COMPARISON OF LINEAR, LABYRINTH AND PIANO KEY WEIRS TO INCREASE THE DISCHARGE CAPACITY OF EXISTING SPILLWAYS FOR A GIVEN HEAD

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COMPARISON OF LINEAR, LABYRINTH AND PIANO KEY WEIRS TO INCREASE THE DISCHARGE CAPACITY OF EXISTING SPILLWAYS FOR A GIVEN HEAD

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ABSTRACT

COMPARISON OF LINEAR, LABYRINTH AND PIANO KEY WEIRS TO INCREASE THE DISCHARGE CAPACITY OF EXISTING SPILLWAYS FOR A GIVEN HEAD

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Dams play an important role in infrastructure of our country and provide drinking water, flood protection, renewable hydroelectric power, navigation, and irrigation as well as facilities for sports activities. However, dams in Turkey are gradually aging and in order to assure the safety of those aging dams, rehabilitation is necessary. Very often, increasing the capacity of a spillway would be required in rehabilitation works. Thus, it is the main goal of this study to investigate some practical methods used in increasing the spillway capacity of dams. In this respect, labyrinth and piano key weir types were selected as the two effective methods to achieve that mentioned goal. Design procedure of labyrinth weirs and piano key weirs were outlined and each one applied in five different existing projects. Comparisons were made with linear weirs, it was concluded that labyrinth and piano key weirs increase the effective crest length of a dam spillway significantly for a given spillway width, therefore, in return, they increase the flow capacity for a given operating head. Moreover, different geometric parameters were also studied to see their effect in changing the discharge capacity.

Keywords: Dams, Rehabilitation, Spillways, Labyrinth Spillways, Piano Key Spillways, Increasing Spillway Capacity.

ÖZ

VERİLEN BİR SU KOTUNDA MEVCUT DOLUSAVAKLARIN DEBİ KAPASİTESİNİ ARTTIRMAK İÇİN LİNEER, LABİRENT VE PİYANO TUŞU SAVAKLARIN KIYASLANMASI

Karaeren, Deniz

Yüksek Lisans, İnşaat Mühendisliği Bölümü

Tez Yöneticisi: Prof. Dr. Zafer Bozkuş

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Barajlar, ülkemizin alt yapısında önemli bir rol oynarlar ve içme suyu, taşkın koruma, yenilenebilir enerji, ulaşım ve sulama ve ayrıca spor etkinlikleri için tesis imkanı sağlarlar. Fakat, Türkiyenin barajları giderek yaşlanmakta olup, bu yaşlanan barajların güvenliğini sağlamak için rehabilite edilmeleri gereklidir. Çoğu kez rehabilitasyon işlerinde dolusavak kapasitesini arttırmak gerekir. Bu nedenle, bu çalışmanın temel amacı barajların dolusavak kapasitelerini arttırmada kullanılan pratik yöntemleri incelemektir. Bu bağlamda, labirent ve piyano tuşu tipi savaklar anılan amacı gerçekleştirmek için kullanılan etkili iki metot olarak seçilmişlerdir. Labirent ve piyano tuşu savakların tasarım prosedürü ortaya konmuş ve her biri beş farklı mevcut projede uygulanmıştır. Lineer savaklarla yapılan kıyaslamalarda, sabit bir dolusavak genişliğinde labirent ve piyano tuşu savakların etkin kret uzunluğunu önemli ölçüde arttırdığı sonucuna varılmış olup, bu da dolayısı ile verilen bir işletme su kotunda dolusavak kapasitesini arttırmıştır. Ayrıca, dolusavak kapasitesini değiştirmedeki etkilerini görmek için farklı geometrik parametreler de çalışılmıştır.

Anahtar Kelimeler: Barajlar, Rehabilitasyon, Dolusavaklar, Labirent Dolusavaklar, Piano Tuşu Dolusavaklar, Dolusavak Kapasitesinin Arttırılması

To my family

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CHAPTER 1

INTRODUCTION

1.1 Motivation for the Study

There are more than 590 dams in Turkey, and these dams are getting older and older day by day. This situation poses a threat to life, health, assets and environment.

Neglect and inadequate design and poor engineering, inadequate foundation conditions and unpredicted changes related to foundation conditions, damage by cavitation, material deterioration, leakage, insufficient spillway capacity are common problems associated with dams.

In the last few years, the behavior of the water in the nature has changed because of the change in the climate. Climate change triggers extreme water; an example of this situation is that excessive rainfall rate has increased. The flow of water entering a reservoir is undetermined because of the fact that it is related to the intensity of the rainfall. It is known that intensity increase in the rainfall causes significant changes in reservoir water levels. This situation can end up with the failure of a dam.

