that accounts for how each parameter and variable affect the final cost of the structure. The proposed project emphasizes the changing of five different variables using a systematic approach inside a macro-enabled spreadsheet that analyzes the cost and performance criteria of the proposed structure to obtain the minimum cost solutions and analyze them in terms of value.

The accuracy of the expected hydraulic discharge is based on physical model studies carried out by Christensen [2012] and Crookston [2010]. The calculated values of discharge coefficients at different headwater ratios experienced on scale models are a key factor when obtaining an expected hydraulic behavior calculated by this procedure.

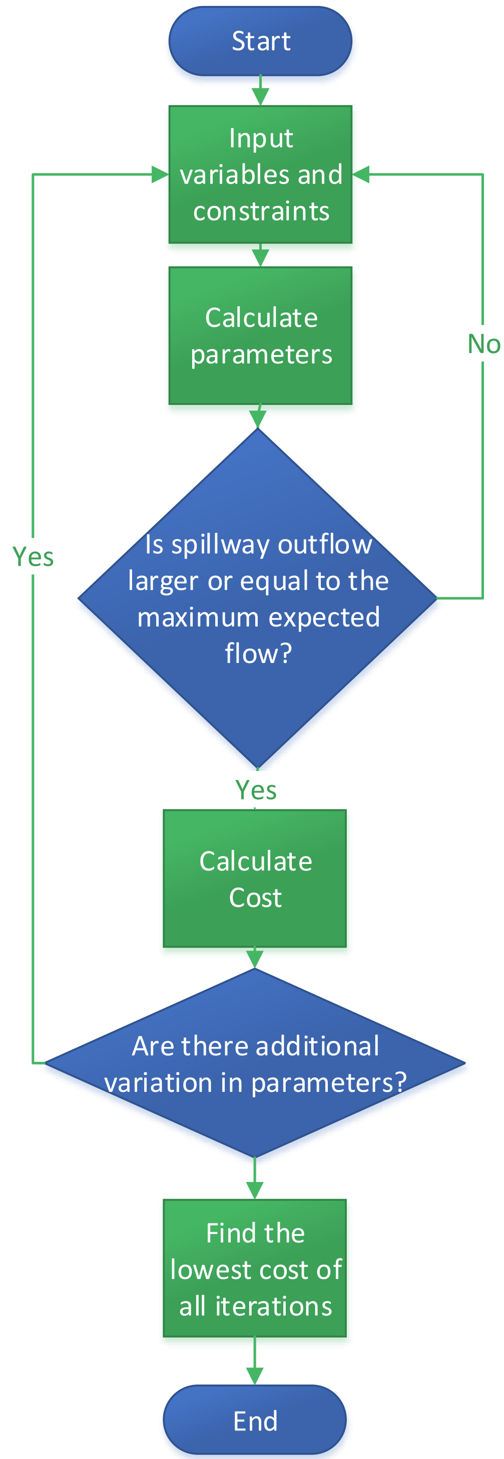

Figure 4-1 Flowchart of the optimization procedure using Monte Carlo simulation for the determination of minimum cost of structure

4.1 Value Engineering Process Implementation

With present arced labyrinth weir design methods, excessive time consuming iterations and man power are required to reach to an acceptable solution that would not necessarily be a minimum cost solution; thus this new proposed iterative approach along with its economic and value analysis aims to be considered a tool to evaluate possible solutions in terms of value for auxiliary spillway designs. Later sections of this chapter will explain a new approach that must be overtaken to achieve such solutions so a value engineering process can occur. The presented process of a new design procedure will outline the first steps in the speculation phase of the value engineering process. By obtaining enough solutions, the team or designers can evaluate all or the lowest cost solutions that will result in a high or acceptable value solution. Acceptable solutions are solutions that exist in the region where constraints are satisfied and given by evaluating the objective function. Figure 4-2 presents an idealized region where solutions of the objective function are found, performance criteria have been set, and regions of acceptable and non-acceptable solutions co-exist. The solutions are part of the speculation phase where all solutions are gathered and impractical solutions are discarded later. Impractical solutions are solutions that do not comply with the required discharge performance of the spillway to mitigate the potential flooding risk. The two areas are separated by the simple analysis of equation 4-1.

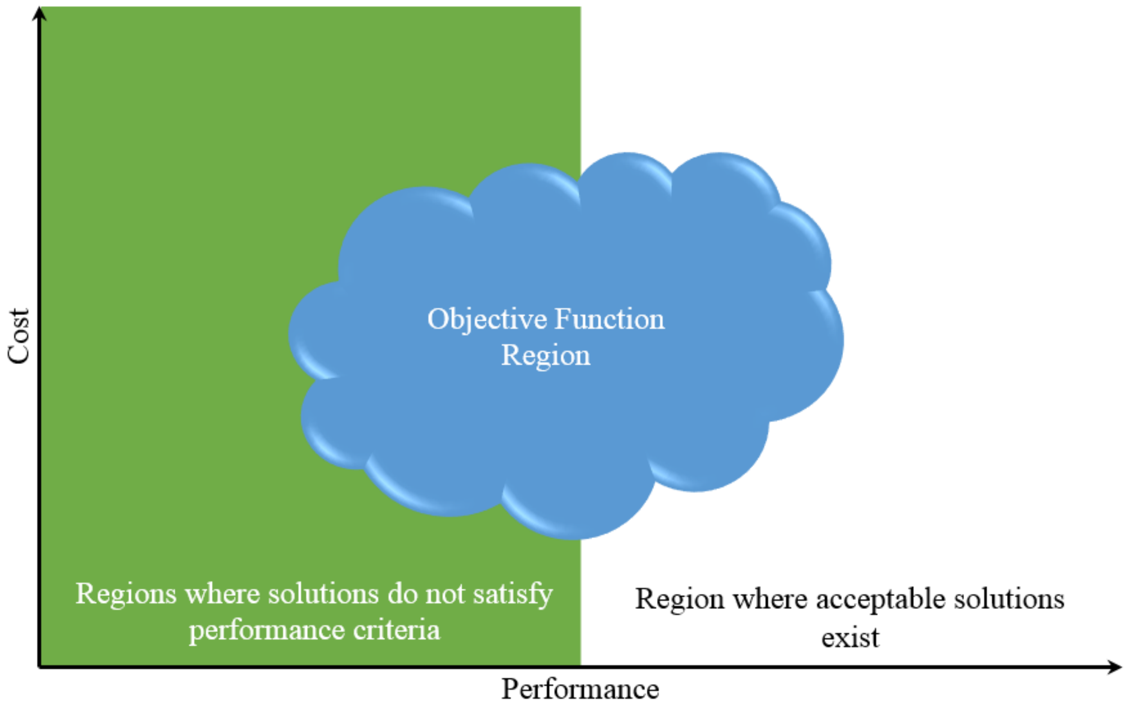

Figure 4-2 Example of Region bounded by the objective function

4.1.1 *Influence of variables in the objective function*

The region bounded by the objective function is a function that depends on a set of eight (8) different variables. To obtain a variety of solutions, these variables have to be analyzed between a specified set of constraints which for this procedure seven will be evaluated, and five will be predominantly changed. Figure 4-3 expresses the region of the objective function as a function of each variable. The contributions of each variable are not proportional to the circle, but as the variables keep changing, the region of the objective function becomes larger; thus these would be available possible solutions during the early stages of the analysis. The apex width will be kept as a constant based on constructability issues that may arise during construction, thus a list of seven independent variables can be considered for this geometric optimization scheme.

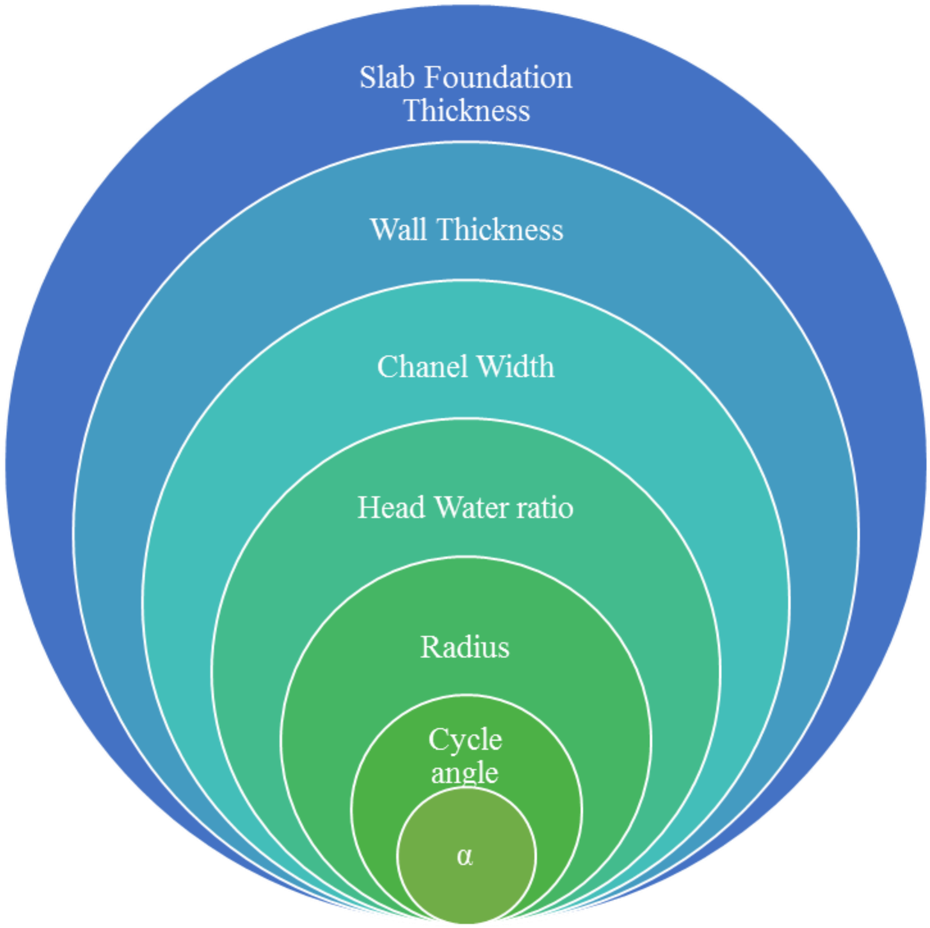

Figure 4-3 Influence of each variable to the objective function region based on the proposed procedure.

The relationship of these variables between performance and cost is presented in Figure 4-4. The variables shown are based on a new approach to the design procedure that aids in the development of faster solutions compared to previous design procedures. The proposed geometric design optimization tool is developed so that the value engineering methods can be applied to the solution. In past methods, solutions were evaluated based on the engineer's judgment while, with this tool, the team evaluating the solutions can evaluate arced labyrinth spillways between each other and later compare the arced labyrinth weir solution to other types of spillway structures. A variable that will remain unchanged will be the apex. This parameter will remain unchanged because further hydraulic studies should determine how the discharge coefficient will behave in terms of changes in this parameter as well as flow directionality which will impact the cycle efficiency. These studies have to be analyzed using a physical model and numerical analysis. Upon further inspection of the influence of this parameter, the rating curves for specific weirs need to be developed as well as the hydraulic coefficients that will describe the behavior of the curve.

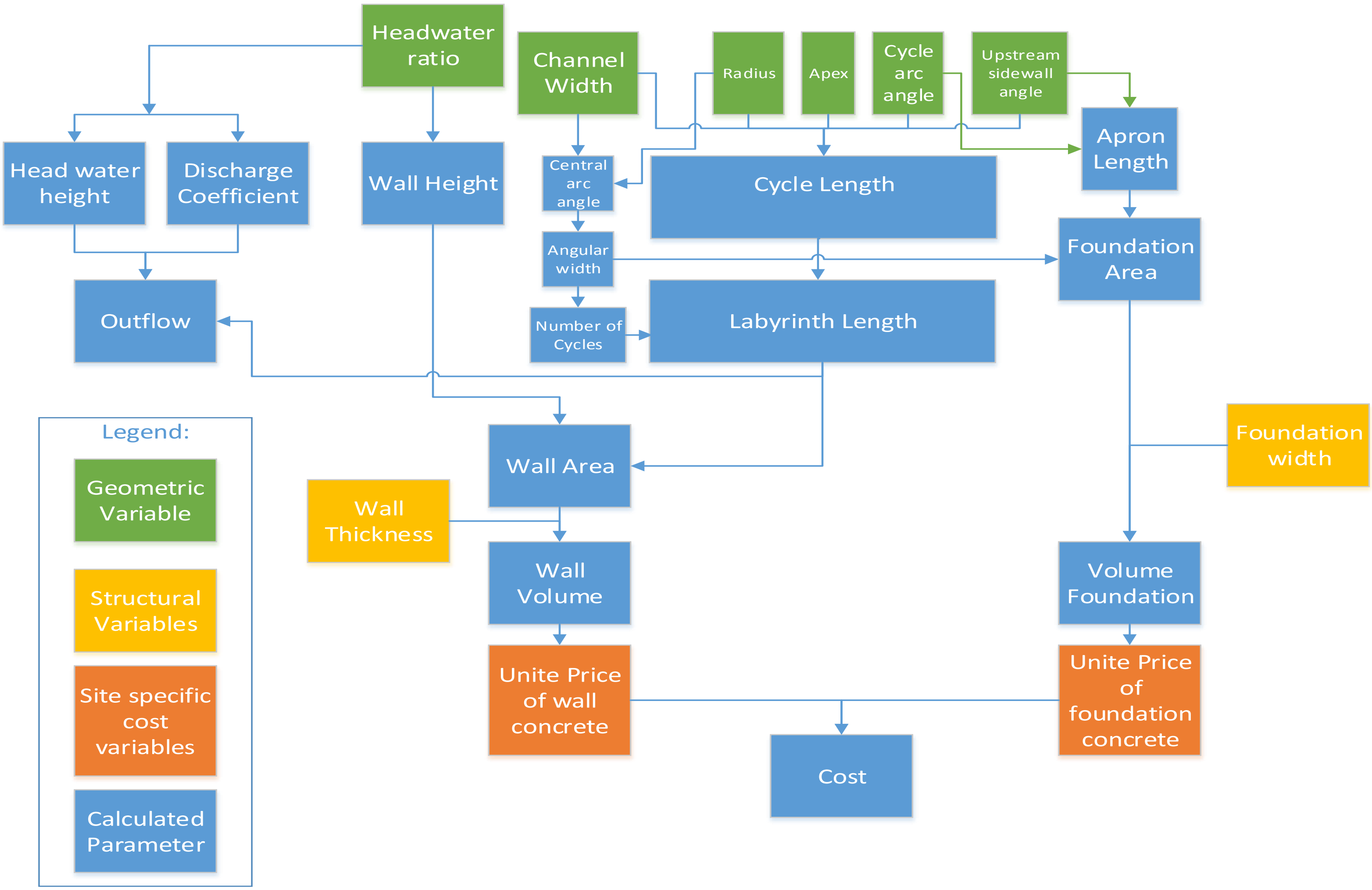

Figure 4-4 Objective function variables relationship to cost and discharge outflow.

4.2 Arced Labyrinth Spillway Design Methodology, Assumptions, and Constraints

The creation of arced labyrinth spillway design is accomplished by means of a proposed optimization program based on a combination of VBA programming language and Microsoft Excel cell formulation. Limited hydraulic data for arced labyrinth weirs are available, thus the design will be limited to the range of available scale model data. Geometric designs will have the following constrains.

Table 4-3. Geometric parameter constraints.

Parameter		Range
N	Number of cycles	5 to 10
θ	Cycle arc angle	10^{o} to 30°
α	Upstream sidewall angle	6^{o} to 20°

Geometric constraint ranges are based on current physical model information. Table 4-4 and Table 4-6 contain the trend line coefficients for the discharge coefficients developed by physical model studies. The spreadsheet based tool is designed in a way that future information regarding the coefficients to determine the discharge coefficients as well as any change in range constraints can be added and change internal parameters to the user's desire. These changes ensure that future developed data can be used with the proposed geometric design tool; thus future scale models would be compared against in terms of hydraulic efficiency and analyzed for economic feasibility of the designs against other geometric designs.

The program is intended for use after an inspection and review of a dam structure determines that a spillway capacity is not sufficient to pass the design flood flow. The risk assessment inspection must be accompanied by a detailed hydraulic analysis of the dam and the careful measurement of the dam and spillways dimensions as well as adjacent areas that could sustain the development of an auxiliary spillway. After a hydraulic analysis is set, the design flow (Q_{design}) and the hydraulic parameters for the design flow water surface elevation (H) are determined. Dimensions of the dam including the height, current spillway width (W), and the approach channel elevation (H_{apron}) need to be obtained for any design. This design approach utilizes the previous mentioned parameters (Q_{design}, H, W, and H_{apron}) as the only in-situ conditions/factors required to commence the design of an arced labyrinth spillway. In this optimization method, it is up to the designer to specify the area constrains, if any, for spillway placement limitation purposes. The space limitation is defined by the maximum length perpendicular to the channel where the arced labyrinth spillway must be contained. If the spillway designer does not have a space limitation this benefits the design as a greater amount of geometric designs can be developed.

Although the height of the dam is not used during the spillway design, it is necessary to understand if the current dam height will accommodate the design flow water surface elevation, and if needed, propose a change in height of the dam. For this design approach, the wall height (H_{crest}) is calculated by equation 4-4, which is based on the maximum height of water anticipated during a flood event and the selection of the expected water height ratio above the weir wall (H_T/P). The determination of this ratio is based on the designers' safety concerns, economic analysis of the structure, and approach velocity. This author suggests a headwater ratio range from 0.1 to 0.5. This head water ratio range was chosen for the following reasons.

- No data exist for H_T/P values above 0.5 for the 10 cycle/ θ=12/ α=10 and the 7 cycle/ θ=12/ α=10 weirs.
- Hay and Taylor [1970] disregard the use of submerged weirs while Crookston [2010] found that, at $H_T/P \geq 0.5$, submergence effects take over, and the control starts shifting downstream which greatly limits the weir efficiency.

The head above the spillway will determine the velocity of the outflow that will have implications on sediment transportation of the system, potential scour in the downstream area, and trash buildup. The spillway design manages the overflow of the maximum expected spillover level during a flood event and may or may not carry the outflow for normal water situations and everyday use based on pool level.

$$\boldsymbol{H_{crest}} = \frac{H + (\frac{H_T}{P} * H_{apron})}{1 + \frac{H_T}{P}} \qquad \textbf{4-4}$$

where:

H_{crest} Wall height based from the datum

H	Design flow water surface elevation expressed from the datum also expressed as the expected total height of the outflow at flood events in terms of total head influenced by the velocity head and depth of flow on top of the weir
$(V^2/2g)$	Velocity head
h	Depth of flow on top of the weir
H_T/P	Headwater ratio
H_T	Total head that is a function of the static head and the kinetic energy head due to the velocity of water as expressed in equation 4-5, this distance is measured from the top of the weir crest.
P	Weir height measured from $H_{apron.}$
H_{apron}	Approach channel elevation expressed as the height relative to a datum.

$$\boldsymbol{H_T} = h + \frac{V^2}{2g} \tag{4-5}$$

The above mentioned parameter placement can be analyzed in Figure 4-5.

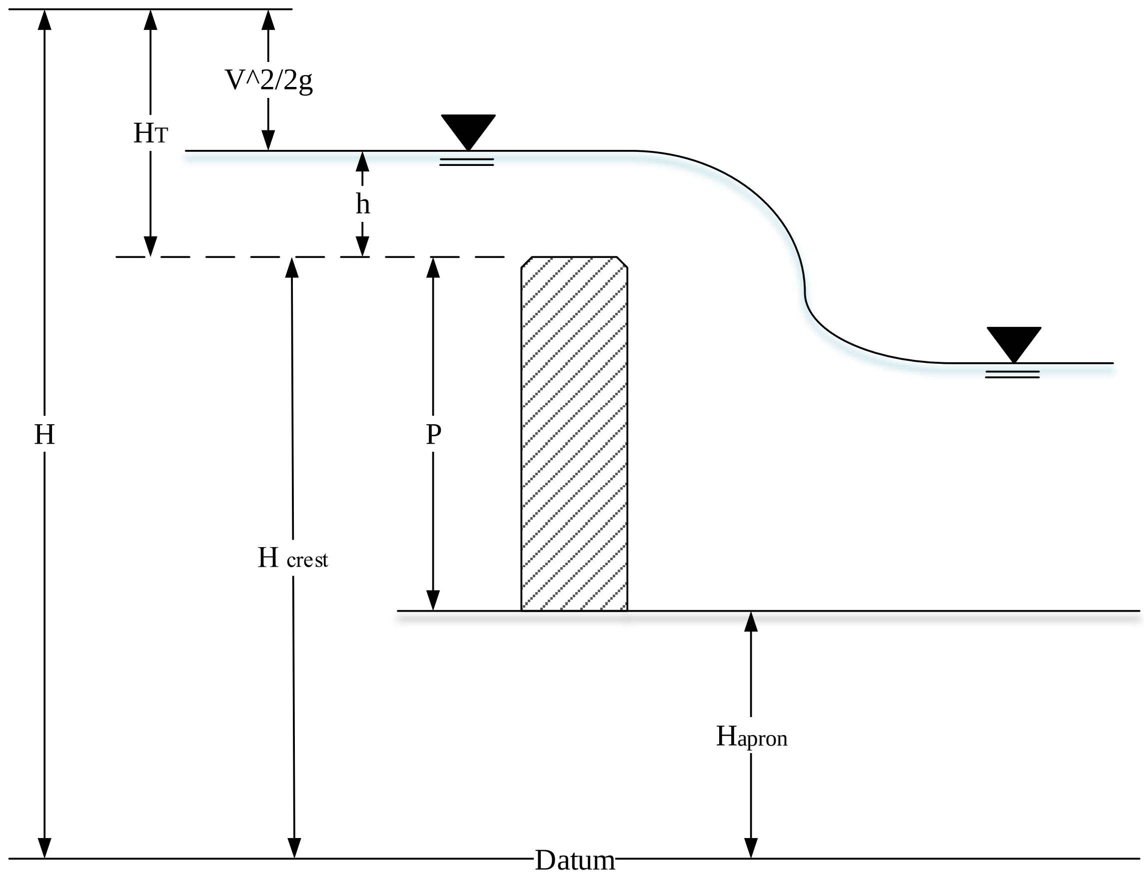

Figure 4-5 Upstream head parameters

The hydraulic data for arced labyrinth weirs are based on the discharge coefficients and headwater ratio curves compiled by Crookston [2010] and Christensen [2012]. The discharge coefficient as expressed by Lux [1989] is dependent on a wide range of parameters presented in equation 4-6, where D is the downstream wall height chosen by Lux [1989], in which for this design, the wall height is constant. P is the upstream wall height, which, as mentioned earlier, is assumed constant. S_c is a parameter defining the labyrinth weir crest shape while H_o is the total head and H_d is the downstream head.

$$\boldsymbol{Cd} = \left(\frac{L_c}{w}, \frac{\alpha}{w}, \frac{w}{P}, \frac{D}{P}, \frac{t_w}{P}, S_c, \frac{H_0}{P}, \frac{H_d}{D}\right) \qquad \textbf{4-6}$$

Crookston [2010] presents the calculation of the discharge coefficient based on four parameters (A, B, C, D) presented in

Table 4-4, which fit the polynomial regression in equation 4-7.

$$\boldsymbol{Cd} = A * \left(\frac{H_T}{P}\right)^3 + B * \left(\frac{H_T}{P}\right)^2 + C * \left(\frac{H_T}{P}\right) + D \qquad \textbf{4-7}$$

Table 4-4. Selected program trend lines coefficients based on Crookston [2010].