In addition to these, underestimation and change in the peak discharge of the inflow design flood are other more common cases.

In order to assure the safety of the existing dams, rehabilitation is necessary. Underwater repair of concrete, relining and repairing water passages, rehabilitation of gates, rehabilitations of penstocks, using roller compacted concrete (RCC) are some of the rehabilitation methods.

However, being a safe dam not only means a structurally stable dam but also means a hydrologically safe dam. In other words, a dam may have inadequate spillway capacity making the dam unsafe hydrologically. For this reason, two practical methods used for increasing the spillway capacity of the dams will be investigated and compared in the present study, and they are labyrinth weirs and piano key weirs. Their advantages and disadvantages will be discussed by considering the hydraulic and economic aspects.

1.2 The Objective of the Study

In order to be protected from probable maximum flood and to ensure dam safety hydrologically, rehabilitation works have been done on the spillways to increase their discharge capacity. Consequently, it is the main objective of this study to investigate some practical methods used in increasing the spillway capacity of dams. In this respect, labyrinth weirs and piano key weirs were selected as the two effective methods to achieve it. Eq. (1-1) demonstrates head discharge relationship for a linear weir, Fig. 1-1.

$$Q = \frac{2}{3} C_d \, L \sqrt{2g} \, H_T^{3/2} \qquad (1\text{-}1)$$

Where,

Q= Discharge over the weir (m^3/s)

C_d= Discharge coefficient

L= Crest length (m)

g= Acceleration due to gravity (m/s^2)

H_T= Total head over the crest (m)

H (water depth between maximum reservoir water level and crest elevation) and H_T (total head over the crest elevation) parameters are illustrated in Fig. 1-1.

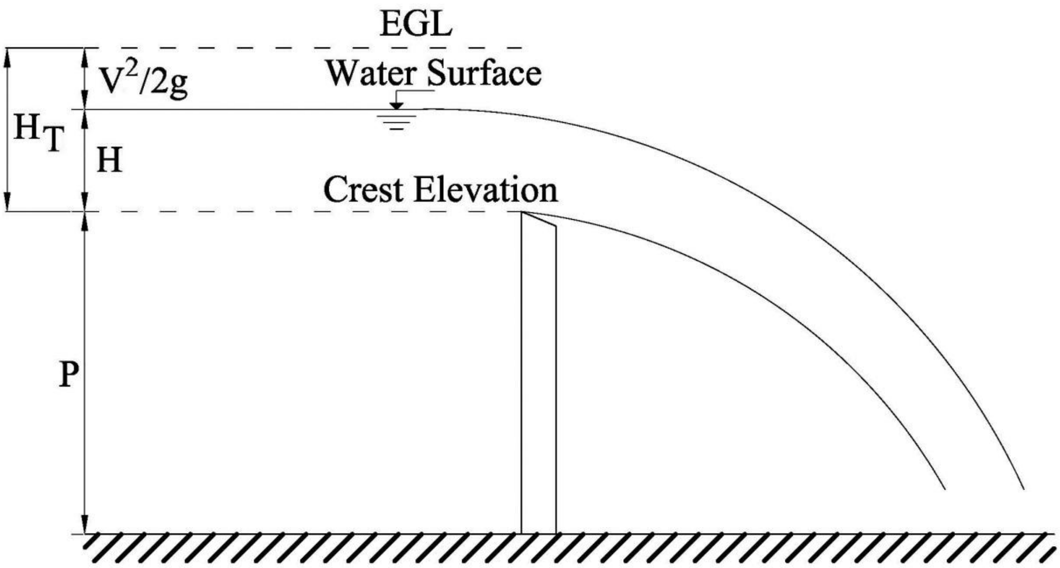


Figure 1-1 Weir Parameters on a Sharp Crested Linear Weir (Anderson, 2011)

By using labyrinth weirs and piano key weirs, the crest length and the discharge capacity of the spillway can be increased.

These types of spillways can be applied for the cases in which rehabilitation should be carried out by means of increasing the discharge capacity that enable to overcome the insufficient spillway capacity. The only considered criterion is the capacity of the spillway that the other hydraulic structures and the downstream conditions are not considered. These kinds of spillways might be applicable for the dams having side channel, ungated and uncontrolled spillways.

Labyrinth weirs supply an increase of crest length for a given channel width, Figure 1-2. Therefore, they increase the flow capacity for a given water head. The crest length can be increased around five times by using a labyrinth spillway instead of a standard spillway. Furthermore, the discharge capacity of a labyrinth spillway can be twice as much as that of a standard spillway.