CYCLE	θ (º)	α (º)	A	B	C	D
5	10	6	-3.2392	5.709	-3.9526	1.1798
5	20	6	-3.3019	5.9622	-3.9526	1.1798
5	30	6	-4.193	7.3673	-4.6092	1.2327
5	10	12	1.21107	-1.0806	-0.4449	0.8128
5	20	12	1.4404	-1.3929	-0.4088	0.8606
5	30	12	1.5198	-1.3712	-0.5984	0.9124

This equation works better when there are adequate model data to fit the curve. Constraints of this equation are encountered when using the polynomial fit, from a specific physical model parameters and headwater ratios that exceed the maximum headwater ratio modeled. The polynomial fit is valid confidently when the maximum studied ratio is not exceeded, else the equation for the discharge coefficient may not be accurate. For the data presented by Christensen [2012] extrapolation of discharge coefficients using the proposed equation are not possible when trying to use the coefficient methodology proposed by Tullis et al. [1995].

Christensen [2012] presented the hydraulic data for the discharge coefficient as a function of four parameters, presented in Table 4-5, that fit equation 4-8.

$$\boldsymbol{Cd} = \frac{1}{a\left(\left(\frac{H_T}{P}\right) + b\right)^2 + c} + d\ \ln\left(\frac{H_T}{P}\right) \qquad \textbf{4-8}$$

The equation was prepared by the software LAB Fit® and was selected because of its high correlation with the experimental data. The usage of this equation could lead to potential extrapolations at higher H_T/P ratios thus increasing the spreadsheet-based tool's capabilities; however, equation 4-8 will not be used for the proposed geometric design optimization program calculations. Note that the coefficients are for the specific equation developed by Christensen [2012] and not for a polynomial fit methodology proposed by Tullis et al. [1995].

Table 4-5. Selected program trend line parameters based on Christensen [2012] for equation 4-8.

CYCLE	**θ (º)**	**α (º)**	**a**	**b**	**c**	**d**	**R^2**
10	10	12	2.4572	0.1127	0.7944	0.1872	0.9782
7	10	12	2.1314	0.1591	0.7328	0.2055	0.9956
5	20	12	2.0912	0.1214	0.6269	0.2918	0.9968
5	10	12	1.7196	0.2250	0.5141	0.3258	0.9982

10	10	20	1.9911	0.0794	0.8145	0.2085	0.9948
5	30	20	1.6622	0.1051	0.6522	0.3178	0.9977
5	20	20	1.1346	0.2869	0.5312	0.3312	0.9955
5	10	20	0.8835	0.507	0.447	0.2745	0.9852

The discharge coefficient solutions used for the Excel-based tool are based on the lineal regression and polynomial equation presented by Crookston [2010] and Tullis et al. [1995]. A linear regression, presented in Appendix A, was applied to the hydraulic data from the physical models presented by Christensen [2012]. After the extracted data were fitted using polynomial regression, the coefficients for the discharge coefficient were used with equation 4-7. The final data presented for the tool is tabulated in

Table 4-6. The maximum water head ratio, H_T/P, is set at 0.5 to avoid weir submergence, thus the flow of the spillway is calculated up to this value and then compared to the expected flood design flow.

Table 4-6. Trend line coefficients compilation.

Configuration			**Coefficients**			
Cycle	**θ (º)**	**α (º)**	**A**	**B**	**C**	**D**
5	10	6	-3.2392	5.709	-3.9526	1.1798
5	20	6	-3.3019	5.9622	-3.9526	1.1798
5	30	6	-4.193	7.3673	-4.6092	1.2327
5	10	12	1.21107	-1.0806	-0.4449	0.8128
5	20	12	1.4404	-1.3929	-0.4088	0.8606

5	30	12	1.5198	-1.3712	-0.5984	0.9124
5	10	20	1.4851	-2.2055	0.5674	0.6414
5	20	20	2.2401	-3.4167	1.1157	0.6033
5	30	20	2.7405	-4.2113	1.4155	0.5792
7	10	12	4.8391	-5.129	1.0487	0.6165
10	10	12	7.4326	-6.8233	1.354	0.606
10	10	20	11.705	-11.107	2.9109	0.4664

Based on Crookston [2010] finding the local submergence behavior and the downstream capacity can influence the discharge capacity of the arced labyrinth weir; thus it is important to verify that this factor is taken into consideration in the geometric design and hydraulic analysis.

To obtain the trend line coefficients for models that have not been physically tested, the tool uses a multivariate interpolation from selected data. The function is based on the XonGrid interpolation library function add-in integrated to Microsoft Excel, which was developed as a XonGrid project for SourceForge (web-based source code repository). The tool uses the Kriging method of interpolation in a 3D interpolation matrix to obtain the most probable interpolated value. The method interpolates values based on cycle number (N), θ, and finally α, to obtain the trend line coefficients. The non-homogeneity of the selected parameters is considered in the interpolated function and is explicitly defined; as a result, it can be scaled in the function. The data interpolations are validated when iterations coincide with the physical model characteristics at which point the calculated trend line coefficients are the same as the trend line coefficients of the physical models. Crookston [2010] suggests that linear interpolation for C_d is recommended for values that are not presented; this approach uses the interpolation of the coefficients A, B, C, and D for the behavior of the weir. This method makes it possible to go through various parameters and interpolate between similar weir designs.

Flow discharge analysis for arced labyrinth weirs is based on the general weir equation 4-9 that considers the discharge coefficient for half-round weirs. In equation 4-9, Q is the total outflow discharge for the weir, and C_d represents the discharge coefficient, which is a dimensionless coefficient based the flow characteristics and spillway geometric arrangement. L_c is the total centerline length of an arced labyrinth weir, g is the acceleration of gravity, and H_T is the total upstream head defined as ($V^2/2g + h$), where V is the average flow approach velocity and h is the piezometric head measured relative to the weir crest.

$$\boldsymbol{Q} = \left(\frac{2}{3}\right) C_d \, L_c \, \sqrt{2g} \, H_T^{3/2} \qquad \textbf{4-9}$$

Arced labyrinth weir geometric parameters set by the spillway designer include the maximum and minimum number of cycles, approach channel width, height of crest, apex width, and if needed a footprint limitation. The program will then only focus on a range of spillways in which the footprint area limitation is not exceeded if there exist such a limitation. Note that the delimitation of a specific area that the arced labyrinth weir is to be fit is specified by the designer in the input window area designated to the factor ME seen in Figure 4-6 which presents the complete input window of the program. This area factor highly limits the searches but is effective when area limitations are expected for the design footprint. The only hydraulic parameter that is set by the user is the expected outflow conditions, which are defined by hydrologic and hydraulic evaluation studies. Slab thickness is the only construction parameter defined by the user in this methodology since the thickness of the wall is calculated based on the height of the spillway. Wall thickness is based on the scale models studied by Wilmore [2004], where the ratio of weir where the thickness of the labyrinth weir was expressed as a function of the spillway as $P/t_w = 8$. For the economic analysis, the concrete for slab and wall are defined in the input menu. The cost per cubic yard of concrete gives the designer an idea of the initial costs of construction of the proposed structure and can be then compared to the construction costs of other spillway structures to ensure the financial feasibility of the structure. Further detailed cost analysis will need to be undertaken when a final design is selected, but an initial concrete cost per cubic yard allows the comparison of solutions presented by this procedure. The tool is based on a half-round crest weir. This type of weir crest is a more efficient shape when compared to flat or quarter-round crest weirs and was the crest type selected in previous physical model tests. The Apex width (A) parameter is a function of the thickness of the wall. The program is designed in a way that after the height and thickness are calculated, it provides to the designer 20 possible apex widths based on previously selected parameters.

The program's computational time for the analysis and solution calculation is proportional to the precision the user desires and, consequently, the amount of iterations processed. Following the constraints presented in Table 4-3 the spillway designer defines the increments of α, θ and R at which to do the iterations. The iterations are based on the step increments for the cycle arc angle for an arced labyrinth weir, the sidewall angle, and the radius of the cycle containing the weir. Recommendations on which numbers can be used for better precision are presented in the input window of the program.

PROJECT:			**DATE:**	
SITE			**AGENCY**	
FLOOD CRITERIA:			**BY:**	
Parameter	**Symbol**	**Value**	**Units**	**Source / Equations / Notes**
		Hydraulic Conditons - Input Data		
Units		-	-	
Design Flow	Q_{design}		(cfs)	Input
Design Flow Water Surface Elevation	H		(ft)	Input
Crest Elevation	H_{crest}		(ft)	Calculated Based on Maximum water height ratio-H-Hapron
Approach Channel Elevation	H_{apron}		(ft)	Input
Unsubmerged Total Upstream Head	H_T		(ft)	(Piesometric Head + Vel Head - Losses)
Width of Labyrinth Entrance (Normal to Flow)	W		(ft)	
Is there a Space Limitation				
Maximum Length for area limitation	ME		(ft)	Length of Middle oridnate+External distance<= of this value
Thickness of Weir Wall at Crest	t_w		(ft)	$t_w \approx P/8$
Inside Apex Width	A		(ft)	$tw \le A \le 2t_w$
Crest Shape	Crest Shape		-	Quarter or Half Round
Crest Height	P		(ft)	Set $P \sim 1.0H_T$
Maximum Water Height Ratio	Ht/P			Input (Maximum height wanted, Suggested 0.5 or Less)
Slab thickness	$Slab_{th}$		ft	
Unit Cost for Wall Concrete CUBIC YARDS	$\$_{wall}$		$/CuYds	Input(Include rebar, placement, mobilization, form, equipment)
Unit Cost fow Slab Concrete CUBIC YARDS	$\$_{slab}$		$/CuYds	Input(Include rebar, placement, mobilization, form, equipment)
Unit Cost fow Wall Concrete	C_{wall}		$\$/ft^3$	
Unit Cost fow Slab Concrete	C_{slab}		$/ft3	
Maximum number of cycles in our Weir	TopCycleLimit		#	Input a limitation (# between 1-18)
Minimum cycle in our weir	Lower CycleLimit		#	Input a limitation (# between 1-18 but not higher than TopCycleLimit
Labyrinth Weir Geometry- Counter Variable				
Angle of Side Legs Step	**α**		step	1 to 10 (one is more precise)
Cycle Arc Angle Step	**θ**		step	1 to 10 (one is more precise)
Radius enesimal step	**#**		**step**	**(100 of more is more precise)the radius willl be divided by this number and it will be aded to create a new radius therefor the step**
		Start		

Figure 4-6. User interface input window for current programmed methodology.

The sidewall angle and cycle angle increments are the growth rate for each corresponding angle, the radius nth step is the inverse number at which the radius will be incremented; for example, an nth step of 100 means that the increments for the radius will be at a rate of R/100. The program initiates by using the START button located at the bottom of the input window. Following the program initiation button, the tool reads the maximum and minimum cycle angles defined by the user. This is important to constrain our search to only specific searches that satisfy that criterion.

4.3 Calculations Procedures

The program then calculates the maximum arc radius (R) and minimum central weir arc angle for an ached labyrinth weir (Θ), equations 4-10 and 4-11, respectively, which can be contained within the channel width (W). The usage of the presented equation is based on entering all the angles in radians. Since current physical models have been studied for a minimum cycle arc angle for an arced labyrinth weir θ_{min}=10°, then this becomes the limiting factor for the equation. Restraining θ constrains the maximum number of cycles to 18 for any width. The top cycle limit is defined by the designer based on previously studied data. The most cycles studied up to this point is 10 cycles for aced labyrinth weirs, while the minimum cycles studied is 5.

$$R_{max} = \frac{W}{2 * \sin\left(\frac{TopCycleLimit * \theta_{\min}}{2}\right)} \qquad \textbf{4-10}$$

$$\Theta_{min} = MinCycleLimit * \theta_{\min} \qquad \textbf{4-11}$$

Based on the defined geometric parameters, the iterations start for the maximum radius. The program then provides the minimum arc angle (θ_{min}=10°) and the minimum sidewall angle (α=6°). For the same radius, all possible combinations of θ and α based on the input increments are analyzed. To continue the iterations until the stopping criteria is satisfied, the program continues to increase the radius for the same width as suggested by Figure 4-7.

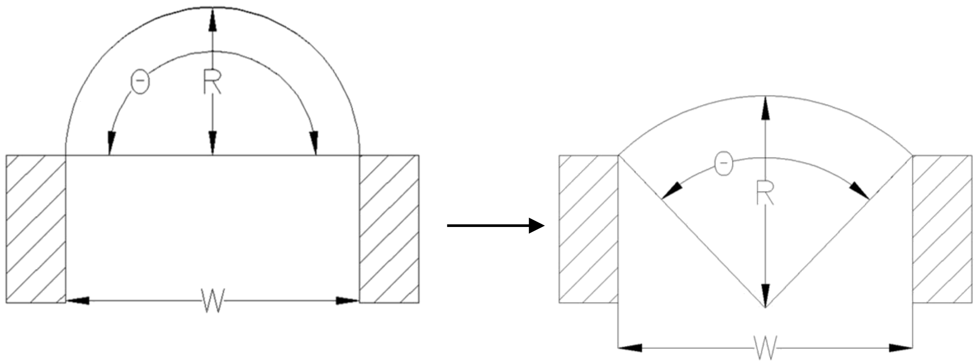

Figure 4-7. Cycle design procedure based on radius change for a constant width.

To geometrically design the structure, the parameters Θ, w', W', N, l_c, B, $L_{c\text{-cycle}}$, and L_c need to be calculated. The following equations were developed for obtaining the geometric information for the design of the structure and optimizing procedure. The equations are based on the assumption that θ, α, and R are known parameters since this parameters are imposed during the iteration process. The proposed design procedure is based on iterations that include a variation of the radius constrained by a minimum calculated radius. This variation in radius is an iterative process that is a crucial part of the process and the basis for the proposed equations from 4-12 to 4-19. The equations define the geometric parameters of a proposed iteration. These parameters dictate the spectrum of possible solutions for those that would apply for the designers' needs, while the output is solely based on surpassing expected hydraulic conditions and arranged in an economic basis.

$$\boldsymbol{\Theta} = 2 * \sin^{-1}\left(\frac{W}{2R}\right) * \frac{180}{\pi} \qquad \textbf{4-12}$$

$$\mathbf{w'} = R * \theta \tag{4-13}$$

$$\mathbf{W'} = R * \Theta \tag{4-14}$$

$$\boldsymbol{N} = W'/w' \tag{4-15}$$

$$\mathbf{l_c} = \left(\frac{R}{\sin\alpha} * \left(\left(\frac{\theta}{2}\right) - \left(\frac{A}{2 * R}\right)\right)\right) - \left(\frac{A}{2 * \sin\alpha}\right) \tag{4-16}$$

$$\boldsymbol{B} = \sin(90 - \alpha) * \mathrm{l_c} \tag{4-17}$$

$$\mathbf{L_{c-cycle}} = 2 * (\mathrm{l_c} + \mathrm{A}) \tag{4-18}$$

$$\mathbf{L_c} = \mathrm{L_{c-cycle}} * \mathrm{N} \tag{4-19}$$

After geometric parameters have been assigned and calculated, the hydraulic conditions for each weir are calculated. The trend line coefficients are interpolated and assigned for the weir. The discharge coefficient is then calculated based on the trend line coefficients previously interpolated and equation 4-7 using five H_t/P ratios. Only the discharge coefficient for the design H_t/P ratio is used to calculate the expected outflow condition of the designed arced labyrinth since this will be the maximum outflow design criteria. This flow is then compared to the maximum discharge expected by the design flood event to determine is the design is acceptable or not. The parameter ME acts as a constraint in the design of the weir by limiting the maximum area extension of the weir perpendicular to the channel width. Setting the parameter ME limits the area to where the weir should fit, and only those designs to which the parameter ME is not exceeded and pass the flood event flow will be considered for the cost analysis. The program then calculates the slab area as well as the linear area of the weir. The area calculations are then combined with the slab and wall thickness to establish a volume, and finally the costs for the walls and slab are calculated. The developed equations for volume calculations are presented as equation 4-21 and 4-22. The designed arced labyrinth weir ordered from the lowest cost spillways to the highest based only on the top ten most economical alternatives.

4.4 Spillway Construction Cost Estimate

A construction cost estimate for the arced labyrinth concrete structure is based on the assumptions discussed in this section. The construction cost estimates for concrete structures, in general, are based on a specified structure design and a series of foreseen circumstances and construction methods. Since cases considered herein are not structurally designed for the purpose of this thesis, the structural design will be based on the engineering manual for standard practice for concrete for civil works structures, EM-1110-2-2000 (U.S. Army Corps of Engineers 2000). This manual is the latest construction guideline for civil work structures for the U.S. Army. The construction methods will be based on the procedure applied by Archer Western contractors on the Lake Brazos labyrinth spillway as reported by Vasquez et al. [2009]. The Lake Brazos dam is composed of two modified labyrinth weirs. The spillway was positioned in a 600-ft-wide channel. Geometric design parameters for this spillway include an 8° sidewall angle, rounded apexes, and ogee type crest. The spillway is constructed in two sections. In the left section, the spillway consists of 13.5 cycles, while the right section contains 11.5 cycles. Dimensions for these spillways include a wall thickness of 2 ft and wall heights of 12 ft and 20.5 ft for the left and right sections, respectively (Vasquez 2008). The total length of the spillway is nearly 3,000 ft. The left section extended 307 ft into the river while the right section extends 240 ft into the river. The final construction cost for this project was a total sum of $16,373,502 while it duration was 706 days (Vasquez et al. 2009). The calculated unit cost per average footprint area of the structure is $100/ft^2$. The cost per area was calculated using equation 4-20.

$$\frac{\boldsymbol{Cost}}{\boldsymbol{Area}} = \frac{Total\ Cost}{(W * B_{ave})} \qquad \textbf{4-20}$$

where:

Total Cost	Complete cost of construction of the spillway structure,
W	Width of the channel, and
B_{ave}	Average length of the extension of the weir into the channel.

The equation takes into account the variable length of the extension into the river as the average length.

Demolition and structure removal costs will vary depending on the construction site, location, equipment needed, and type of structures. Since the demolition cost is specific to the site, this is a direct cost that the designer must take into account and is not included in this estimate. The construction cost estimate is solely for the foundation and walls of the concrete structure and does not include any ancillary tasks for example hauling of material, earthwork, and pool drainage among other tasks that can arise. Construction costs do not include the cost of increasing the dam height, lowering of pool levels, flow rerouting or construction of cofferdams for auxiliary spillway construction since these are considered an additional task.

Concrete structure construction is based on single use 5/8-in, plywood formwork. Neat material factors, form material loss factors, and crew composition (Appendix B) are based on Clark [1983]. The formwork of the wall is taken as cast in place, 16 ft of higher form that will rise at a rate of 7 ft/hr. The formwork for the footing is expected as an 8-ft height with a rise of 7 ft/hr. Both of these combinations are expected to sustain up to a maximum pressure of 1,200 psf when being built. Formworks expected are limited to a one time use. Cost for crew and equipment is based on the RS Means Online database for the 2014 national average. The concrete proposed for the structure is 4,000-psi reinforced concrete placed using a concrete pump. Ancillary tasks supported by the estimate include the concrete sealant, curing, and required concrete strength tests. The productivity is varied by crew composition and is based on the productivity documented by Clark [1983].

The construction estimate for the concrete structure was created as a guide of potential values for the concrete and wall concrete cost required by the program. This is needed in the program to calculate an estimate of the cost of the proposed arced labyrinth spillway structure. A cost estimate of the structure is part of the feasibility analysis of the possible solutions. The program gives enough information to the designer about arced labyrinth weirs so that the proposed designs can be compared to other potential outflow structures in a value engineering job plan. Other potential designs to be compared would be widening the width of the channel and adding a section to the existing spillway, the complete removal of the dam, a linear spillway or even a labyrinth spillway.

The unit cost per cubic yard of concrete for an arced labyrinth structure was calculated at $692/CY. Cost estimate considerations are available in Appendix B. Paxson et al.[2014] tabulated the unit cost per cubic yard for a concrete wall at 1040 USA$/CY while the slab concrete was estimated at 390 USA$/CY. The average cost between the foundation and the wall concrete is about 715 USA$/CY which is comparable to the average estimated cost presented by the author for reinforced concrete obtained for the concrete of the linear labyrinth weir and, which is going to be used for arced labyrinth weirs. The construction cost estimate was developed only for the concrete structure using as a basis the linear labyrinth weir constructed in Lake Brazos in Texas and is presented in Appendix B.

Based on the geometric and hydraulic information provided by Vasquez et al. [2009] for a linear labyrinth weir constructed in Texas (Figure 4-8), a new design was calculated using the proposed design procedure embedded into the spreadsheet tool. The inputs for the design are tabulated in

Table 4-7. Although the Texas structure is not a reservoir application the project was selected based on the vast amount of information available about this successfully completed labyrinth weir. Since the costs of the spillway in Texas included the costs of all the tasks required to create a new spillway rather than only the concrete structure, the cost per area for the Lake Brazos spillway of $100/ft^2 will be applied to the calculated solutions, to get a rudimentary cost per area construction estimate. The proposed arced labyrinth weirs differ from the Lake Brazos design in crest shape, apex shape, wall height, and foundation planning. The crest shape for the calculated arced labyrinth weirs are half-round shapes unlike the ogee type. Although it has been proven that ogee-type crests are more efficient for outflow than half round, only available data for half-round weir are available. The apex from the arced labyrinth weirs are based on a trapezoidal geometry while the Texas spillway was constructed with rounded apexes. In the Brazos spillways, the heights of the walls are variable, unlike the arced labyrinth spillways proposed designs in which the height of the spillway is constant and a function of the H_T/P ratio.