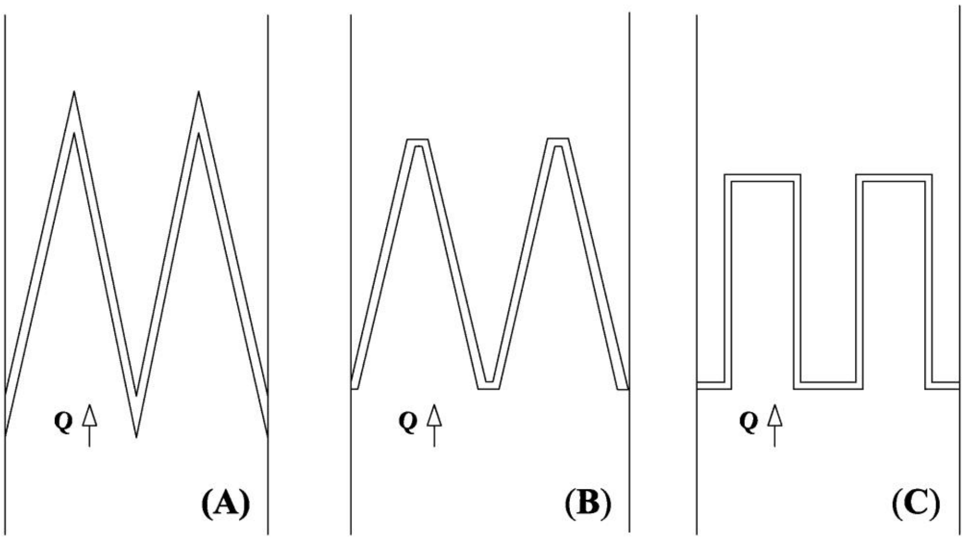


Figure 1-2 General Classification of Labyrinth Weirs:
Triangular (A), Trapezoidal (B), and Rectangular (C) (Crookston, 2010)

A piano key (PK) weir is an alternative to the traditional labyrinth weirs, Figure 1-3. Similar to the labyrinth weirs, the piano key weirs increase the discharge capacity with their longer crest lengths.

The plan view of a piano key weir has a rectangular shape. The apex of a labyrinth weir is vertical; on the contrary, the apex of a PK weir is not vertical. However, the apex of a piano key weir is inclined both in upstream and downstream direction.

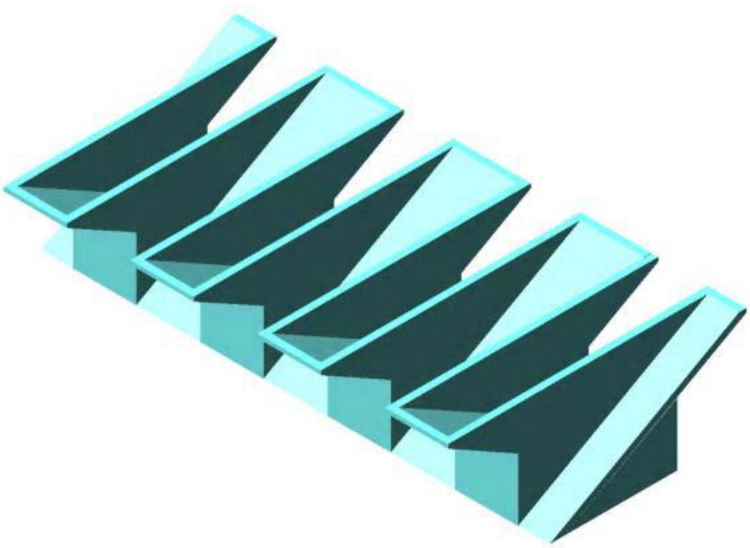


Figure 1-3 Schematic of PK Weir (Paxson, et al.2012)

The piano key weir has been developed to imitate the function of labyrinth weirs on smaller footprints of foundations. This situation can be explained that apart from the hydraulic advantages, the piano key weirs are effective and economic due to the fact that the piano key weirs can be easily placed at a very limited foundation space. (Lempérière and Ouamane, 2003)

In the present study, design methods of the labyrinth weirs and piano key weirs will be explained and these methods are compared both in hydraulic and economic aspects with one another as well as with linear weirs.