Figure 4-8. Labyrinth weir in Lake Brazos Texas (from Freese and Nichols 2014).

The structural cost of the arced labyrinth structure is based on the calculations of the concrete volume. The cost is calculated with the unit cost of concrete to obtain the entire structure cost. The volume concrete structure was calculated as

$$\boldsymbol{Wall\ Structure\ Volume} = \mathrm{L_c} * t_w * P \quad \textbf{4-21}$$

$$\boldsymbol{Slab\ Structure\ Volume} = \frac{\Theta}{2} * ((R + B)^2 - R^2) * Slab_{th} \quad \textbf{4-22}$$

where:

L_c	Total spillway length as presented from equation 4-19,
t_w	Wall thickness,
P	Structure height,
Θ	Central weir arc angle for an arced labyrinth weir,
R	Radius from the arc center to the midpoint of the arc,
B	Length of labyrinth weir (Apron) in flow direction, and
$Slab_{th}$	Thickness of the slab layer.

Table 4-7. Parameter Selection for Lake Brazos Spillway.

Parameter	Value	Unit
Q_{design}	80,000	(CFS)
H	386	(FT)
H_{crest}	378.50	(FT)
H_{apron}	363.5	(FT)
H_T	7.50	(FT)
W	600.00	(FT)
Space Limit	NO	
ME	-	(FT)

Cont.		
t_w	2.0	(FT)
A	4.4	(FT)
Crest Shape	HALF ROUND	-
P	15.00	(FT)
Ht/P	0.50	-
$Slab_{th}$	6.00	FT
$\$_{wall}$	\$ 692.00	\$/CuYd
$\$_{slab}$	\$ 692.00	\$/CuYd
C_{wall}	\$25.63	\$/FT^3
C_{slab}	\$25.63	\$/FT^3
Top Cycle Limit	10.00	#
Lower Cycle Limit	5.00	#
α	3.000	STEP
θ	5	STEP
#	100	STEP

The most cost effective solutions based on the entered parameters are presented in Table 4-8 while geometric parameters are presented in

Table 4-9. The weirs are arranged by cost from lowest to highest. The presented weirs are arranged from the lowest cost to the highest based on the most economic weirs for the parameters presented by the designer. An influential parameter in the cost, for a constant width series of iterations was the parameter B, which is needed to calculate the slab area. The increment in the weir extension is proportional to the cost of the concrete structure. Based on numerical solutions for a large number of iterated top ten weir solutions, the cost of the parameter B is related directly to the cost of the weir (Figure 4-9) which shows that the cost is proportional to the spillway magnitude.

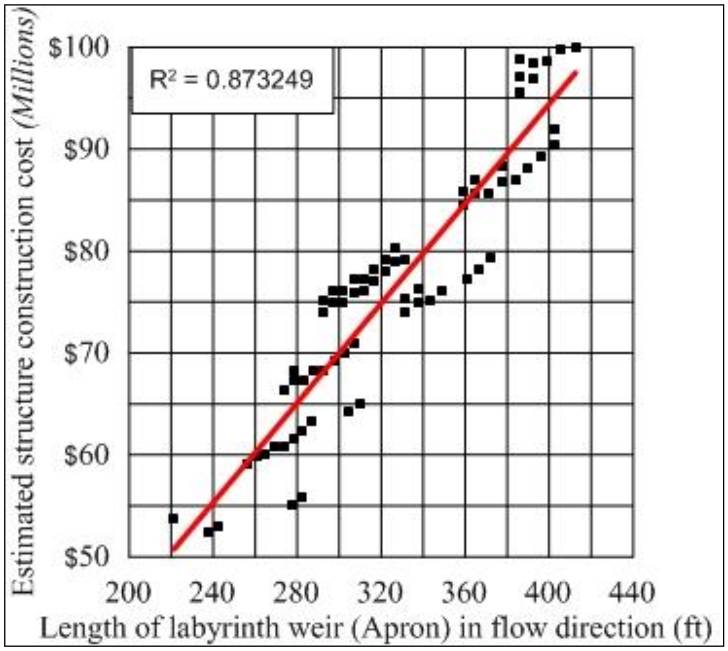

Figure 4-9. Cost trends based on the apron length.

Table 4-8. Arced labyrinth weir costs based on Lake Brazos weir cost and concrete structure cost (600-ft width).

Top Weirs	Cost/ Footprint Area	Footprint Area	Expected Total Cost	Concrete Structure Cost
	$/Ft²	***Ft²***	***$***	***$***
Arced Labyrinth Weir 1	100	184,664	18,466,368	$12,308,451.09
Arced Labyrinth Weir 2	100	191,071	19,107,107	$12,467,306.24
Arced Labyrinth Weir 3	100	187,708	18,770,828	$12,548,524.41
Arced Labyrinth Weir 4	100	194,003	19,400,281	$12,710,678.46
Arced Labyrinth Weir 5	100	189,854	18,985,368	$12,792,082.43
Arced Labyrinth Weir 6	100	196,014	19,601,351	$12,956,597.53

Arced Labyrinth Weir 7	100	202,272	20,227,164	$13,122,675.59
Arced Labyrinth Weir 8	100	208,628	20,862,807	$13,290,169.67
Arced Labyrinth Weir 9	100	203,134	20,313,375	$13,371,059.70
Arced Labyrinth Weir 10	100	209,323	20,932,272	$13,539,715.49

Table 4-9. Geometric parameters for arced labyrinth weirs based on Lake Brazos hydraulic conditions (600-ft width).

Top Weirs	**Cycles**	**θ**	**α**	**R**	$L_{c-cycle}$	**Cycle Width (W)**	L_c	**B**	$L_{c\text{-}Cycle}$/ **W Ratio**
	#	*Deg (°)*	*Deg (°)*	*Ft*	*Ft*	*Ft*	*Ft*	*Ft*	
Arced Labyrinth Weir 1	10.0	10.0	18.0	391.6	201.5	68.4	2015.1	91.6	2.9
Arced Labyrinth Weir 2	10.0	10.0	18.0	397.6	204.9	69.4	2049.0	93.3	3.0
Arced Labyrinth Weir 3	9.5	10.0	18.0	403.6	208.3	70.4	1978.7	94.9	3.0
Arced Labyrinth Weir 4	9.5	10.0	18.0	409.6	211.7	71.5	2010.9	96.5	3.0
Arced Labyrinth Weir 5	9.0	10.0	18.0	415.6	215.1	72.5	1935.6	98.1	3.0
Arced Labyrinth Weir 6	9.0	10.0	18.0	421.6	218.5	73.6	1966.1	99.7	3.0
Arced Labyrinth Weir 7	9.0	10.0	18.0	427.6	221.8	74.6	1996.6	101.3	3.0
Arced Labyrinth Weir 8	9.0	10.0	18.0	433.6	225.2	75.7	2027.1	102.9	3.0
Arced Labyrinth Weir 9	8.5	10.0	18.0	439.6	228.6	76.7	1943.3	104.5	3.0
Arced Labyrinth Weir 10	8.5	10.0	18.0	445.6	232.0	77.8	1972.1	106.1	3.0

With the current parameters, the cost of the arced labyrinth weir is more expensive than the 25-cycle weir in Texas. The procedure proposed is developed as a remediation alternative for an dam by creating an auxiliary spillway. Remediation in dams is based on reservoir applications rather than in-channel application like Lake Brazos in Texas. Although this proposed design approach is based on reservoir use, the applications for flow discharge are the same. Variating the channel width parameter optimizes the geometric design, based on hydraulic performance while minimizing costs. To better understand the consequences of a constrained-width based method, it is crucial to be aware of the specific rating curves specific for each weir, presented in Figure 4-10, and compare them to the expected hydraulic values. A rating curve plots the hydraulic characteristics of a weir or any other discharge structure. The flow over the structure is plotted against the height taking into account the discharge coefficients based on the height of the reservoir. The calculated rating curves are based on a free-flow channel with no obstructions in the weir. The provided information in Figure 4-10 reveals that the current solutions are hydraulically overdesigned in terms of outflow when compared to the design that is currently in place in the channel. With the design width of 600 ft, the arced labyrinth spillway does not reach its highest capacity for the expected probable maximum flood while the built weir reached it maximum capacity at 80,000 cfs at 386 ft; the arced labyrinth weir for the same amount of flow reaches nearly 384 ft.

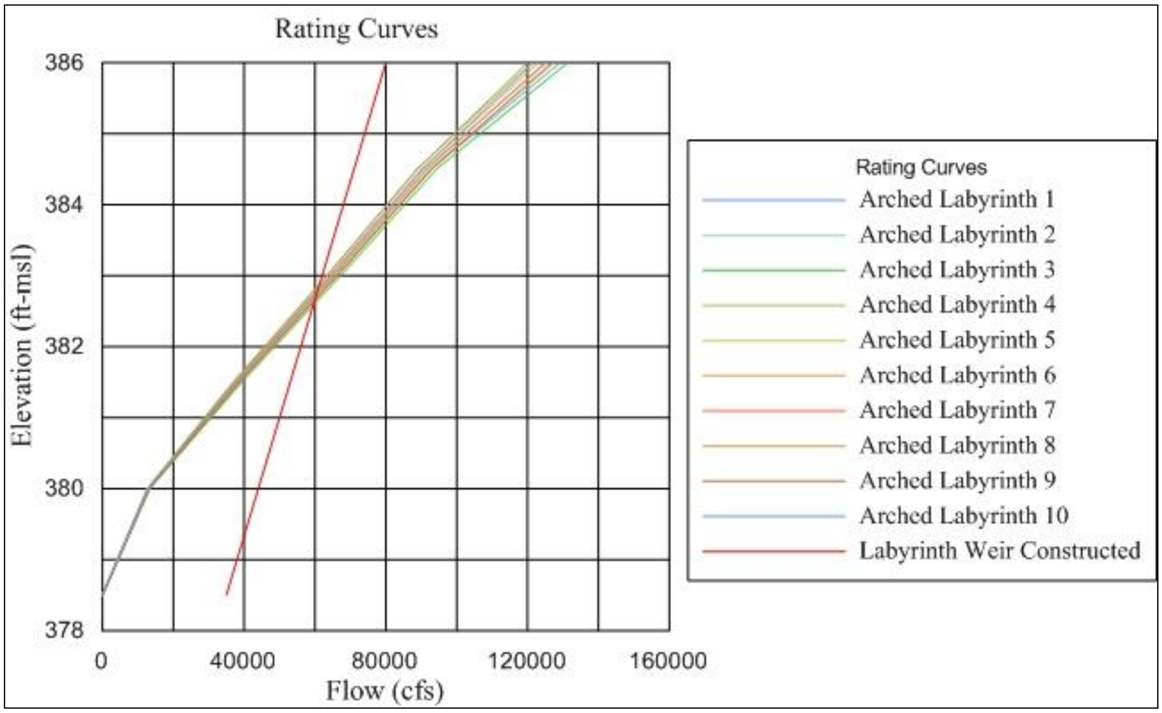

Figure 4-10. Rating curve for Lake Brazos weir and arced labyrinth weir 600-ft-width solution.

The designs proposed using the Excel spreadsheet tool, when designed for the same width as a linear labyrinth weir, are extensive in size and as a result more expensive than the built weir, based on the cost per area method. It is important to note that the coefficients for the discharge coefficients calculations are based on reservoir applications. Flow directionality plays an important aspect in the discharge coefficient for arced labyrinth weirs; it must be reminded that the expected flows would be slightly less for in-channel arced labyrinth weir designs. Crookston [2010] analyzed the ratio of in-reservoir applications of arced labyrinth weirs to a linear channel-placed labyrinth weir and is presented in Figure 4-11. It is apparent with this ratio analysis that arced labyrinth weirs have higher discharge coefficients for in-reservoir functions than linear arced labyrinth in channel applications with the same channel width. At low heads, the discharge coefficient is relatively higher than for in-channel applications while at high-head water ratios values of 0.6, the discharge coefficients of the arced labyrinth weir drops significantly. A comparison was made which compared arced projecting labyrinth weirs to arced projecting linear and even with this reduction in discharge coefficient, the discharge capacity is higher than arced linear weirs (Crookston 2010). This behavior was attributed mostly to the significantly longer crest lengths in the arced labyrinth weir.

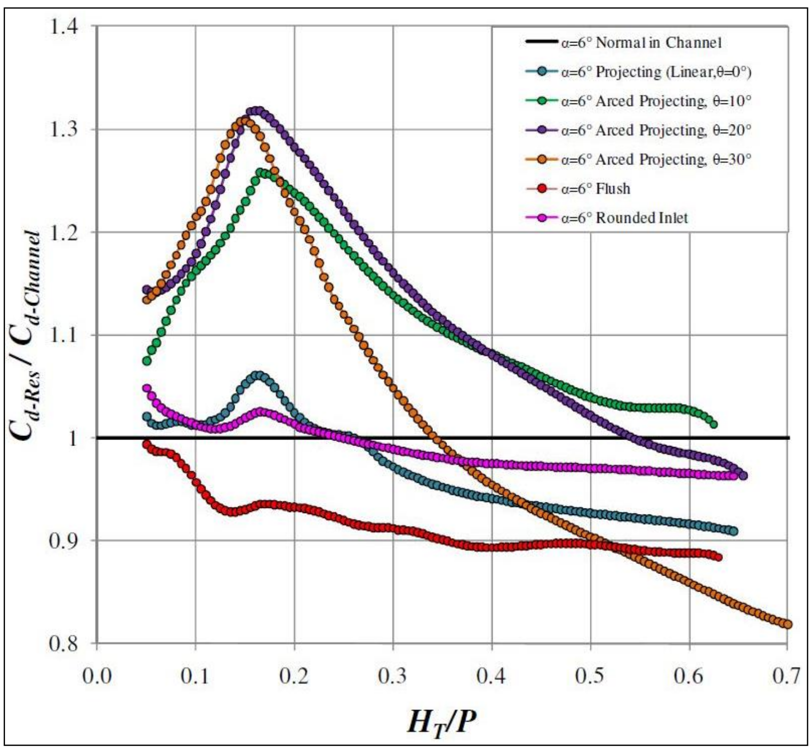

Figure 4-11. Comparison of labyrinth weir orientations for a=6°(Crookston 2010).

4.5 Design Feasibility

To understand the feasibility of this design method, a parameter that plays a significant role in the design is the spillway width. To verify how this parameter influenced the results of a weir design, another weir design iteration was computed. This new design was set at half the past proposed weir, thus using only a channel width of 300 ft. Proposed solutions costs are found in Table 4-10 while the geometric parameters are found in Table 4-11. During computation, it was found that a weir with a 300-ft width was capable of passing nearly the same outflow as the linear weir of 3,000 ft length constructed in Texas. Using the concrete cost estimate of $692/CY, the concrete structure cost for the most economic arced labyrinth spillway is nearly $6.4 million, while the total cost of the whole spillway complex was calculated at an approximate $13.4 million. This analysis indicates that arced labyrinth weir spillways are economically and hydrologically feasible design options that can be considered in new spillway construction for dam rehabilitation. When compared to the $16.3 million of the completed linear weir structure, the arced labyrinth weir spillway is more economical while achieving the hydrological capacity needed to alleviate outflow needs.

Table 4-10. Arced labyrinth weir costs based on Lake Brazos weir cost and concrete structure cost (300-ft width).

Top Weirs	Cost/Footprint Area	Footprint Area	Total Cost	Concrete Structure Cost
	$/Ft²	*Ft²*	*$*	*$*
Arced Labyrinth Weir 1	100	136,993	13,699,268	$ 6,386,030.75
Arced Labyrinth Weir 2	100	142,556	14,255,597	$ 6,493,114.47
Arced Labyrinth Weir 3	100	140,818	14,081,842	$ 6,532,882.52
Arced Labyrinth Weir 4	100	146,314	14,631,378	$ 6,640,572.35
Arced Labyrinth Weir 5	100	143,919	14,391,877	$ 6,678,166.97
Arced Labyrinth Weir 6	100	149,324	14,932,408	$ 6,786,082.42
Arced Labyrinth Weir 7	100	154,829	15,482,897	$ 6,894,645.14
Arced Labyrinth Weir 8	100	160,433	16,043,344	$ 7,003,795.70
Arced Labyrinth Weir 9	100	303,674	30,367,444	$10,233,913.33
Arced Labyrinth Weir 10	100	316,112	31,611,207	$10,408,468.15

Table 4-11. Geometric parameters for Arced labyrinth weirs based on Lake Brazos hydraulic conditions (300-ft width).

Top Weirs	Cycles	θ	α	R	$L_{c-cycle}$	Cycle Width (W)	L_c	B	$L_{c\text{-}cycle}$/ w Ratio
	#	*DEGREES (°)*	*DEGREES (°)*	*FT*	*FT*	*FT*	*FT*	*FT*	
Arced Labyrinth Weir 1	10.0	10.0	9.0	195.8	171.0	34.2	1710.1	80.1	5.0
Arced Labyrinth Weir 2	10.0	10.0	9.0	198.8	174.4	34.7	1743.6	81.8	5.0
Arced Labyrinth Weir 3	9.5	10.0	9.0	201.8	177.7	35.2	1688.2	83.4	5.0
Arced Labyrinth Weir 4	9.5	10.0	9.0	204.8	181.1	35.7	1720.0	85.1	5.1

Arced Labyrinth Weir 5	9.0	10.0	9.0	207.8	184.4	36.3	1659.6	86.7	5.1
Arced Labyrinth Weir 6	9.0	10.0	9.0	210.8	187.7	36.8	1689.7	88.4	5.1
Arced Labyrinth Weir 7	9.0	10.0	9.0	213.8	191.1	37.3	1719.8	90.0	5.1
Arced Labyrinth Weir 8	9.0	10.0	9.0	216.8	194.4	37.8	1750.0	91.7	5.1
Arced Labyrinth Weir 9	10.0	10.0	6.0	195.8	251.6	34.2	2515.6	120.7	7.4
Arced Labyrinth Weir 10	10.0	10.0	6.0	198.8	256.6	34.7	2565.7	123.2	7.4

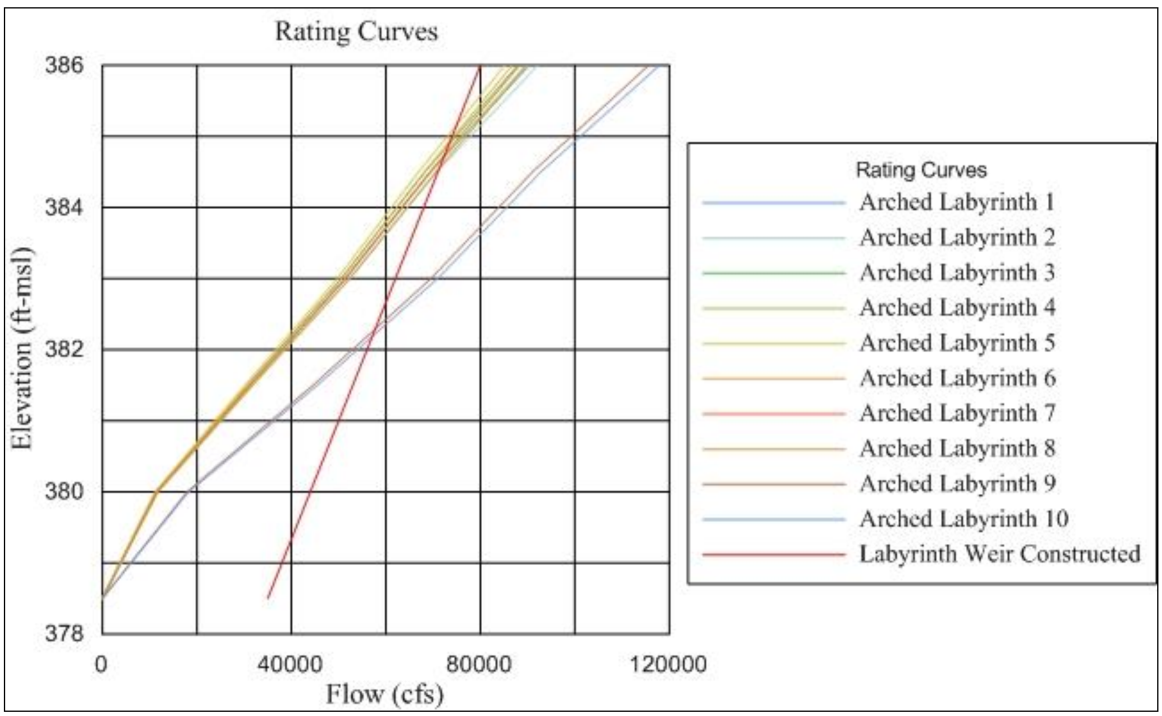

Figure 4-12. Rating curve for Lake Brazos weir and arced labyrinth weir 300-ft-width solution.

The proposed optimization scheme is based on an iterative process which goal is to find the most economical alternatives from a range of possible solutions in a fraction of the time it would take to make a similar analysis with current design procedures. The solutions are based on limiting the iterations into geometrically acceptable solutions rather than to iterate between all possible solutions. There exists an infinite number of possible solutions when designing an arced labyrinth weir, thus from all the possible solutions that exist, the most economical solutions for given a set of search parameters can be evaluated in terms of the spillways value. The solutions evaluated by the program are presented as the top 10 most economical choices as well as the geometric characteristics specific to each weir and the rating curves that define the weir. It is important to understand that a hydraulic overdesign of a structure is possible and that the hydrological rating curve for the site must be obtained to be compared to the potential designed solutions as well as compared to the downstream discharge channel capacity. This is important since Crookston [2010] found that highly efficient weirs may be limited by local submergence and eventually the discharge capacity of the outlet.

4.6 Obtaining the value of the design

To compare the solutions, it is clear that the cost of the solution is important as well as the discharge expected from the spillway. The lowest cost solutions will be compared among each other based on the hydraulic performance or function and the cost in a function qualitative model adapted from Li & Liu [2006]. The performance index and the cost index will be calculated following equations 4-23 and 4-24, respectively:

$$F_i = \frac{Q_i}{\sum_{i=1}^{n} Q_i} \quad \textbf{4-23}$$

$$C_i = \frac{Cost_i}{\sum_{i=1}^{n} Cost_i} \quad \textbf{4-24}$$

where:

Q_i	Expected spillway discharge,
$\sum_{i=1}^{n} Q_i$	Total discharge from a selected group of arced labyrinth weir solutions,
F_i	Performance index of a selected spillway,
$Cost_i$	Expected construction cost of a selected spillway structure,
$\sum_{i=1}^{n} Cost_i$	Total cost from a selected group of arced labyrinth weir solutions, and
C_i	Cost index of a selected spillway structure.

Using the minimum cost of only ten spillway solutions for the case presented in Table 4-10, it is possible to obtain a value for each spillway design. This can be done knowing that all solutions are acceptable in terms of expected discharge; thus equation 4-1 is satisfied. Using equation 3-2, it is possible to obtain the value index of a solution based on a comparison between a given set of solutions after performance and cost indices have been calculated from equations 4-23 and 4-24 respectively.

Although the value analysis compares each arced labyrinth weir between each other in terms of value it is important to understand the added function when compared to an already built structure, thus comparing arced labyrinth weirs with a base linear labyrinth weir is done to establish the added functionality, in this case the flow discharge capacity. A value analysis and an added value are inverse functions thus the highest value spillway design yields the lowest cost per discharge as seen in the last two columns of Table 4-12. When comparing linear labyrinth weirs it is important to note that the reduction in cost is due to a reduction in width necessary to pass the expected outflow conditions for arced labyrinth weirs. If the channel width is sustained the same for both cases the total structure cost will increment as seen from Table 4-8. The reduction in area is necessary because an overdesign of a spillway structure will happen if the width of the channel or the headwater ratios are not changed. Table 4-12 shows the calculated value coefficients as well as the cost per discharge between the selections of the 10 most economic weirs as well as the cost per discharge of a spillway. The comparison was done between 10 arced labyrinth weirs and the linear labyrinth spillway from Texas. This last spillway will be our base comparison. The structure cost for the linear labyrinth weir was made by using the estimated unit cost of concrete and calculating the concrete volume based on the information presented by Vasquez et al., [2008] and Vasquez et al., [2009]. By choosing Arced labyrinth Weir 2 the value of the spillway is raised from 0.92 (linear labyrinth weir constructed in Texas) to 1.122 thus when compared to the base design the selection of an arced labyrinth weir can be seen as an improvement since it is adding value to the base design. Note that estimated construction cost are lower than the linear labyrinth weir which infers a lower total length of a weirs, which is true for this case since the linear labyrinth was designed at 3,000 ft while the arced labyrinth weir is expected to be 1,710 ft long. This is possible when taking into account the expected discharge efficiency of arced labyrinth weirs.

Table 4-12 Example calculations of value calculations.

Spillway structure	Structure Cost	Discharge (cfs) at $H_T/P=0.5$	C_i	F_i	Value	$/Discharge
Arced Labyrinth Weir 1	$6,386,031	90,399	0.079	0.088	1.119	$70.64
Arced Labyrinth Weir 2	$6,493,114	92,169	0.080	0.090	1.122	$70.45
Arced Labyrinth Weir 3	$6,532,883	87,913	0.081	0.086	1.064	$74.31
Arced Labyrinth Weir 4	$6,640,572	89,569	0.082	0.088	1.067	$74.14
Arced Labyrinth Weir 5	$6,678,167	85,176	0.083	0.083	1.009	$78.40
Arced Labyrinth Weir 6	$6,786,082	86,722	0.084	0.085	1.011	$78.25
Arced Labyrinth Weir 7	$6,894,645	88,268	0.085	0.086	1.012	$78.11
Arced Labyrinth Weir 8	$7,003,796	89,814	0.087	0.088	1.014	$77.98
Arced Labyrinth Weir 9	$10,233,913	115,596	0.126	0.113	0.893	$88.53
Arced Labyrinth Weir 10	$10,408,468	117,898	0.129	0.115	0.896	$88.28
Lake Brazos Linear Labyrinth	$6,876,558	80,000	0.085	0.078	0.920	$85.96
Total	$80,934,230	$1,023,523				

The value index can be classified into three separate classes.

1. Value < 1 shows that the cost is excessive for the expected functionality or that the functionality of the spillway is deficient. This can be that, although it is possible to pass the expected conditions, it is not as efficient in terms of functionality.
2. Value = 1 shows that the performance of the weir matches the expected cost. In this case, it can be denoted as solutions that can be feasible.
3. Value > 1 types of solutions are the focus of this study. These are solutions that outperform the construction costs thus getting higher performance for an expected structural cost. In these cases, high value solutions later need to be compared to other possible flow discharge structures in order to determine the best structure for specific site criteria.

This type of approach combined with operational, maintenance, and life cycle costs and other analysis will then be used to completely evaluate and select a specific type of flow discharge structure for dams. This tool aids in the separation of the best spillway structures based on value so that high performance-low cost arced labyrinth spillways can be compared with other spillway structures. This value comparison is a new comparison procedure for the selection of low cost- high performance spillways that can be used as an auxiliary spillway comparison methodology.

5 Example Applications

5.1 Case Study

The program was used to identify potential solutions for an auxiliary spillway. The project is a government owned dam under risk assessment evaluation. The dam was identified with a series of possible critical failures that might result in a high risk for failure. The critical failures include the risk of dam overtopping due to the undersized capacity of the spillway and structural deficiencies that consist of high pore pressures underneath the dam that could lead to backward erosion piping, high seepage flows, and other land specific hazards. The dam consists of two embankment dams, a main embankment and an auxiliary dam. An undersized capacity spillway is located between the two dams to capture the outflow of these two structures. The current site spillway has an ogee-type crest and is 140 feet of length. The design head of this spillway is 21.5 ft above the weirs crest and a discharge of nearly 52,700 cfs; at this design height, the flood height was expected to have a 6.5-ft freeboard from the dam. Based on a global datum (NAVD88), the crest elevation of the main and auxiliary dam is 2637.26 ft. This means that the original flood design was to reach a height of 2630.76 ft.

A revision to the probable maximum flood revealed that the peak inflow expected for this reservoir is 607,107 cfs. From this new revision, it is expected to raise the height of the dam and design a new emergency spillway. The dam would need to be elevated 12.5 ft to be at the height of the probable maximum flood. Current designs are expected to pass the probable maximum flood with a 4-ft freeboard. With the current structure spillway (no changes whatsoever to the spillway), it would require a 36-ft rise of the dam to pass the probable maximum flood outflow with a 3-ft freeboard. Studied alternatives included a 4-ft rise of the dam and a design that would allow the pool to rise up to where the dam was initially 2637.26 ft. based on datum. This type of approach considered wall crest heights from 9 to 30 ft. Ultimately, a recommendation of a 16-ft raise to the dam was proposed and the creation of a labyrinth weir as an emergency spillways, along with other recommendations to the auxiliary spillway, main dam, auxiliary buttress, and nearby highway. The maximum width of the spillway was selected as 900 ft. The maximum expected height for a PMF in this area is f 2,655 ft (from datum), which would be reached if the amount of outflow is not matched by the designed emergency spillway.

5.2 Program Implementation

A range of solutions were developed based on the case study hydraulic and geometric parameters. The solutions were developed for a series of iterations to prove the capabilities of the program in obtaining the most economical weirs that would satisfy the specified geometric and expected hydraulic criteria. To observe the behavior of the design recommendations, variation of parameters H_T/P and channel width were evaluated. By changing these parameters the variation of 7 parameters in completed and the optimum solutions for a specific flow discharge becomes apparent based on lowest cost solutions.

5.2.1 *Input Parameters*

The dam crest elevation presently sits at 2637.26, and it is proposed to be raised 16 ft; to achieve this and obtain a freeboard of 4 ft., the height of the design flow elevation was calculated to be 2649.26 ft from the datum. The base of the spillway was chosen as the crest of the auxiliary spillway, thus being at 2609.23 ft. The maximum water height ratio was selected at 0.5 based on reasons previously discussed and a minimum of 0.1. The design outflow chosen was 607,107 cfs. Full parameters selected for this design optimization are listed in Table 5-1.

Table 5-1. Parameter selection for first optimization case study.

Parameter Description	Symbol	Value	Units
Design Flow	Q_{design}	607,107	(cfs)
Design Flow Water Surface Elevation	H	2649.26	(ft)
Crest Elevation	H_{crest}	2635.93	(ft)
Approach Channel Elevation	H_{apron}	2609.26	(ft)
Unsubmerged Total Upstream Head	H_T	13.33	(ft)
Width of Labyrinth Entrance (Normal to Flow)	W	900.00	(ft)
Is there a Space Limitation		No	
Maximum Length for area limitation	ME		(ft)
Thickness of Weir Wall at Crest	t_w	4.0	(ft)
Inside Apex Width	A	5.0	(ft)
Crest Shape	Crest Shape	Half Round	-
Crest Height	P	26.67	(ft)
Maximum Water Height Ratio	H_t/P	0.50	
Slab thickness	$Slab_{th}$	6.00	ft
Unit Cost for Wall Concrete CUBIC YARDS	$\$_{wall}$	$ 692.00	$/CuYd
Unit Cost for Slab Concrete CUBIC YARDS	$\$_{slab}$	$ 692.00	$/CuYd
Unit Cost for Wall Concrete	C_{wall}	$25.63	$\$/ft^3$
Unit Cost for Slab Concrete	C_{slab}	$25.63	$\$/ft^3$
Maximum number of cycles in our Weir	TopCycleLimit	10.00	#
Minimum cycle in our weir	Lower CycleLimit	5.00	#
Labyrinth Weir Geometry- Counter Variable			
Angle of Side Legs Step	α	3.000	step
Cycle Arc Angle Step	θ	5	step
Radius nth Step	#	100	step

5.2.2 *Solution*

For each headwater ratio and channel width parameter change, the output of the spreadsheet-based program lists the top ten most economical weirs along with the geometric parameters, hydraulic parameters, and discharge capacity for each specific spillway design. Table 5-2 expresses the solutions based on one series of iterations with a 900ft channel width and a headwater ratio of 0.5 while Table 5-3 portrays the geometric parameters for this series of iterations. The analysis for the solution of the top ten most economical weirs does not include weirs that have larger than ten cycles or less than five cycles. Note that these limits are a constraint based on current knowledge of the hydraulic characteristics of the arced labyrinth weirs. Geometric parameters include the sidewall angle, number of cycles, length of one cycle, and others parameters that are presented in Table 5-3, which are calculated using the developed equations 4-12 to 4-19. Following by the weir geometry features, the hydraulic parameters, which are plotted in the form of the rating curves in Figure 5-1, are presented for hydraulic performance behavior considerations. The calculations for the hydraulic performance are based on the 3D interpolation for the polynomial fit coefficients. These hydraulic factors aid in the solution of the discharge capacity of the weir; both the rating curves of the weir and the discharge coefficients are included as outputs of the program.

Table 5-2. Top weirs for case study based on a 900 ft channel and Ht/P of 0.5.

Top Weirs	Cost	Cost/Area
Arced Labyrinth Weir 1	$53,797,217.82	$52.54
Arced Labyrinth Weir 2	$73,945,174.74	$42.09
Arced Labyrinth Weir 3	$74,899,943.70	$41.23
Arced Labyrinth Weir 4	$75,018,431.20	$42.07
Arced Labyrinth Weir 5	$75,984,629.28	$41.25
Arced Labyrinth Weir 6	$76,084,323.17	$42.24
Arced Labyrinth Weir 7	$77,056,827.39	$41.46
Arced Labyrinth Weir 8	$78,037,877.47	$40.71
Arced Labyrinth Weir 9	$79,026,670.00	$40.00
Arced Labyrinth Weir 10	$79,090,542.91	$41.14

Table 5-3. Geometric characteristics for top weirs of case study based on a 900 ft channel and Ht/P of 0.5.

Top Weirs	Cycles	θ	α	R	$L_{c-cycle}$	Cycle Width (W)	L_c	B	$L_{c\text{-Cycle}}$/ W Ratio
	#	DEG (°)	DEG (°)	FT	FT	FT	FT	FT	
Arced Labyrinth Weir 1	10.00	10.00	12.00	596.43	462.58	104.10	4625.83	221.35	4.44
Arced Labyrinth Weir 2	10.00	10.00	9.00	587.43	601.47	102.53	6014.71	292.09	5.87
Arced Labyrinth Weir 3	10.00	10.00	9.00	596.43	611.51	104.10	6115.12	297.05	5.87
Arced Labyrinth Weir 4	9.50	10.00	9.00	605.43	621.55	105.67	5904.76	302.01	5.88
Arced Labyrinth Weir 5	9.50	10.00	9.00	614.43	631.59	107.24	6000.15	306.97	5.89
Arced Labyrinth Weir 6	9.00	10.00	9.00	623.43	641.64	108.81	5774.72	311.93	5.90
Arced Labyrinth Weir 7	9.00	10.00	9.00	632.43	651.68	110.38	5865.09	316.89	5.90
Arced Labyrinth Weir 8	9.00	10.00	9.00	641.43	661.72	111.95	5955.47	321.85	5.91
Arced Labyrinth Weir 9	9.00	10.00	9.00	650.43	671.76	113.52	6045.84	326.81	5.92
Arced Labyrinth Weir 10	8.50	10.00	9.00	659.43	681.80	115.09	5795.31	331.76	5.92

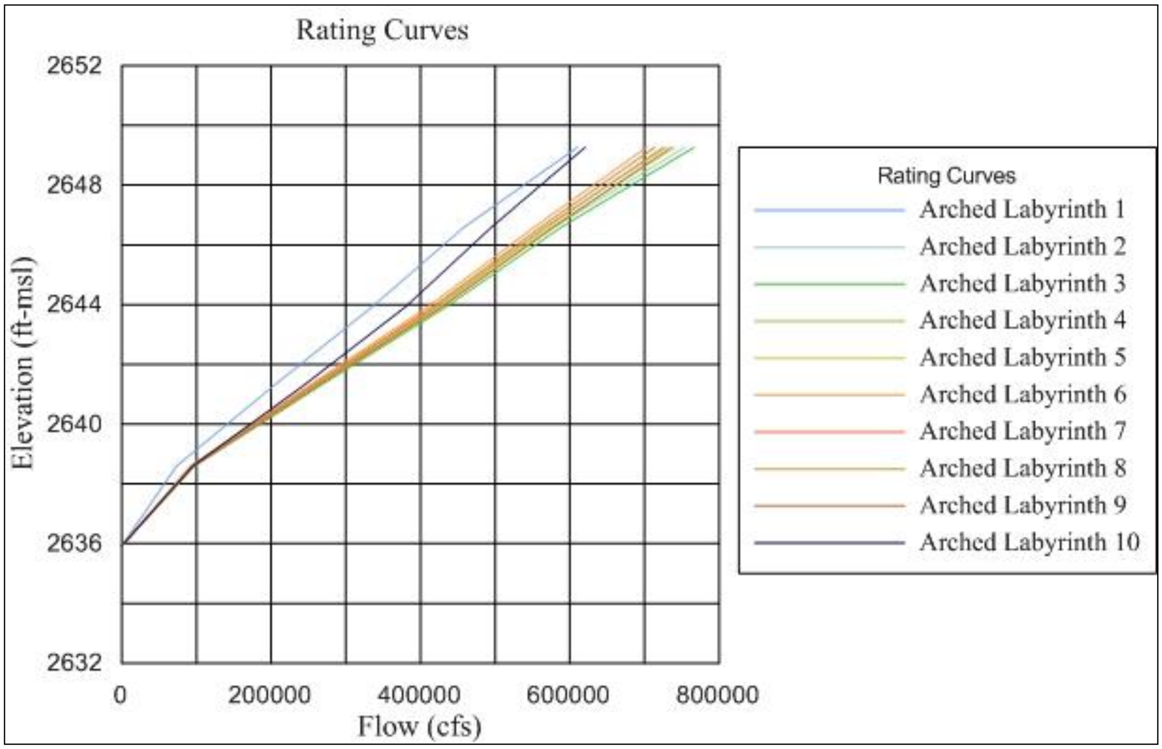

Figure 5-1. Rating curves for the case study top weirs based on a 900 ft channel and Ht/P of 0.5.

Considerations taken into account for the solution of the most optimum weirs are based on upstream pool elevation limitations, area limitations, and flow discharge capacity. The principle behind the vast amount of data presented as an output is to give the designer the idea of an economic point of view, the parameters needed to create the structural design of the structure, and the hydraulic behavior of the structure. The combination of the obtained solutions from the program with site specific considerations, which include flow characteristics, foundation analysis, and seismic concerns, will ultimately define the direction of the design. The information provided by this geometric optimization scheme is to give the designer specific solutions that can be implemented and modified rather than to start an iterating process that could lead to elevated research costs, given that there is a vast number of possible arced labyrinth spillway options. Applying a value analysis for the approach of the design for the presented parameters, solution arced labyrinth weir 1 was chosen as the most economic spillway and complies with the required capacity to pass the expected probable maximum flood discharge. If the top weir is not chosen as the weir because of other considerations, the information presented narrows the search to economic, yet feasible spillway options for the expected conditions for any site. Keep in mind that this set of solutions (Table 5-2) was only for a constrained channel width and a set headwater ratio of 0.5. To minimize cost and optimize performance, which is the ultimate goal, a sensitivity analysis must be made to the independent variable parameters taking into consideration that there is a specific flow discharge that needs to be surpassed at the lowest cost possible. The goal then is to minimize the cost while complying with the critical outflow characteristics.

5.2.3 *Sensitivity Analysis on Design Geometry*

Although the solution is the most economical for the specified width of channel of 900 ft, this needs to be compared to solutions that will satisfy all the parameters by changing the width of the channel and changing the H_T/P. The change in the width is based on decreasing the width of the channel by 50 ft and develop a series of solutions for a specified width. At the widths chosen, the H_T/P ratio is varied, expecting to get other geometric types that would satisfy the site specific hydraulic criteria. The test matrix in Table 5-4 was selected to solve for possible solutions if solutions exist. The change in this type of parameter was done in order to further optimize the design and obtain the most economical solution for a given outflow discharge. Solutions are available if there are any arced labyrinth spillways capable of surpassing the expected outflow. The test matrix below is expected to analyze over 45,000 iterations to obtain the top 15 most economic arced labyrinth weirs based on the parameters from Table 5-1 and varying the Ht/P ratio and channel width.

Table 5-4. Test matrix selected for parameter variation and indication of solution availability.

Width (ft.)	H_T/P				
	0.1	**0.2**	**0.3**	**0.4**	**0.5**
450	No Solution	No Solution	No Solution	No Solution	No Solution
500	No Solution	No Solution	No Solution	No Solution	No Solution
600	No Solution	No Solution	No Solution	No Solution	Solution Available
650	No Solution	No Solution	No Solution	No Solution	Solution Available
700	No Solution	No Solution	No Solution	Solution Available	Solution Available
750	No Solution	No Solution	No Solution	Solution Available	Solution Available
800	No Solution	No Solution	Solution Available	Solution Available	Solution Available
850	No Solution	No Solution	Solution Available	Solution Available	Solution Available
900	No Solution	No Solution	Solution Available	Solution Available	Solution Available

The top weir of each solution will be used to further analyze what geometries are the most cost efficient and most economical and how the behavior of internal angle affects the cost, cost trends, and geometric trends in the process of optimization. The top weir of each solution is presented in Table 5-5, ordered by width from lowest to highest, while the geometric parameters for each weir are ordered in Table 5-6 .

Table 5-5. Lowest cost spillways for each variable parameter analysis.

Top Weirs Trends	Width	Ht/P	Cost	Cost/Area
	ft.		$	$
Arced Labyrinth Weir 1	600	0.5	$55,051,514.25	$34.90
Arced Labyrinth Weir 2	650	0.5	$64,175,298.20	$33.82
Arced Labyrinth Weir 3	700	0.4	$75,293,242.40	$33.51
Arced Labyrinth Weir 4	700	0.5	$73,970,824.96	$32.92
Arced Labyrinth Weir 5	750	0.4	$85,866,915.41	$32.70
Arced Labyrinth Weir 6	750	0.5	$52,357,592.56	$44.66
Arced Labyrinth Weir 7	800	0.3	$98,883,744.11	$32.59
Arced Labyrinth Weir 8	800	0.4	$97,112,322.31	$32.00
Arced Labyrinth Weir 9	800	0.5	$59,151,674.62	$43.69
Arced Labyrinth Weir 10	850	0.3	$110,923,672.35	$31.94
Arced Labyrinth Weir 11	850	0.4	$68,337,386.40	$42.66
Arced Labyrinth Weir 12	850	0.5	$66,347,536.29	$42.84
Arced Labyrinth Weir 13	900	0.3	$123,635,339.39	$31.38
Arced Labyrinth Weir 14	900	0.4	$75,119,687.43	$42.76
Arced Labyrinth Weir 15	900	0.5	$53,797,217.82	$52.54

Table 5-6. Geometric parameters for variable parameter analysis.

Top Weirs	Cycles	θ	α	R	$L_{c\text{-}cycle}$	Cycle Width (w)	L_(c)	B	Lcycle/ w Ratio
	#	(°)	(°)	ft.	ft.	t	ft.	ft.	
Arced Labyrinth Weir 1	10	10	6	391.62	568.23	68.35	5682.30	277.59	8.31
Arced Labyrinth Weir 2	10	10	6	424.26	622.72	74.05	6227.22	304.68	8.41

Top Weirs	Cycles	θ	α	R	$L_{c\text{-}cycle}$	Cycle Width (w)	L_(c)	B	Lcycle/ w Ratio
	#	(°)	(°)	ft.	ft.	t	ft.	ft.	
Arced Labyrinth Weir 3	10	10	6	456.89	677.21	79.74	6772.13	331.78	8.49
Arced Labyrinth Weir 4	10	10	6	456.89	677.21	79.74	6772.13	331.78	8.49
Arced Labyrinth Weir 5	10	10	6	489.53	731.70	85.44	7317.05	358.88	8.56
Arced Labyrinth Weir 6	10	10	9	489.53	492.24	85.44	4922.38	238.15	5.76
Arced Labyrinth Weir 7	10	10	6	522.16	786.20	91.13	7861.96	385.97	8.63
Arced Labyrinth Weir 8	10	10	6	522.16	786.20	91.13	7861.96	385.97	8.63
Arced Labyrinth Weir 9	10	10	9	522.16	528.65	91.13	5286.49	256.13	5.80
Arced Labyrinth Weir 10	10	10	6	554.80	840.69	96.83	8406.88	413.07	8.68
Arced Labyrinth Weir 11	10	10	9	563.30	574.54	98.31	5745.44	278.80	5.84
Arced Labyrinth Weir 12	10	10	9	554.80	565.06	96.83	5650.60	274.11	5.84
Arced Labyrinth Weir 13	10	10	6	587.43	895.18	102.53	8951.79	440.17	8.73
Arced Labyrinth Weir 14	10	10	9	587.43	601.47	102.53	6014.71	292.09	5.87
Arced Labyrinth Weir 15	10	10	12	596.43	462.58	104.10	4625.83	221.35	4.44

Note that for the 700-ft weir (solution 3 and 4), the solutions are practically the same design, but the costs are different. This is possible because the headwater ratios are different; thus for the 0.4 head water ratio curve, the wall is going to be higher and the discharge will be lower. The rise in height will increment the cost of the weir thus making it more expensive for the same geometric design. Headwater ratio parameter is important because it influences the cost of the structure since the arced labyrinth spillway wall height is dependent of this parameter.

From the above solutions it can be noted that the lowest cost spillways are not necessarily those with lower weir lengths as is the case with solutions 6 and 15. This is true taking into consideration the footprint area of the spillway which increases the foundation cost. This can be explained in the following manner, for the proposed design procedure an increase in α is proportional to an increase in the length of B, which means at the end increases the footprint area which increases the overall cost.

Upon inspection of the most economic weirs, it is clear that the lowest cost is not necessarily at the width that the project was originally trying to be developed. The optimization scheme suggests that, for this specific discharge and site specific criteria, the lowest cost weir lies around a channel width of 750 ft. A CAD spillway schematic was developed and is presented in Figure 5-2 and Appendix D. A cost trend for the widths are shown in Figure 5-3 which it is observed that there cost of the weir is higher for lower H_T/P ratios.

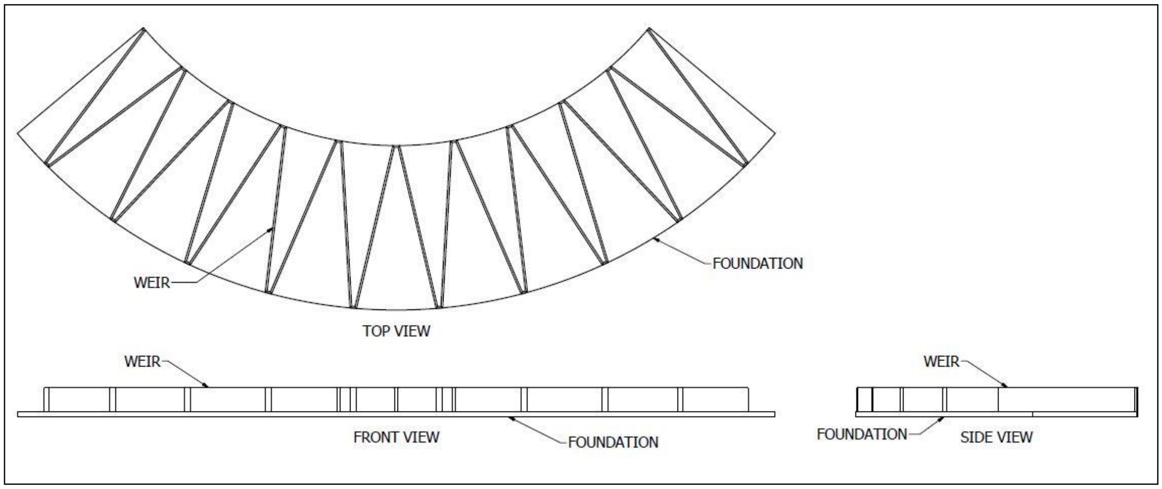

Figure 5-2. Drawing of arc labyrinth weir 6, with expected geometric features.

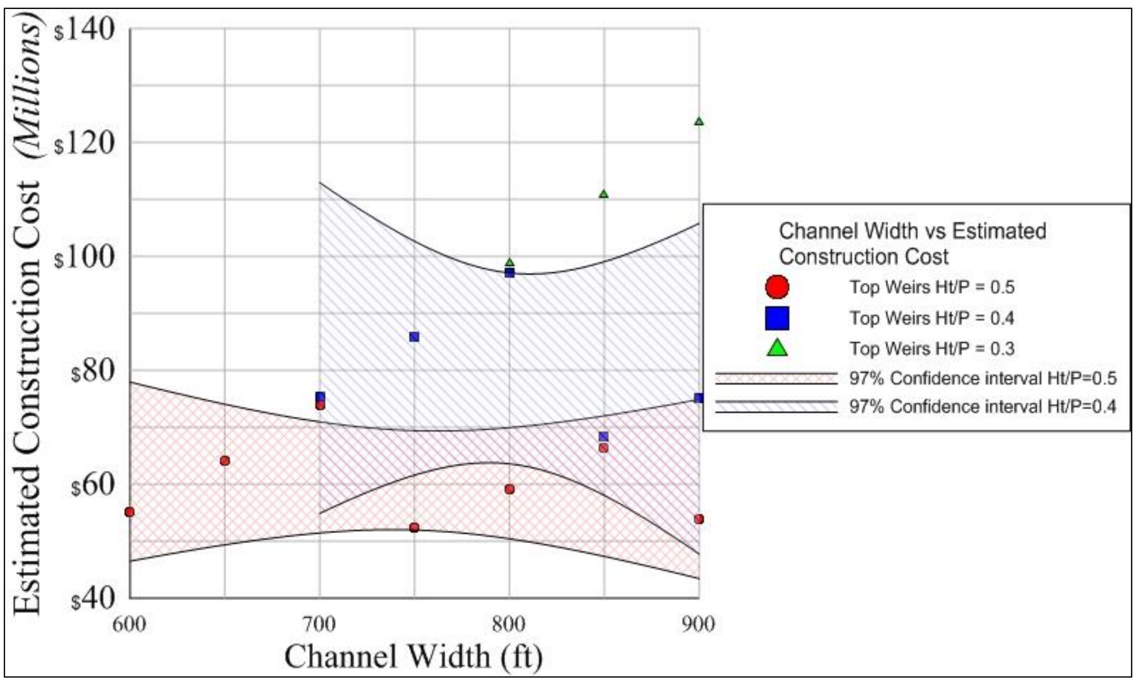

Figure 5-3. Cost trend analysis for variations in independent variables based on Ht/P ratio.

The parameters seem to coincide that the most efficient weir is a 10 cycle, θ=10 weir with a slight variation of the internal angle between 6° and 12°. The variation in the internal angle indicates that there is no clear angle that will completely optimize the design. With the same internal angle and varied width, Figure 5-4 indicates that both have the tendency that, at lower channel widths, the cost decreases up to a critical value where no solution exists. The rule is that small internal angles provide the lower cost weirs but will have great cost variation based on geometry factors.

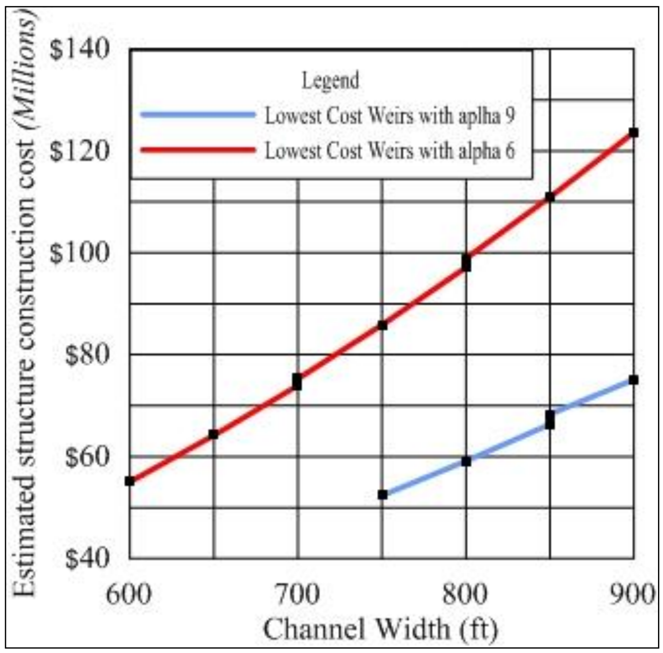

Figure 5-4. Structural cost of spillway while varying the channel width trend for internal angles.

The trends of these angles can be observed in Figure 5-5 where the cost increases as weir length is increases, but it can be observed that initially higher internal angles create shorter cycle lengths. Costs for the 600 and 750 ft width are very close, and it's up to the designer to ultimately base the solution on other factors and not only on the economic analysis of the structure.

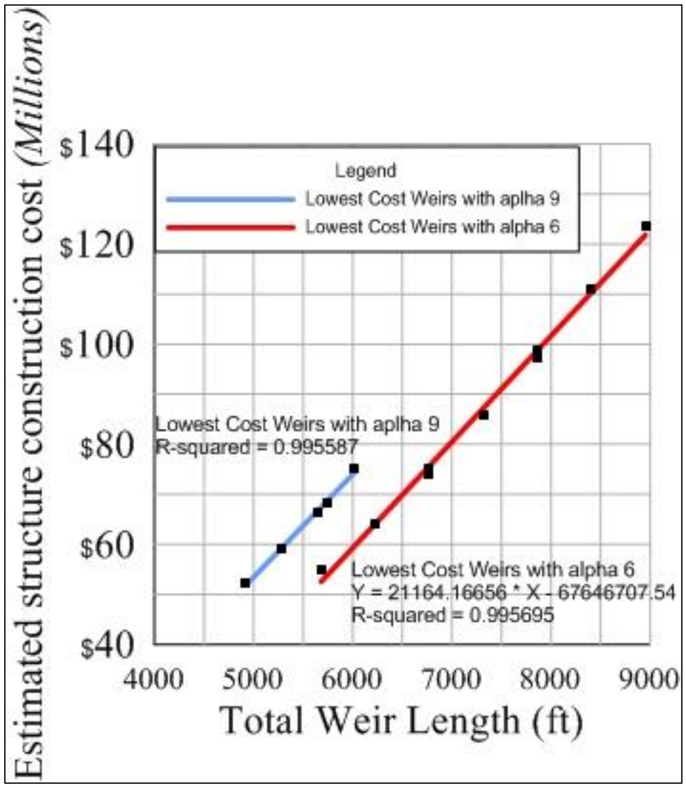

Figure 5-5. Cost trend based on weir length for different wall angles.

To ultimately observe the behavior of the variability of the geometric parameters, Figure 5-6 was developed. The figure has the top 10 solutions (when solutions exist) in the test matrix for each varied H_T/ P ratios and widths. The red line represents the lowest cost weir obtained for 750-ft-wide channel. Most geometric parameters of the design coincide in the values of 10 cycles, θ=10 and α = 6. These common denominators suggest that these parameters, for cycle limits between 5 and 10, lowest cost spillways lie between this geometries. High θ can be obtained in circumstances where it is more economical to create large apexes with large values for B, thus reducing the radius, although at a point this can happen as part as this proposed methodology, it is not necessarily the overall most economical solution.

The relation for the H_T/P ratio and the cost is presented in Figure 5-7. Since the weir design is limited by this parameter, it means that at low H_T/P, the walls would be higher thus impacting the cost directly. An implicit consequence of a high Ht/P ratio is that, since the discharge has to happen in such little height, the weir length has to compensate for this head loss which will make the length longer thus impacting the cost of the structure. A longer structure means more concrete for the walls and more foundation placement.

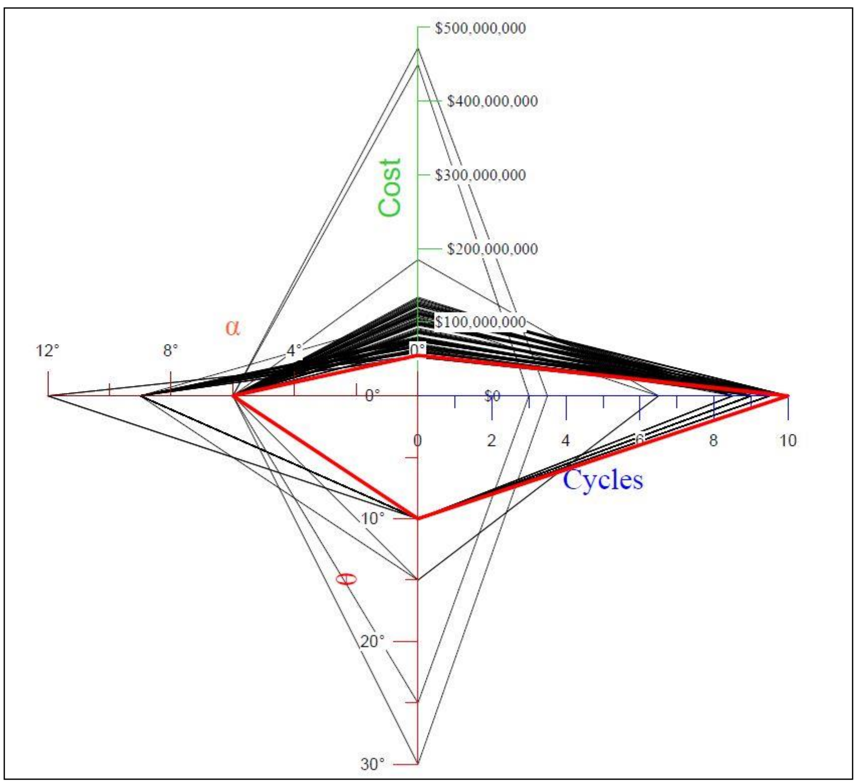

Figure 5-6. Geometric parameters analysis (α is the sidewall angle and θ is the Cycle arc angle).

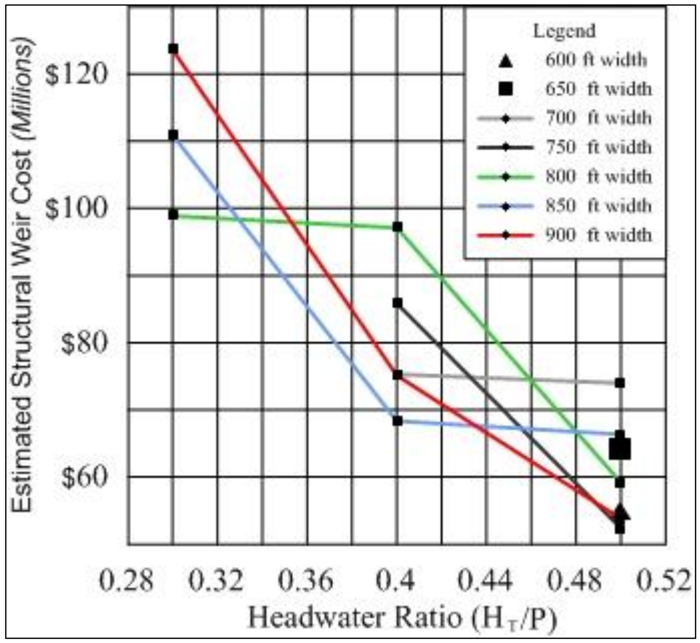

Figure 5-7. Relationship trend between headwater ratio and the cost of the weir at various widths.

Another analysis prepared from the most cost effective solution takes into consideration that the cost effectiveness of the spillway is defined as the cost per spillway capacity in a certain width. This method is not used to optimize the design; instead it is used to give an insight of how much discharge the design is capable compared to its cost. The curve is then compared for the lowest cost weirs for different widths. From Figure 5-8, the relationship between discharge and flow for different widths can be observed. Using this approach, the spillway for a 750-ft-wide weir is the most economical weir for the amount of discharge it provides.

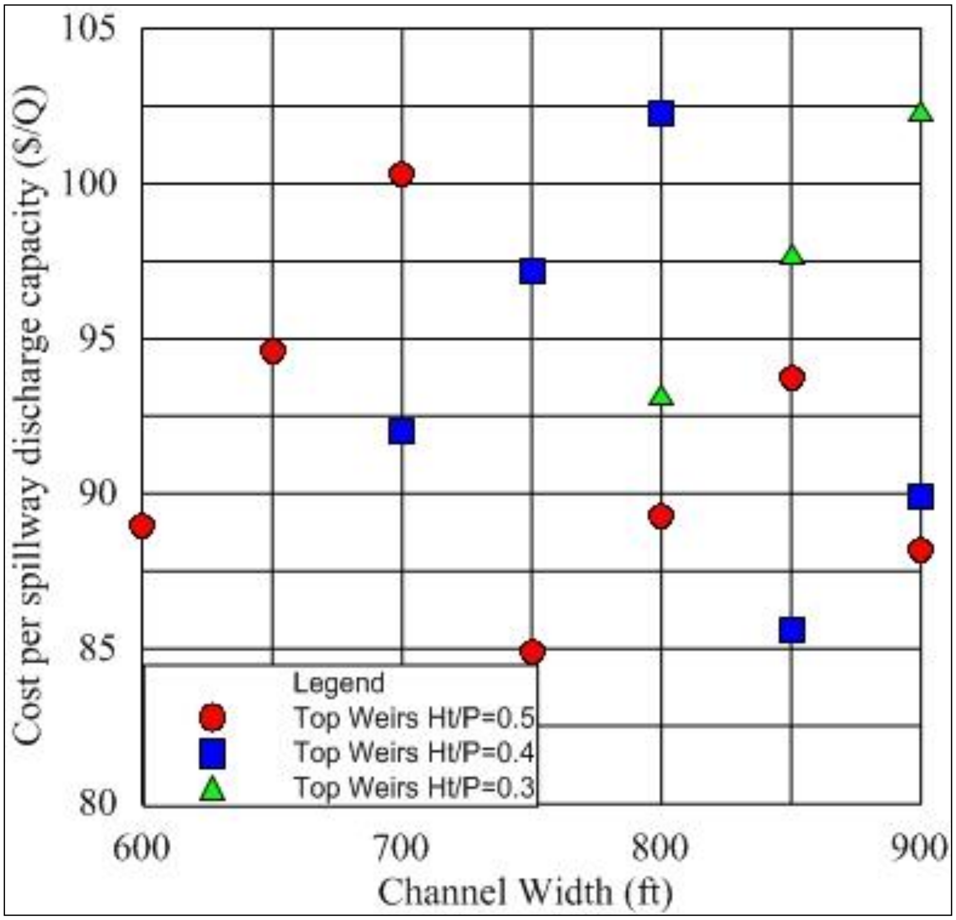

Figure 5-8. Cost per discharge for different widths.

Discharge curves are an important part of the analysis in which the behavior of the weir is idealized. The important part of the design is that it should comply with the expected outflow discharge thus effectively passing the amount of water is necessary for crest height chosen. This means that the selection of the headwater ratio plays a critical part in the design. Another design consideration is that the proper scaled physical models or numerical model hydraulic outputs play a critical role in the determination of the hydraulic effects and behavior of the designed spillway.

The rating curves for the least cost spillways are presented in Figure 5-9. It is clear that all the solutions presented in Figure 5-9 comply with the minimum discharge of nearly 600,000 cfs and be noted at the same time that other weirs exceed the discharge by a considerable amount. As the overflow capacity increases, the cost of the weir also increases, thus the lowest cost weirs will be ones closer to the specified discharge.

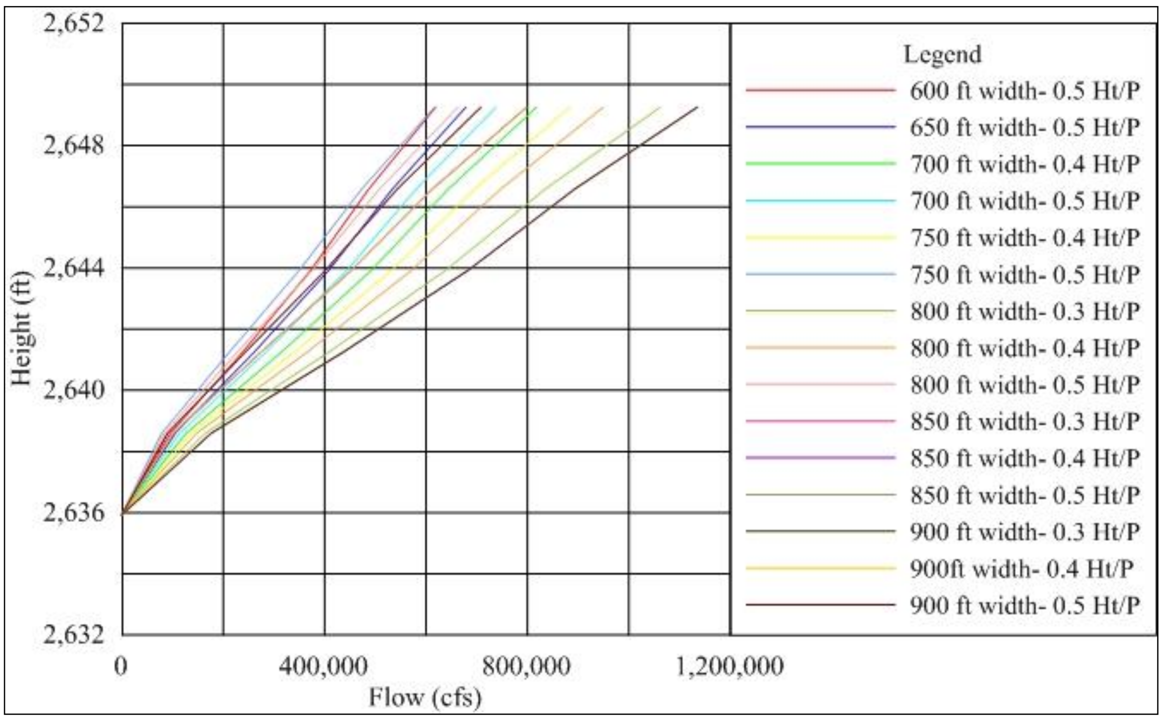

Figure 5-9. Rating curve for top weirs in variable parameter analysis.

As part of the hydraulic study, the cycle efficiency is observed to investigate the behavior of the weir under expected flood conditions. Cycle efficiency is a representation of the discharge per cycle. The study of the cycle efficiency is taken into consideration to obtain information about the ability of the weirs to discharge the outflow based on different sidewall angles. From Figure 5-10, the cycle efficiency is higher for small angle weirs when compared to other relative values. The curves also suggest that the highest efficiency of the weir occurs at low headwater ratios and that efficiency decreases as the ratio increments. As a general approach for the design of labyrinth spillway, the use of small wall angles makes the weir more efficient.

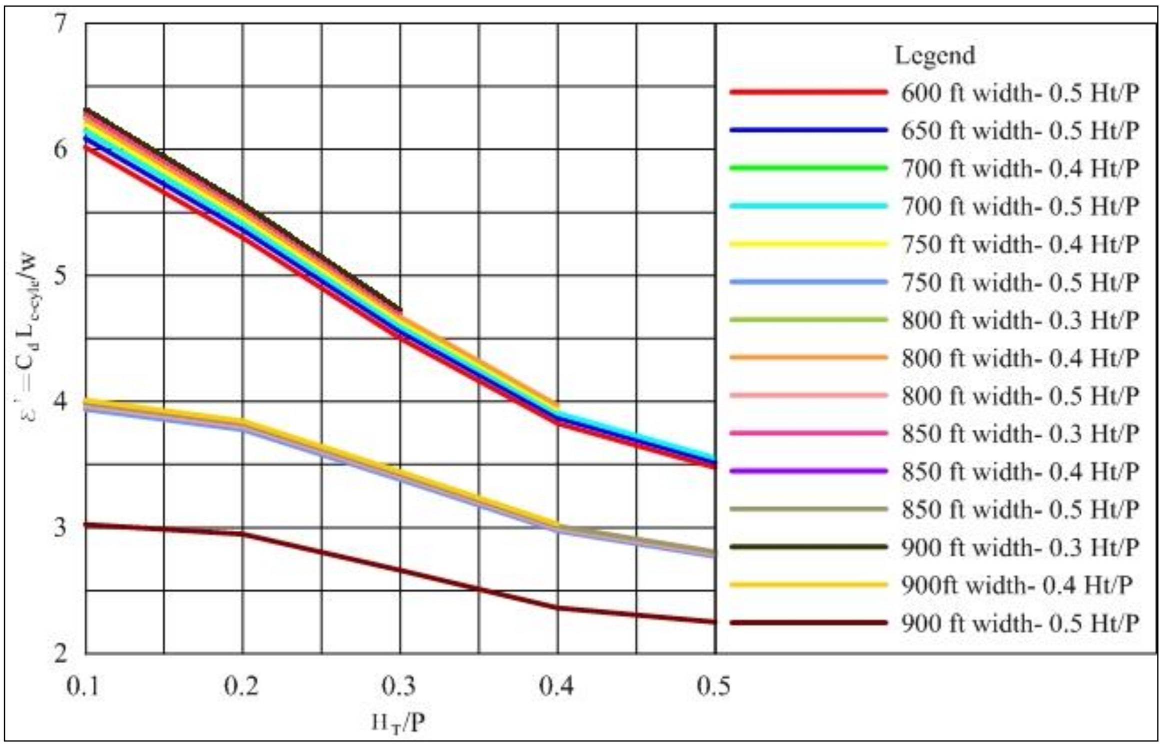

Figure 5-10. Cycle efficiency vs. H_T/P for variations in channel width.

5.2.4 *Value Analysis*

Following the procedure from section 4.6, it is possible to obtain how much value each solution represents among the choices of the minimum cost spillway structures. It is clear that minimum cost is not the only criteria for weir selection as risk factors, site specific criteria, and others affect the final choice, but in an environment where the owner seeks the lowest cost solution, a set of high value solutions are presented. Table 5-7 presents the value analyses for the minimum cost solutions of the parametric sweep.

Table 5-7. Calculations of value based on cost and performance parameters.

Top Weirs Trends	Width	Ht/P	Outflow	Cost	F_i	C_i	Value
	ft		CFS	*$*			
Arced Labyrinth Weir 1	600	0.5	618,927	55,051,514	0.050	0.047	1.058
Arced Labyrinth Weir 2	650	0.5	678,281	64,175,298	0.055	0.055	0.995
Arced Labyrinth Weir 3	700	0.4	818,061	75,293,242	0.066	0.065	1.023
Arced Labyrinth Weir 4	700	0.5	737,634	73,970,825	0.060	0.064	0.939
Arced Labyrinth Weir 5	750	0.4	883,886	85,866,915	0.072	0.074	0.969
Arced Labyrinth Weir 6	750	0.5	616,781	52,357,593	0.050	0.045	1.109
Arced Labyrinth Weir 7	800	0.3	1,061,373	98,883,744	0.086	0.085	1.010
Arced Labyrinth Weir 8	800	0.4	949,710	97,112,322	0.077	0.084	0.921
Arced Labyrinth Weir 9	800	0.5	662,404	59,151,675	0.054	0.051	1.054
Arced Labyrinth Weir 10	850	0.3	1,134,937	110,923,672	0.092	0.096	0.963
Arced Labyrinth Weir 11	850	0.4	798,405	68,337,386	0.065	0.059	1.100
Arced Labyrinth Weir 12	850	0.5	708,027	66,347,536	0.057	0.057	1.005
Arced Labyrinth Weir 13	900	0.3	1,208,502	123,635,339	0.098	0.107	0.920
Arced Labyrinth Weir 14	900	0.4	835,824	75,119,687	0.068	0.065	1.047
Arced Labyrinth Weir 15	900	0.5	609,978	$53,797,218	0.050	0.046	1.067
		Total	12,322,731	$1,160,023,968			

From the value calculations alone and data presented in Table 5-7, an objective selection can be made in terms of which spillway would be selected. Risk associated with each selection have to be considered and compared to the expected flood criteria. In this case, the highest value weir is Arced Labyrinth Weir 6, which coincides with the lowest cost spillway of all the choices.

5.3 Suggested Optimization Parameter

The proposed geometric optimization scheme for arced labyrinth weirs is based on obtaining the most economical solutions from a vast amount of possible designs. From all the designs, the search limit was limited do the data presented in Table 5-1. A parameter that would represent the most optimum design or be close to this design based on existing hydraulic conditions was found. The most optimum weirs from the parameters selected reside in an R/W ratio close to 1.53. The range of most optimum weirs is for $1.508 \leq R/W \leq 1.532$. This parameter becomes important when a rapid solution is necessary. When only the width of a channel is known, a rapid solution to the most optimum weir that could fit in that area and a possible guess of the most economical weir lie on this ratio. With the known radius, it is possible to obtain the internal angle of the weir Θ thus obtaining the first parameters for the rapid design of a weir. The selection of the number of cycles will need to be based on previous effective designs; it is recommended to use the maximum number of weirs from available data, ten (10). The selection of the sidewall angle will need to be based on the designs studied in this document with a recommended value of 6°. From this and further geometrical computations, the design of an arced labyrinth weir can be completed. Further analysis of the discharge capacity needs to accompany the weir selection process, but this procedure will give the designer a rapid response of which weir to analyze when no software integration is available. Figure 5-11 demonstrates the results of the cost for all the top weirs at changing widths and headwater ratios. The most optimum values, even changing the width and headwater ratios occur for similar R/W. The cost changes reflect the difference in geometrical parameters between the weirs.

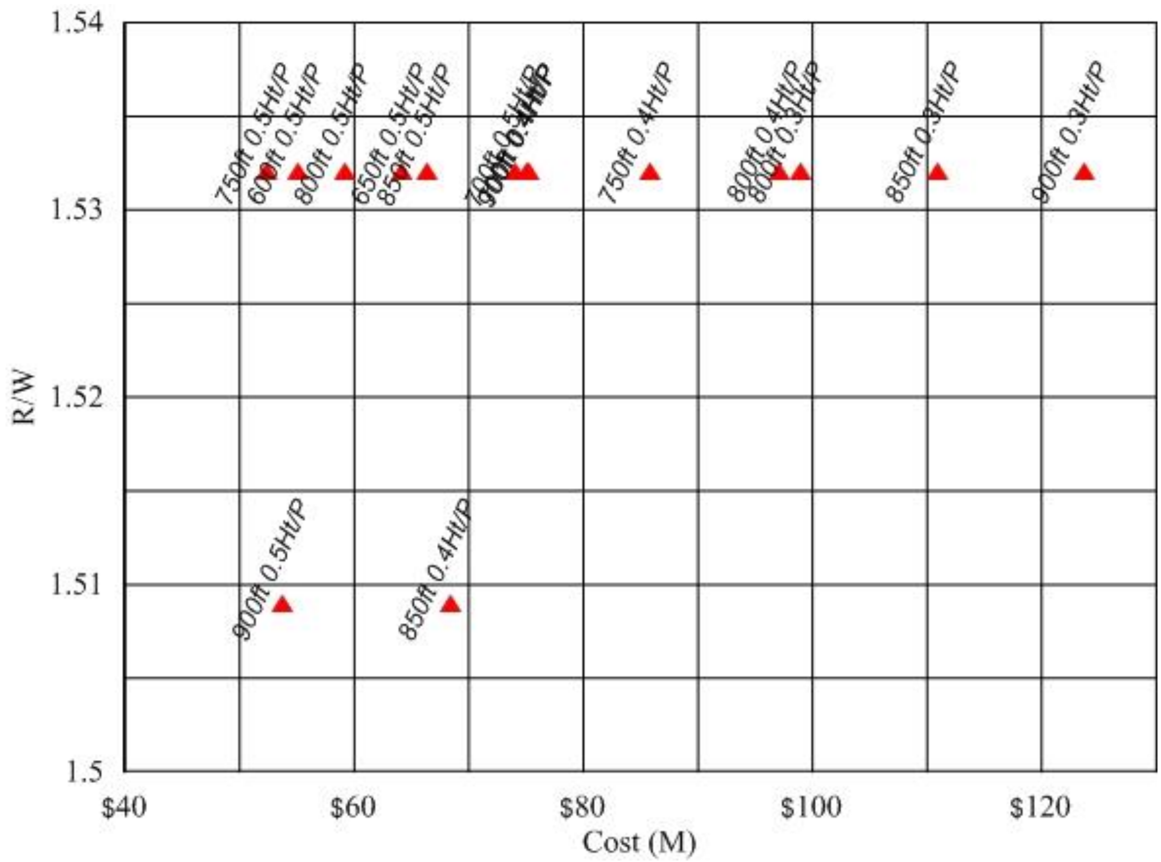

Figure 5-11. Lowest cost spillways relation between R/W to weir cost.

6 CONCLUSIONS

6.1 Summary

A proposed geometric optimization tool was developed for the geometric design of arced labyrinth spillways. This tool can be used by varying eight geometric variables to minimize the cost of a spillway that can perform adequately for an expected outflow, which only five where varied for the purpose of this document. Output parameters include the geometric data necessary to design an auxiliary spillway along with the hydraulic parameters and expected hydraulic behavior. Varying geometric parameters include the change of α, θ, H_t/P, W and R in order to obtain the geometric designs to be evaluated in a cost and value analysis. The program has its limitations in terms of the available hydraulic experimental data. The hydraulic data for the weirs is important in terms that the more data available for other weirs, the more iterations can be made, thus optimizing the spillway design based on all available configurations. It is possible that once this hydraulic data is available, it can be accommodated in the program to obtain solutions for a larger number of internal angles and larger number of cycles. The configuration possibilities for arced labyrinth weirs are infinite, but from an economic point of view, there exist optimum solutions that can satisfy all the specified constrains and provide the highest value indexes based on the construction cost estimate and its discharge capacity. The program attacks site specific constrains such as area and width limitations, provides an economic assessment of the possible weirs, provides information about the weir geometry that will create such structure, and provides information about the hydraulic behavior of the designs. All of these parameters are considered important and must be addressed when taking into consideration a design of a spillway. Other considerations that will influence the flow discharge are the directionality of the flow, which is not explicitly considered for this design procedure.

For arced labyrinth weir geometries, the most economic weirs tend to have short apron width, B parameter. It has been observed that the longer the apron, the higher the cost of the weir. Since studied wall angles range from 6° to 35°, it is important to notice from the case study that the lowest cost weirs tend to have small internal angles, most of them are near 6°, but values tend to range from 6° to 12° for most cases. A design parameter that greatly affects the cost of the spillway is the headwater ratio. This parameter influences the weir wall, the lower the headwater ratio the higher the wall, thus affecting the cost but at the same time implicitly affecting negatively the discharge capacity of the design since it can increase the length of the weir to accommodate the flow. This is done by the effect it has on the water height, which is a coefficient that impacts the flow, and to stabilize this decrease in head as the length of the weir increases to comply with discharge needs. It was found that at higher headwater ratios, designs imply a reduction in the structural cost of the spillway.

Although weir length affects the cost, the longer the weir, the costlier it is; it has been shown that larger sidewall angles develop low cycle length weirs, while the lower sidewall angles tend to initially have higher weir lengths. Although this is true, it is also true that the lowest cost spillways are not necessarily those with lower weir lengths. This is true taking into consideration the footprint area of the spillway which increases the foundation cost. This can be explained in the following manner, for the proposed design procedure an increase in α is proportional to an increase in the length of B, which means at the end increases the footprint area.

To get the most optimum of solutions, a substantial test matrix for different widths was analyzed. This test matrix included fractions of the maximum expected width. Specific site constraints may affect the proposed channel width, thus having alternatives widths compared increased the search matrix within the program. At the moment it is configured to run for a user specified channel width, thus a series of successive iterations will need to be applied in order to obtain a valuable set of solutions.

For high-risk projects, which, a rapid solution is necessary rather than the lowest cost possible solution. The economic feasibility of arced labyrinth weirs was presented as well as a complete design methodology that was embedded into a program that aids in the process of the initial design. Economic feasibility of the weir is presented comparing the cost and hydraulic performance of a linear labyrinth weir to a series of other arced labyrinth weirs. For a given case study an arced labyrinth weir presented a solution in which a smaller channel width was able to discharge a larger volume of water capacity at a lower cost when compared to a linear labyrinth weir. A smaller area indicates less earthwork movement, thus saving money not only in the structural cost but also in earthwork as well as other ancillary areas.

The spreadsheet-based tool is a rapid tool for developing a solution and can be further developed as new information becomes available. If other tools, for example the spreadsheet developed by Crookston (2010), wanted to be used to find the high value coefficient arced labyrinth weir, a good first iteration for the analysis is to start with a R/W ratio of 1.532 as found by this study. The tools' solutions would be limited only to the hydraulic information provided by other authors' physical model studies. By using other previous design procedures, the spillway designer must note that each design is individual instead of searching through all the available possible solution.

Also found were two cases where the value of the spillway is at its highest when the cost is at its lowest. It is known that the design will not be evaluated solely in terms of economic reasons since other spillways with higher performance and value analysis higher than 1 can be selected based on other specified criteria.

6.2 Future Research

Further research is a critical part of the analysis for solving the undersized spillways capacity. The spreadsheet-based program is written in such a way that entering new information into the program and adding new parameters from future research is possible thus, it can continue to operate while incorporating new research data.

- *Feasibility of using a multi-objective parameter optimization approach.* Conducting an investigation of how the parameters change the effect of the overall design was conducted in this research. Future research should include the optimization of individual parameters to find the ultimate optimization of the design, thus a multi-objective parameter study is recommended. This statistical approach can quantify the variability in the design and optimize parameters individually to find the most economical solution.

- *Adding a change in width factor to the current program*. Since the width of the channel seems to play an important role in the optimization of the weir solution, it is important to include it as another variable in the optimization procedure. An implementation of this parameter as a dynamic variable, treated like a range, should be implemented in the developed program code.
- *The structural components of arced labyrinth weirs have to be analyzed.* The study is based on the geometrical characteristics and does not focus on the structural analysis of its components. The structural analysis of the design will affect the cost of the structure. A complete structural analysis should include the effects of negative pressure on the wall outflow, recommendations of headwater ratios for structural stability, and recommendations for wall thickness. The analysis of seismic events on the structure and the structure behavior need further studies. Other considerations would include the effects of water freezing and thawing, as well as water hammer effects and impulse waves on the structure while including recommendations to alleviate the stress effects on the structure.
- *Change in foundation to reduce cost.* It has been demonstrated that the apron length (B) plays an important factor in the cost of the structure. Thus, a study of developing

non-continuous foundations to reduce the cost of the structure can be studied. The analysis of the cost must be taken into account from a geotechnical and structural analysis background.

- *Spillway outflow matched to channel capacity*. The effects on the downstream area have not been evaluated in the design nor have taken into account, which is why a headwater ratio not exceeding 0.5 was chosen. Studies about the nape behavior and efficiency of the hydraulic behavior in arced labyrinth weir are taken into account in the discharge coefficient, but the channel where the water will discharge into has not been evaluated. Correct channel dimensioning to receive the outflow is necessary as well as implementation, if needed, of energy dissipation structures.
- *Maintenance of the structure.* The maintenance of an arced labyrinth weir that will investigate the debris cleanup as well as preventing sedimentation and trash buildup. Arced labyrinth weirs are a relatively new spillway design susceptible to known problems like trash buildup, but the author has no knowledge of studies on the effects on discharge efficiency due to this type of problems.
- *Numerical models.* Numerical models are a cost effective way to analyze the behavior of a structure due to environmental factors. The numerical models should be able to mimic the behavior of past physical models as well as to be able to obtain the hydraulic behavior for new designs. Numerical models can be used for site-specific criteria as well as physical scale models. The data suggested from

numerical model can be used to further increase the hydraulic data available for arced labyrinth weirs.

- *Physical modeling.* Physical modeling of arced labyrinth weir is necessary to calibrate numerical models as necessary. Increasing the physical models variety in cycle numbers, sidewall angles, and other geometric parameters would extract enough information to add the data to this spreadsheet based program and calibrate numerical models. This information is used in the optimization of the structure and would provide more parameters to consider for a more accurate optimum solution.
- *Economic study of material and construction method*. The construction estimate of the structure includes assumptions on the construction methods that are to be used. A study of the proposed construction methods can be compared to other construction methods and materials used. It is also important to consider the options and benefits of using pre-fabricated structures to be included in the construction of the spillway.
- *Higher headwater ratios.* Although current research has been able to test up to 0.9 H_T/P, for some cases, there exists incomplete data of weirs up to this level, and even higher headwater ratios should be studied to fully understand the hydraulic behavior of the model. Values of maximum headwater ratios should be revised to examine up to what headwater ratios the effects of the labyrinth become negligible. Structural implications of the structure walls should be verified for high headwater ratios.

- *Staged arced labyrinth weirs.* For lower head water ratios than the expected flood condition in normal or daily usage of an arced labyrinth weir, the study of staged arced labyrinth weirs can be considered. This would verify the feasibility of the weirs for normal usage and flood events with only the arced labyrinth weir structure.

6.3 Final Thoughts

It is important to acknowledge that the presented data are based on case studies and available hydraulic data. The final design of the structure will depend on considerations by the designers that should include flow directionality and site specific factors. The presented designs serve as a guide for a final structure with the basic geometric parameters selected. Further development and continuous update to the spreadsheet-based program are strongly encouraged to include new data as it becomes available. Higher headwater ratios can be considered in the solutions, but implications of structural behavior is uncertain. Higher head water ratios reduce cost, thus reducing efficiency of the weir thus the leveling of this two parameters is key to obtaining a cost effective weir.

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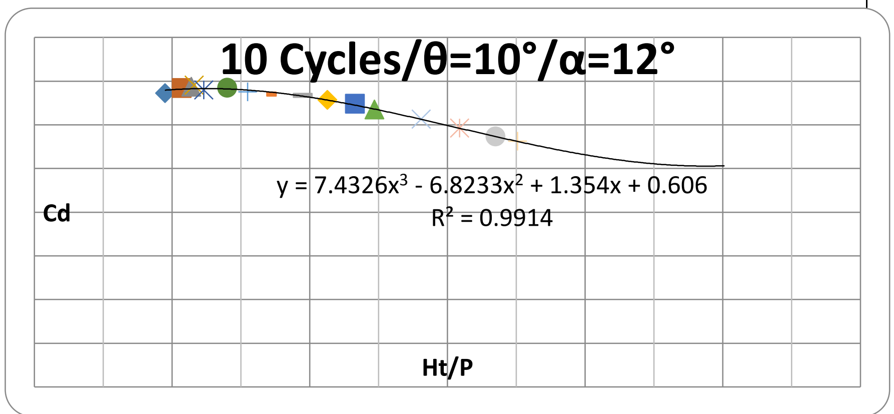
APPENDIX A-TREND LINE COEFFICIENTS

A-1. Hydraulic trend lines based on data from (Christensen 2012)
for N=10, θ =10°, α= 12°.

A	B	C	D
7.4326	-6.8233	1.354	0.606

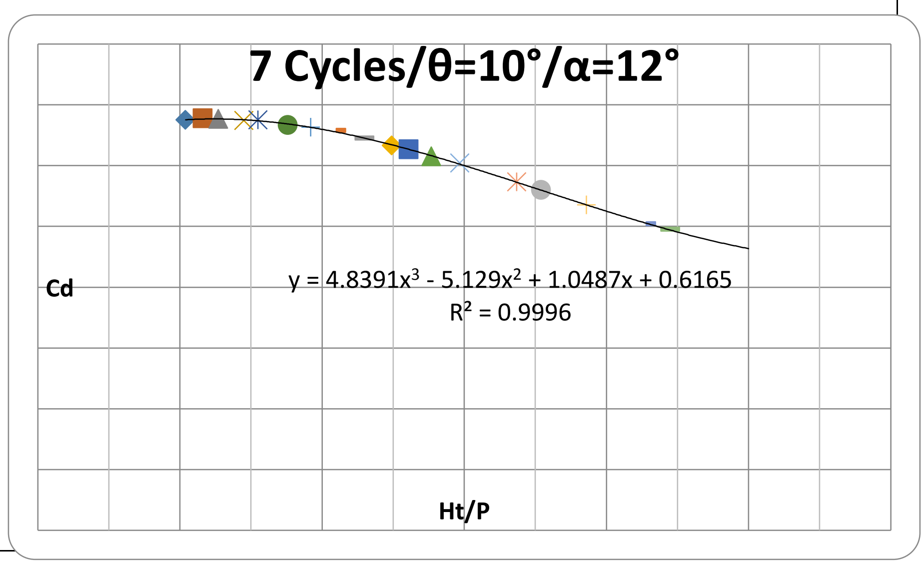
Cycle	10
Θ	10
α	12
HT/P	Cd
0.095	0.672
0.107	0.684
0.114	0.687
0.116	0.691
0.123	0.68
0.14	0.685
0.155	0.675
0.169	0.67
0.195	0.667
0.213	0.657
0.233	0.648
0.247	0.635
0.281	0.613
0.309	0.592
0.335	0.573
0.351	0.562



A-2. Hydraulic trend lines based on data from (Christensen, 2012)
for N=7, θ =10°, α= 12°.

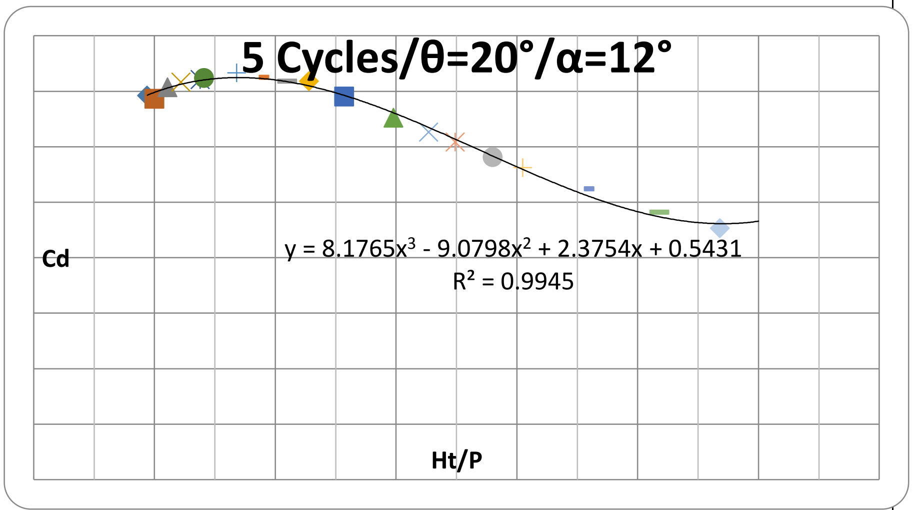
A	B	C	D
4.8391	-5.129	1.0487	0.6165

Cycle	7
Θ	10
α	12
HT/P	Cd
0.104	0.675
0.116	0.678
0.127	0.677
0.145	0.674
0.155	0.675
0.176	0.667
0.192	0.663
0.21	0.658
0.23	0.645
0.249	0.633
0.261	0.627
0.277	0.615
0.297	0.604
0.337	0.573
0.354	0.56
0.386	0.535
0.428	0.504
0.445	0.495



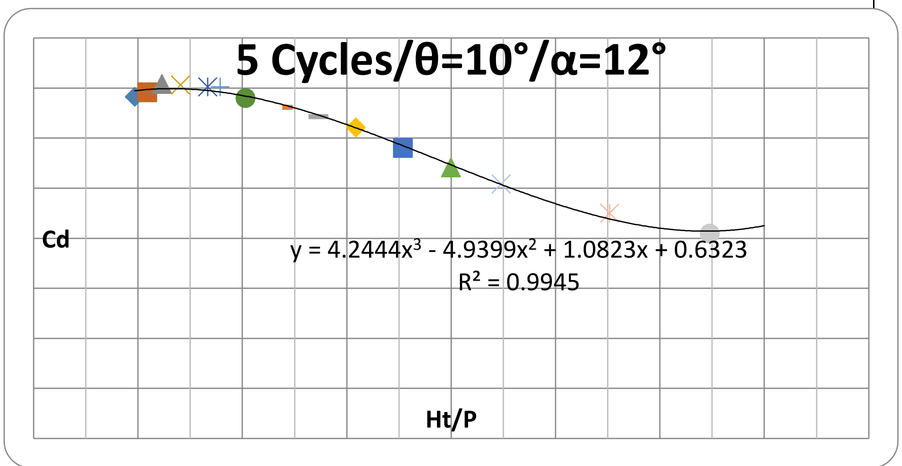
A-3. Hydraulic trend lines based on data from (Christensen, 2012) for N=5, θ =20°, α= 12°.

		A	B	C	D
Cycle	5				
Θ	20	8.1765	-9.0798	2.3754	0.5431
α	12				
HT/P	Cd				
0.094	0.692				
0.1	0.686				
0.111	0.707				
0.122	0.716				
0.138	0.721				
0.141	0.724				
0.168	0.733				
0.187	0.725				
0.21	0.718				
0.228	0.718				
0.257	0.69				
0.298	0.652				
0.327	0.626				
0.349	0.608				
0.38	0.581				
0.405	0.562				
0.456	0.524				
0.518	0.482				
0.568	0.453				



A-4.Hydraulic trend lines based on data from (Christensen, 2012) for N=5, θ =10°, α= 12°.

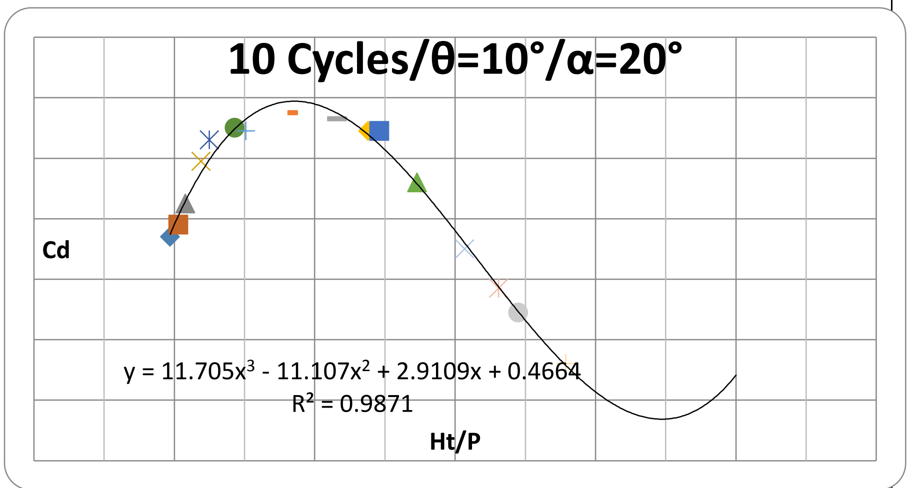
		A	B	C	D
Cycle	5				
Θ	10	4.2444	-4.9399	1.0823	0.6323
α	12				
HT/P	Cd				
0.097	0.682				
0.109	0.691				
0.123	0.708				
0.141	0.706				
0.167	0.702				
0.203	0.68				
0.179	0.702				
0.239	0.661				
0.273	0.643				
0.309	0.621				
0.354	0.58				
0.4	0.541				
0.448	0.508				
0.552	0.45				
0.648	0.409				



A-5. Hydraulic trend lines based on data from (Christensen, 2012) for N=10, θ =10°, α= 20°.

			A	B	C	D
Cycle	10		11.705	-11.107	2.9109	0.4664
Θ	10					
α	20					

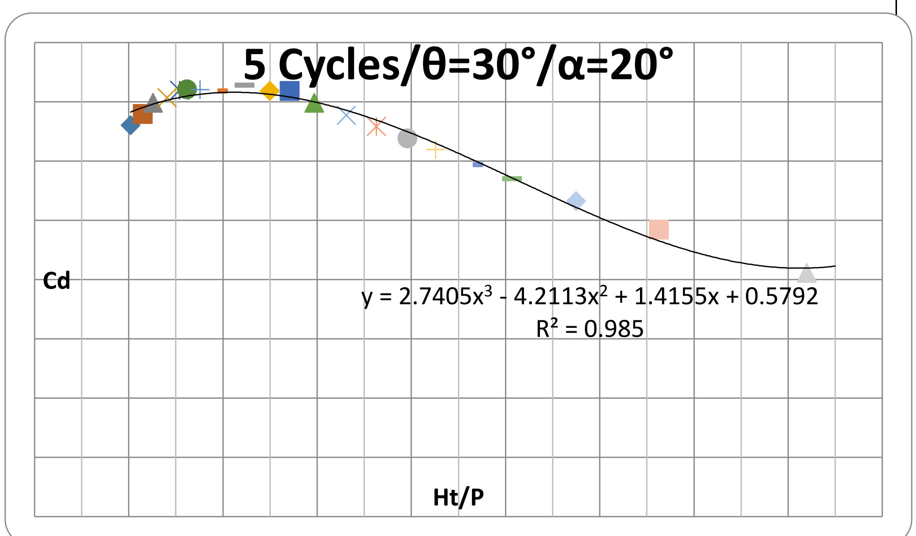
HT/P	Cd
0.097	0.654
0.103	0.658
0.108	0.665
0.119	0.679
0.125	0.686
0.143	0.69
0.151	0.689
0.181	0.695
0.216	0.693
0.238	0.689
0.246	0.689
0.273	0.672
0.307	0.65
0.331	0.637
0.345	0.629
0.379	0.612



A-6. Hydraulic trend lines based on data from (Christensen, 2012) for N=5, θ =30°, α= 20°.

			A	B	C	D
Cycle	5		2.7405	-4.2113	1.4155	0.5792
Θ	30					
α	20					

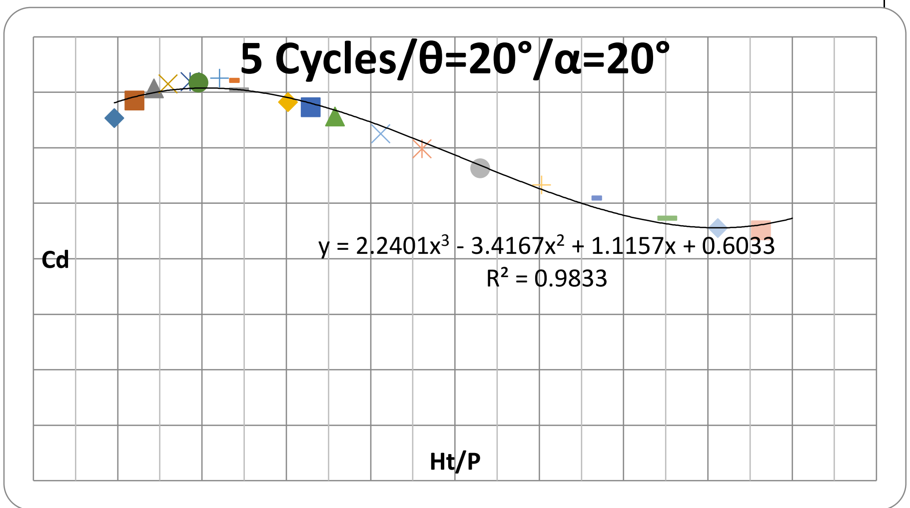
HT/P	Cd
0.102	0.66
0.115	0.679
0.126	0.698
0.141	0.707
0.154	0.719
0.162	0.721
0.176	0.72
0.195	0.718
0.223	0.728
0.25	0.718
0.271	0.718
0.297	0.698
0.331	0.677
0.363	0.658
0.396	0.638
0.426	0.619
0.466	0.594
0.507	0.57
0.575	0.532
0.663	0.484
0.82	0.411



A-7. Hydraulic trend lines based on data from (Christensen, 2012) for N=5, θ =20°, α= 20°.

			A	B	C	D
Cycle	5		2.2401	-3.4167	1.1157	0.6033
Θ	20					
α	20					

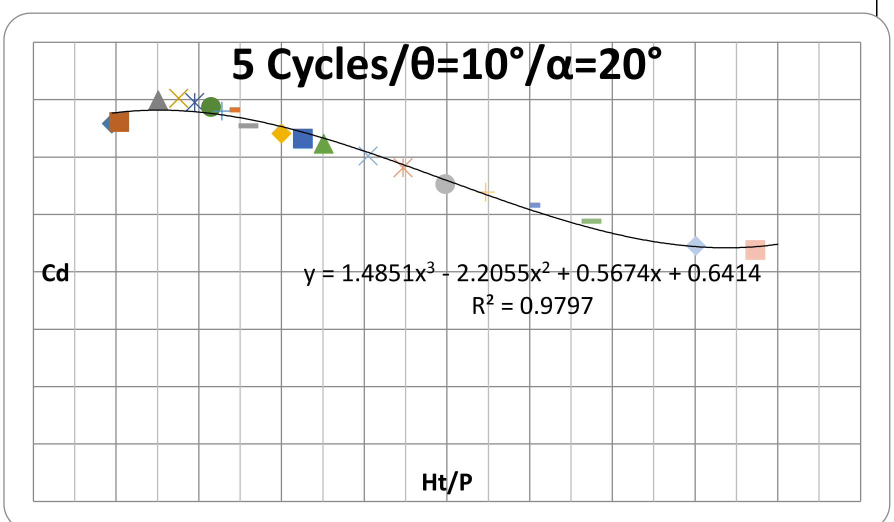
HT/P	Cd
0.096	0.653
0.12	0.685
0.143	0.707
0.16	0.715
0.186	0.719
0.196	0.717
0.221	0.725
0.233	0.721
0.244	0.704
0.302	0.682
0.329	0.673
0.358	0.656
0.412	0.625
0.461	0.598
0.53	0.563
0.603	0.533
0.663	0.509
0.752	0.473
0.812	0.455
0.863	0.451



A-8. Hydraulic trend lines based on data from (Christensen, 2012) for N=5, θ =10°, α= 20°.

			A	B	C	D
Cycle	5		1.4851	-2.2055	0.5674	0.6414
Θ	10					
α	20					

HT/P	Cd
0.095	0.658
0.104	0.661
0.151	0.699
0.176	0.702
0.195	0.695
0.215	0.687
0.228	0.68
0.238	0.682
0.26	0.654
0.3	0.641
0.326	0.632
0.351	0.623
0.405	0.602
0.447	0.581
0.498	0.553
0.547	0.539
0.601	0.516
0.675	0.488
0.801	0.445
0.873	0.438



APPENDIX B-CONSTRUCTION ESTIMATE AND CREW COMPOSITION

B-1 Quantity Takeoff for linear labyrinth spillway in lake brazos

Project	Labyrinth Weir Spillway										
Owner								**Date**	4/23/2015		
								Estimator	López, J		
Division	**3 Concrete: Walls and Footings**							**Sheet**	M.S. Thesis		
Code	**Description**	**Qty (ea)**	**L (ft)**	**W (ft)**	**H (ft)**	**Forms Contact Area (m2, sf)**	**Forms Area (m2, sf)**	**Concrete m3, cy**	**Finishing (Silane Sealer) (exposed areas) m2**	**Finishing (Class 1 ordinary) (exposed & unexposed areas) m2**	**Curing m2**
	Wall								Wall + 2*Sides (exposed)	all side areas	~ all over areas
						2 Qty (LH+WH)	*2 use*	*L x W x H*	*Qty x (LH+2*WH)*	*Qty x 2 (LH + WH)*	*Qty x LW + Qty x2(LH+WH)*
	Wall, in metric, m	1	521.34146	0.6097561	4.573170732	4773.94	2386.97	**1453.77**	**2389.76**	**4773.94**	**5091.84**
	Wall, in imperial, ft	1	1710	2	15	**51386.31**	**25693.15**	**1901.46**	**25723.17**	**51386.31**	**54808.06**
	Footing, in imperial, ft	1	181.60	6	181.60	**68133.15**	**34066.57**	**7328.22**	**35156.15**	**68133.15**	**69222.72**
	Form Materials (Wall)										
	Clark T4.6A neat factors: 5/8' plywood, Wall, form height 16 + Concrete raise 7ft hr'; T 4.11 loss factor, 1 cycle(use)										
	Form Elements	***Factors***	***Unit***	***Loss F***	***Total***	***Unit***	***notes***				
	Lumber (of forms' area)	2.85	bf/sf	**1.17**	**85673.82**	bf	of form area				
	Ties 3M (of contact's area)	0.22	T/sf	1.10	**12435.49**	ea	of contact area				
	Ties 5M (of contact's area)	0.13	T/sf	1.10	**7348.24**	ea	of contact area				
	Ties 6 M(of contacts area)	0.13	T/sf	1.10	**7348.24**	ea					
	Plywood (of forms' area)	2.85	sf/sf	**1.17**	**85673.82**	sf	of form area				
	Oil (releas agent; 500sf/g))	0.0020	gal/sf	1.10	**113.05**	gal	of contact area				
	Nails (0.1 lb/sf Clark Pg106)	0.1	lb/sf	1.10	**2826.25**	lb	of form area				
	Form Materials (Footings)										
	Clark T4.6A neat factors: 5/8' plywood, Abutment, form height 0-8'; T 4.11 loss factor, 2 cycle(use)										
	Form Elements	***Factors***	***Unit***	***Loss F***	***Total***	***Unit***	***notes***				
	Lumber (of forms' area)	2.95	bf/sf	**1.23**	**123610.56**	bf	of form area				
	Ties 3M (of contact's area)	0.15	T/sf	1.10	**11241.97**	ea	of contact area				
	Ties 5M (of contact's area)	0.11	T/sf	1.10	**8244.11**	ea	of contact area				
	Plywood (of forms' area)	2.95	sf/sf	**1.23**	**123610.56**	sf	of form area				
	Oil (releas agent; 500sf/g))	0.0020	gal/sf	1.10	**149.89**	gal	of contact area				
	Nails (0.1 lb/sf Clark Pg106)	0.1	lb/sf	1.10	**3747.32**	lb	of form area				
	Specs Notes			Table 4.11, 10% loss factor for hardware							
	Concrete class C: 4 K Psi										
						4.14 Use internal Vibrators					
	4.9 Inspection and Testing										
	ACI/CSA Certified test worker	300	assume 1 tech for 2 days								
	air content & slump test	123	at consultant discretion								
	strength test (4 specimens)	**123**									
	4.22.1 Curing Concrete										
	exposed concrete surface … wet burlap										
	unexposed concrete surface … curing compound										
	4.24.1 Concrete Surface Finish										
	unexposed concrete surface … chip out cavities, honeycomb, and other deficiencies							footings (assume all unexposed)			
	exposed surface (inc river piers) … Class 1 Ordinary, C2 Rubbed finish, and C3 bonded (w/ sealer Type 1c or 2)….							abutmnts (assume 1/4 area is unexposed and 3/4 exposed)			
	4.25 Sealer										
	Sealers for surfaces that will receive finishes class 2, 3, 4, 5 Surface Finish										

B-2 Summary Sheet

Project	Labyrinth Weir Spillway			Summary Sheet										
Owner				(Recapitulation Sheet)						Date	#######			
										Estimator	López, J			
Divi	3 Concrete: Wall and foundation									Sheet	M.S. Thesis			

Code	Ref	Description	Qty	Unit	Material Unit M Cost	Total Mat. Cost	Labor UMH LH/Unit	Total Man Hours	Hourly Rate	Unit Cost	Total Labor Cost	Equipment Unit Cost	Total Equip Cost	Total
	Formwork WALLS													
		Building Forms (form area; 1 form for 1 use)	25693.15	sf			0.09545	2452.53	42.18	4.03	$ 103,444	2.01	$ 51,702.22	$155,146.35
		using Clark's crew												
		Erecting Forms (contact area)	51386.31	sf			0.16111	8278.90	41.96	6.76	$ 347,343	2.46	$ 126,383.19	$473,726.08
		using Clark's crew												
		Stripping Forms (contact area)	51386.31	sf			0.05909	3036.46	39.83	2.35	$ 120,933	1.23	$ 63,225.59	$184,158.60
		using Clark's crew												
		Forms Material												
		Lumber (of forms' area) (give $0.5/bf)	85673.82	bf	0.50	$ 42,837								$42,836.91
		Ties 3M (of contact's area); (use 03 15 05.80 1700)	12435.49	ea	3.65	$ 45,390								$45,389.52
		Ties 5M (of contact's area); (use 03 15 05.80 1700)	7348.24	ea	3.65	$ 26,821								$26,821.08
		Ties 6 M (of Contact's area); Use 03 15 05.80 1700	7348.24	ea	3.65	$ 26,821								$26,821.08
		Plywood (of forms' area) (given $1.0/sf)	85673.82	sf	1.00	$ 85,674								$85,673.82
		Oil (of contact's area; 500sf/g) (03 05 13.20 1570)	113.05	gal	9.10	$ 1,029								$1,028.75
		Nails (of forms' area; 0.1 lb/sf) (06 05 23.10 0600)	2826.25	lb	0.83	$ 2,346								$2,345.78
	Formwork FOUNDATION													
		Building Forms Footings (form area; 1 form for 1 use)	34066.57	sf			0.080769	2751.53	39.74	3.41	$ 116,056	1.70	$ 58,005.55	$174,061.20
		using Clark's crew												
		Erecting Forms (contact area)	68133.15	sf			0.111538	7599.47	42.11	4.68	$ 318,837	1.70	$ 116,011.10	$434,848.03
		using Clark's crew												
		Stripping Forms (contact area)	68133.15	sf			0.040625	2767.91	39.94	1.62	$ 110,237	0.85	$ 57,633.72	$167,871.03
		using Clark's crew												
		Form Materials (Footings)												
		Lumber (of forms' area)	123610.56	bf	0.50	$ 61,805								$61,805.28
		Ties 3M (of contact's area)	11241.97	ea	3.65	$ 41,033								$41,033.19
		Ties 5M (of contact's area)	8244.11	ea	3.65	$ 30,091								$30,091.01
		Plywood (of forms' area)	123610.56	sf	1.00	$ 123,611								$123,610.56
		Oil (releas agent; 500sf/g))	149.89	gal	9.10	$ 1,364								$1,364.03
		Nails (0.1 lb/sf Clark Pg106)	3747.32	lb	0.83	$ 3,110								$3,110.28
	Concrete Wall													
		Concrete class C (30 Mpa)	1,901.46	cy	142.00	$ 270,007	0.76087	1,446.76	39.78	30.27	$ 57,550	11.20	$ 21,295.32	$348,852.80
		using Clark's crew												
		waste %	5.00%			$ 13,500								$13,500.37
	Concrete Foundation													$0.00
		Concrete class C (4K psi)	7328		150.00	$ 1,099,233	0.365854	2,681.06	38.61	14.13	$ 103,516	7.12	$ 52,209.11	$1,254,958.06
		using Clark's crew		cy										$0.00
		waste %	5.00%			$ 54,962								$54,961.67
														$0.00
		Ancilaries using concrete cheat sheet & rsmeans												
		Curing (2 clab; spray membrane 883 m2/d) (03 39 23.13 0300)	11526.13	m2	0.52	$ 5,994				0.55	$ 6,339			$12,332.96
Finish: all side areas - break ties & patch voids, 1Cefi, 50.17 m2/d) (03 35 29.60 0020)			11106.96	m2	0.32	$ 3,554	0.159			5.9	$ 65,531			$69,085.31
3 Finish: exposed side areas - Sealer (3.1 m2/liter) (03 05 13.20 1620) [=QTO!K11/3.1]			914.03	Liter	24.00	$ 21,937								$21,936.79
		C2 Finish: exposed side areas: Carb rub, dry(03 35 29.60 0050) [=QTO!K11]	2833.50	m2						11.8	$ 33,435			$33,435.32
		Tests: compresive strength (01 45 23.50 1950)	123.00	ea	20.07	$ 2,469								$2,468.61
		Tests: water/cement/slump test (01 45 23.50 3000)	123.00	ea	157.22	$ 19,338								$19,338.06
		Tests: ACI certified technician (01 45 23.50 5570) (cost/day; use 2d)	300.00	d						245	$ 73,500			$73,500.00
	Reinforcing Rebar													
		Reinforcing Rebar	779.00	mt	955.00	$ 743,945	8.00000	6232.00	43.00	344.00	$ 267,976	0.00	$ -	$1,011,921.00
		4 rodman w average output of means 03 21 10.60 0500, 0750 (see crews)												
		Ancilaries using concrete cheat sheet & rsmeans												
		Reinfocing lap, waste, accessories	20.00%			$ 148,789								$148,789.00
		Unload/sort (C5; 100ton/d; 03 21 10.60 2000)	779.00	mt						26	$ 20,254	8.65	$ 6,738.35	$26,992.35
		Handling, crane cost (C5; 135ton/d; 03 21 10.60 2200)	779.00	mt						19.2	$ 14,957	6.45	$ 5,024.55	$19,981.35
		Bid Item Total Direct Cost				$ 2,875,659					$ 1,759,908		$ 558,229	$5,193,796.21
														$5,193,796.21
		Location Factors				100					100		100	
		Total direct cost (LOCATION)				$ 2,875,659					$ 1,759,908		$ 558,229	$5,193,796.21
		Indirect labor cost	35.00%								$ 615,968			$615,967.89
		O & P	10%											$580,976.41
		Total cost (LOCATION)												$6,390,740.50

Direct project cost, National Average	**$5,193,796.21**
Direct project cost, Location	**$5,193,796.21**
Direct project cost w/o reinforcement	**$3,986,112.51**
Total project cost	**$6,390,740.50**
Total project cost w/o reinforcement	**$5,183,056.80**
Total project cost per CY	**$692.00**
Cost per Length	**$3,736.00**

B-3. Crew composition and cost for wall formwork construction.

Clark	Building FormWall 8+ (Table 4.12)		Labor	L & Equip	Crew Labor	Crew-Equipment		Labor	Labor	Equipment
	#	Crew Formation	Hourly Wage	Daily Rates	bare cost per Labor-hour	bare cost per Labor-hour	Material Cost	Hours per Unit	Unit Cost	Unit Cost
	0.5	Carpenter Foreman	47.85	191.40						
	2	Carpenter	45.85	733.60						
	1	Carpenter Helper	34.65	277.20						
	1	Laborer	36.65	293.20						
	0.5	Crane Operator	50.25	201.00						
	0.25	Truck Driver (heavy)	37.55	75.10						
	0	Welder	51.10	0.00						
	0.5	Crane (25 ton), hyd.		372.90						
	0.25	Service Truck (pickup), 4x4, 3/4 ton		42.10						
	1	Generator Diesel 100 kw		439.20						
	1	Bench Saw		31.21						
	42	Daily Labor Hours			42.18	21.08				
			Output	Unit						
	Examples	SFCA	440.00	SFCA/day			0.00	0.09545	4.03	2.01

B-4. Crew composition and cost for wall formwork placement.

Clark	Erect Form Wall 8' + (Table 4.12)		Labor	L & Equip	Crew Labor	Crew-Equipment		Labor	Labor	Equipment
	#	Crew Formation	Hourly Wage	Daily Rates	bare cost per Labor-hour	bare cost per Labor-hour	Material Cost	Hours per Unit	Unit Cost	Unit Cost
	1	Foreman	47.85	382.80						
	2	Carpenter	45.85	733.60						
	1	Carpenter Helper	34.65	277.20						
	2	Laborers	36.65	586.40						
	0.5	Crane Operator	50.25	201.00						
	0.5	Truck Driver	37.55	150.20						
	0.25	Welder	51.10	102.20						
	0.5	Crane (12 ton), hyd.		372.90						
	0.25	Service Truck (pickup), 4x4, 3/4 ton		42.10						
	1	Generator Diesel 100 kw		439.20						
	1	Bench Saw		31.21						
	58	Daily Labor Hours		3318.81	41.96	15.27				
			Output	Unit						
	Examples	SFCA	360.00	SFCA/day				0.16111	6.76	2.46

B-5. Crew composition and cost for wall formwork strip.

Clark	Form Strip Wall 8' (Table 4.12)		Labor	L & Equip	Crew Labor	Crew-Equipment		Labor	Labor	Equipment
	#	Crew Formation	Hourly Wage	Daily Rates	bare cost per Labor-hour	bare cost per Labor-hour	Material Cost	Hours per Unit	Unit Cost	Unit Cost
	0.25	Foreman	47.85	95.70						
	1	Carpenter	45.85	366.80						
	1	Carpenter Helper	34.65	277.20						
	3	Laborers	36.65	879.60						
	0.75	Equip. Operator (crane)	50.25	301.50						
	0.5	Truck Driver	37.55	150.20						
	0	Welder	51.10	0.00						
	0.75	Crane (12 ton), hyd.		559.35						
	0.5	Service Truck (pickup), 4x4, 3/4 ton		84.20						
	1	Generator Diesel 100 kw		439.20						
	0	Bench Saw		0.00						
	52	Daily Labor Hours		3153.75	39.83	20.82				
			Output	Unit						
	Examples	SFCA	880.00	SFCA/day				0.05909	2.35	1.23

B-6. Crew composition and cost for footing formwork construction.

Clark	Building Form Footing (Table 4.12)		Labor	L & Equip	Crew Labor	Crew-Equipment		Labor	Labor	Equipment
	#	Crew Formation	Hourly	Daily	bare cost per	bare cost per	Material	Hours	Unit	Unit
			Wage	Rates	Labor-hour	Labor-hour	Cost	per Unit	Cost	Cost
	0	Carpenter Foreman	47.85	0.00						
	1	Carpenter	45.85	366.80						
	1	Carpenter Helper	34.65	277.20						
	1	Laborer	36.65	293.20						
	0.25	Crane Operator	50.25	100.50						
	0.25	Truck Driver (heavy)	37.55	75.10						
	0	Welder	51.10	0.00						
	0.25	Crane (12 ton), hyd.		186.45						
	0.25	Service Truck (pickup), 4x4, 3/4 ton		42.10						
	1	Generator Diesel 100 kw		439.20						
	1	Bench Saw		31.21						
	28	Daily Labor Hours			39.74	24.96				
			Output	Unit						
	Examples	SFCA	520.00	SFCA/day			0.00	0.08077	3.41	1.70

B-7. Crew composition and cost for footing formwork placement.

Clark	Erect Form Footing 0-8' (Table 4.12)		Labor	L & Equip	Crew Labor	Crew-Equipment		Labor	Labor	Equipment
	#	Crew Formation	Hourly	Daily	bare cost per	bare cost per	Material	Hours	Unit	Unit
			Wage	Rates	Labor-hour	Labor-hour	Cost	per Unit	Cost	Cost
	1	Foreman	47.85	382.80						
	2	Carpenter	45.85	733.60						
	1	Carpenter Helper	34.65	277.20						
	2	Laborers	36.65	586.40						
	0.5	Crane Operator	50.25	201.00						
	0.25	Truck Driver	37.55	75.10						
	0.25	Welder	51.10	102.20						
	0.5	Crane (12 ton), hyd.		372.90						
	0.25	Service Truck (pickup), 4x4, 3/4 ton		42.10						
	1	Generator Diesel 100 kw		439.20						
	1	Bench Saw		31.21						
	56	Daily Labor Hours		3243.71	42.11	15.81				
			Output	Unit						
	Examples	SFCA	520.00	SFCA/day				0.11154	4.68	1.70

B-8. Crew composition and cost for footing formwork strip.

Clark	Form Strip Footing 0-8' (Table 4.12)		Labor	L & Equip	Crew Labor	Crew-Equipment		Labor	Labor	Equipment
	#	Crew Formation	Hourly	Daily	bare cost per	bare cost per	Material	Hours	Unit	Unit
			Wage	Rates	Labor-hour	Labor-hour	Cost	per Unit	Cost	Cost
	0.25	Foreman	47.85	95.70						
	1	Carpenter	45.85	366.80						
	1	Carpenter Helper	34.65	277.20						
	2	Laborers	36.65	586.40						
	0.5	Equip. Operator (crane)	50.25	201.00						
	0.5	Truck Driver	37.55	150.20						
	0	Welder	51.10	0.00						
	0.5	Crane (25 ton), hyd.		372.90						
	0.5	Service Truck (pickup), 4x4, 3/4 ton		84.20						
	1	Generator Diesel 100 kw		439.20						
	0	Bench Saw		0.00						
	42	Daily Labor Hours		2573.60	39.94	21.34				
			Output	Unit						
	Examples	SFCA	1280.00	SFCA/day				0.04063	1.62	0.85

B-9. Concrete wall placement crew composition and cost.

Clark	Concrete Placement Wall 8'+ - Crane, Table 5.1		Labor Hourly Wage	L & Equip Daily Rates	Crew Labor bare cost per Labor-hour	Crew-Equipment bare cost per Labor-hour	Material Cost	Labor Hours per Unit	Labor Unit Cost	Equipment Unit Cost
	#	Crew Formation								
	1	Labor Forman	38.65	309.20						
	1	Carpenter	45.85	366.80						
	5	Laborers	36.65	1466.00						
	0.5	Cement Finisher	44.05	176.20						
	1	Eq Operator	48.90	391.20						
	0	Equipment op(oiler)	43.55	0.00						
	0.25	Truck Driver	37.55	75.10						
	2	Gas Engine Vibrator		66.00						
	0	Concret Bucket		0.00						
	0.25	Service Truck (pickup), 4x4, 3/4 ton		30.35						
	1	Concrete Pump 110' Boom		934.00						
	70	Daily Labor Hours		3814.85	39.78	14.72				
			Output	Unit						
			92.00	cy/d			142.00	0.76087	30.27	11.20

B-10. Concrete footing placement crew composition and cost.

Clark 5.1	Concrete Placement Footing - Crane		Labor Hourly Wage	L & Equip Daily Rates	Crew Labor bare cost per Labor-hour	Crew-Equipment bare cost per Labor-hour	Material Cost	Labor Hours per Unit	Labor Unit Cost	Equipment Unit Cost
	#	Crew Formation								
	1	Labor Forman	38.65	309.20						
	0	Carpenter	45.85	0.00						
	5	Laborers	36.65	1466.00						
	0	Cement Finisher	44.05	0.00						
	1	Eq Operator	48.90	391.20						
	0	Equipment op(oiler)	43.55	0.00						
	0.5	Truck Driver	37.55	150.20						
	2	Gas Engine Vibrator		66.00						
	0	Concret Bucket		0.00						
	0.5	Service Truck (pickup), 4x4, 3/4 ton		168.40						
	1	Concrete Pump 110' Boom		934.00						
	60	Daily Labor Hours		3485.00	38.61	19.47				
			Output	Unit						
			164.00	Cy/d			142.00	0.36585	14.13	7.12

B-11. Steel reinforcement crew composition and cost.

4Rodman	Rebar		Labor Hourly Wage	L & Equip Daily Rates	Crew Labor bare cost per Labor-hour	Crew-Equipment bare cost per Labor-hour	Material Cost	Labor Hours per Unit	Labor Unit Cost	Equipment Unit Cost
	#	Crew Formation								
	4	Rodman	43.00	1376.00						
	0		0.00	0.00						
	32	Daily Labor Hours		1376.00	43.00	0.00				
			Output	Unit						
	Examples	Rebar Placement, footing 1.91-3.27 ton/day	4.00	ton/d			955.00	8.00000	344.00	0.00
		Average of means 03 21 10.60 0500, 0550								

APPENDIX C-PROGRAM

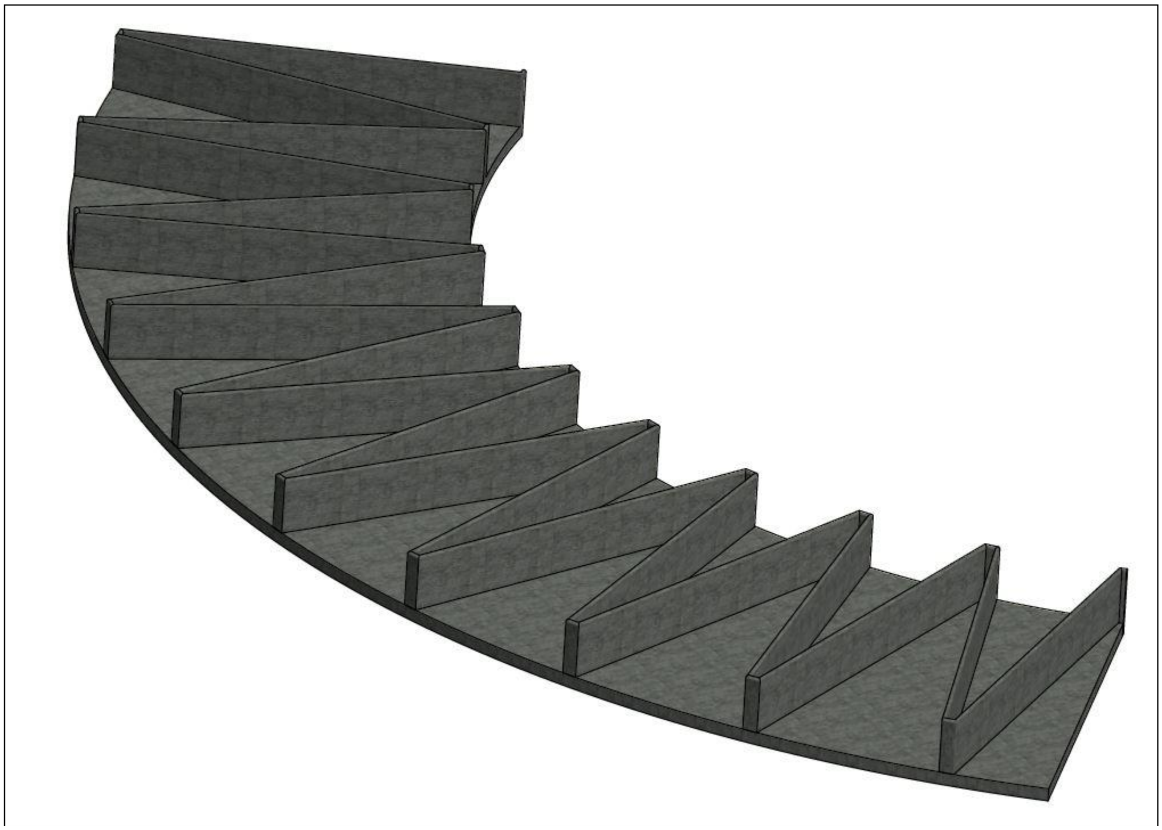
```
Sub LoopsParathetayAlpha()


Dim theta As Single, alpha As Single, x As Single, Radius As Single, counter As Single,
check As Single

' You may not copy, reproduce, distribute, publish, display, perform, modify, create
derivative works, transmit, or in any way exploit any content on this and other modules
and worksheet , nor may you distribute any part of this content over any network,
including a local area network, sell or offer it for sale, or use such content to construct
any kind of database without expressed and written permission from Jamie F. López.
' This part starts with a radius equal to half the width and increments at a 1/100th
interval.
' After this it changes the angle for theta and alpha.

Sheets("Length Calculation").Activate
theta = 10
alpha = 6
x = 12
Radius = Cells(1, "g")
counter = 12
'If theta total > theta minimum for the number of minimum cycles exit for
'Range("D" & x).Value = check
'If check < Cells(3, 6) Then Exit For


Do

    For theta = 10 To 30 Step Cells(4, "c")
       For alpha = 6 To 20 Step Cells(3, "c")
       Range("B" & x).Value = alpha
       Range("A" & x).Value = theta
       Range("C" & x).Value = Radius
       x = x + 1
       Next alpha

   Next theta

counter = counter + 1
Radius = Radius + Cells(1, "c") / Cells(5, "c")

 Range("D12").Select
```

```
   Selection.AutoFill Destination:=Range("D12:D" & Range("A" &
Rows.Count).End(xlUp).row)

Loop Until Range("D" & x - 1).Value < Cells(6, 3)



'
' Update_a_columnas Macro
'
Range("D12:R12").Select
   Selection.AutoFill Destination:=Range("D12:R21")
 Range("D12").Select
   Selection.AutoFill Destination:=Range("D12:D" & Range("A" &
Rows.Count).End(xlUp).row)
Range("E12").Select
  Selection.AutoFill Destination:=Range("E12:E" & Range("A" &
Rows.Count).End(xlUp).row)
Range("F12").Select
  Selection.AutoFill Destination:=Range("F12:F" & Range("A" &
Rows.Count).End(xlUp).row)
Range("G12").Select
  Selection.AutoFill Destination:=Range("G12:G" & Range("A" &
Rows.Count).End(xlUp).row)
Range("H12").Select
   Selection.AutoFill Destination:=Range("H12:H" & Range("A" &
Rows.Count).End(xlUp).row)
Range("I12").Select
  Selection.AutoFill Destination:=Range("I12:I" & Range("A" &
Rows.Count).End(xlUp).row)
Range("J12").Select
  Selection.AutoFill Destination:=Range("J12:J" & Range("A" &
Rows.Count).End(xlUp).row)
Range("K12").Select
  Selection.AutoFill Destination:=Range("K12:K" & Range("A" &
Rows.Count).End(xlUp).row)
Range("L12").Select
  Selection.AutoFill Destination:=Range("L12:L" & Range("A" &
Rows.Count).End(xlUp).row)
Range("M12").Select
  Selection.AutoFill Destination:=Range("M12:M" & Range("A" &
Rows.Count).End(xlUp).row)
```

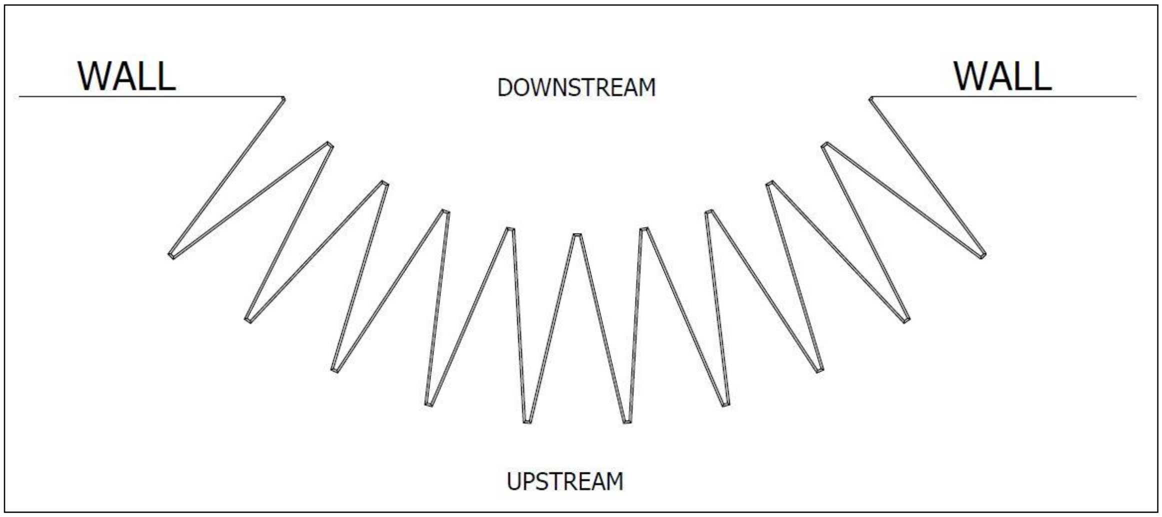
```
Range(“N12”).Select
   Selection.AutoFill Destination:=Range(“N12:N” & Range(“A” &
Rows.Count).End(xlUp).row)
Range(“O12”).Select
  Selection.AutoFill Destination:=Range(“O12:O” & Range(“A” &
Rows.Count).End(xlUp).row)
Range(“P12”).Select
  Selection.AutoFill Destination:=Range(“P12:P” & Range(“A” &
Rows.Count).End(xlUp).row)
Range(“Q12”).Select
  Selection.AutoFill Destination:=Range(“Q12:Q” & Range(“A” &
Rows.Count).End(xlUp).row)
Range(“R12”).Select
  Selection.AutoFill Destination:=Range(“R12:R” & Range(“A” &
Rows.Count).End(xlUp).row)
Range(“S12”).Select
  Selection.AutoFill Destination:=Range(“S12:S” & Range(“A” &
Rows.Count).End(xlUp).row)
Range(“T12”).Select
  Selection.AutoFill Destination:=Range(“T12:T” & Range(“A” &
Rows.Count).End(xlUp).row)
Range(“U12”).Select
  Selection.AutoFill Destination:=Range(“U12:U” & Range(“A” &
Rows.Count).End(xlUp).row)
Range(“V12”).Select
  Selection.AutoFill Destination:=Range(“V12:V” & Range(“A” &
Rows.Count).End(xlUp).row)
  Range(“W12”).Select
  Selection.AutoFill Destination:=Range(“W12:W” & Range(“A” &
Rows.Count).End(xlUp).row)
  Range(“X12”).Select
  Selection.AutoFill Destination:=Range(“X12:X” & Range(“A” &
Rows.Count).End(xlUp).row)


Sheets(“Results”).Select
End Sub
```

```
Sub ClearCells()
‘
‘ ClearCells Macro
‘

‘
 Application.ScreenUpdating = False
Sheets(“Length Calculation”).Activate
    Range(“A22:Y1386”).Select
    Range(“Y22”).Activate
    Selection.Clear

    ActiveSheet.UsedRange

Sheets(“Input Box”).Activate
 Application.ScreenUpdating = True


End Sub
```

APPENDIX D-OPTIMIZATION SOLUTION GRAPHICAL INTERPRETATION



D-1. 3D view of optimized weir and foundation for width of 750 ft, N=10, θ = 10, α=9



D-2. Top view of optimized weir of width of 750 ft,
N=10, θ = 10, α=9 for placement purposes