1.3 Description of the Thesis

This thesis consists of six chapters. Chapter 1 is the Introduction part, the problems related to the dams are mentioned and the aim of the study is introduced in this part. In Chapter 2, the information obtained from previous studies on labyrinth weirs and piano key weirs are provided. Then, in Chapter 3, general information about the spillway rehabilitation methods are explained. In this thesis, labyrinth weirs and piano key weirs are selected as the two practical ways of increasing spillway capacity of the dams wherever applicable. Next, Chapter 4 is about Design Procedure and Case Studies. In this chapter, design procedure of labyrinth weirs and piano key weirs are stated and case studies are presented. Chapter 5 is Discussion part. In this part, different geometric parameters are used to increase spillway capacity. Finally in Chapter 6, conclusions of this study are given.

CHAPTER 2

LITERATURE REVIEW

In order to have a better understanding of the subject, previous works about the ways of increasing spillway capacity are examined and summarized.

In this study focus will be on the labyrinth weirs and piano key weirs as two important alternative ways of increasing spillway capacity.

2.1 Labyrinth Weirs

The basic equation developed for linear weirs is used to design a labyrinth weir. Figure 2-1 shows some relevant labyrinth weir parameters.

$$Q = \frac{2}{3} C_d L \sqrt{2g} H_T^{3/2} \qquad (2\text{-}1)$$

Where,

Q = Discharge over the weir (m^3/s)

C_d = Dimensionless discharge coefficient

L = Effective length of the weir (m)

g = Acceleration due to gravity (m/s^2)

H_T = Total head over the crest (m)

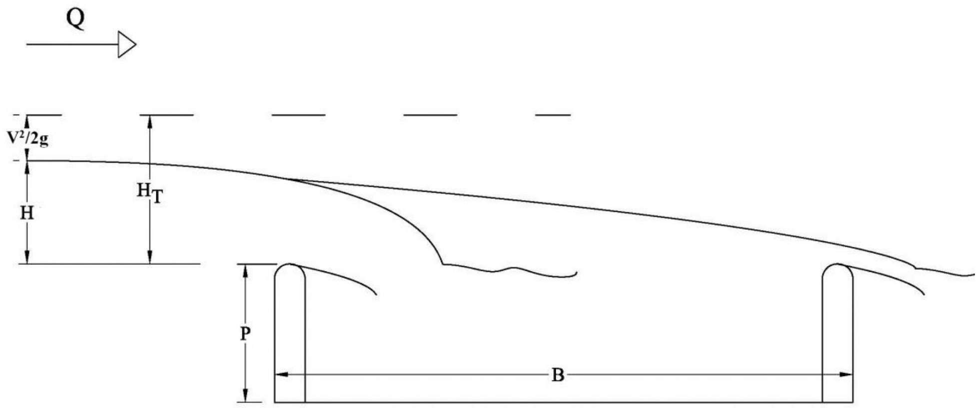


Figure 2-1 Labyrinth Weir Parametric Geometries (Crookston, 2010)

Definition of the terms in the figure

H= water depth between maximum reservoir elevation and crest elevation

H_T= total head over the crest

B= length of labyrinth apron

P= weir heigth

First studies related to the labyrinth weirs are mostly associated with the weir characteristics. For example, the purpose of Taylor's study (1968) is to give sufficient information to weir designer regarding the most efficient design of labyrinth weir for any conditions. The investigation aims to obtain an understanding of the fundamental factors related to labyrinth weirs in order to find a theoretical solution in case of an adverse situation. In the study, it is stated that application areas of labyrinth weirs are for large discharges with small operating head.

According to the Taylor's study (1968) weir performance decreases with increasing water head in accordance with both theoretical and experimental work. It is claimed that a growth in the length magnification factor (l/w) increases the discharge capacity of the weirs, where l is the developed length of one cycle of the weir and w is the width of one cycle of the weir; however, it causes a reduction in design efficiency. It can be thought from the study that if the vertical aspect ratio (w/p) is small, an important performance loss can occur in which w is the width of one cycle of the weir and p is the crest height. If the w/p ratio is greater than 2, this performance loss can disappear. Investigations have shown that, when the w/p ratios are greater than 3, the side wall angle (α) should be as large as possible in order to reach the optimum performance.

Then, in 1995, Tullis, et al. performed a study related to the design of the labyrinth weirs. The total head (H_T), the effective crest length (L) and the crest coefficient (C_d) are stated as the parameters affecting the discharge capacity. Moreover, according to the design procedure of the study, the ratio of H_T/P is approximately 0.9, and the wall thickness of the crest is P/6, which is rounded on the upstream corner at a radius of P/12. If the geometry of the crest is fixed, the discharge coefficient is influenced by only the head and the labyrinth angle (α). Furthermore, discharge coefficients are valid for the labyrinth angle between 6° and 35°, for the recommended weir configurations. It is specified that the number of cycles (N) and labyrinth angle affect the width, the length and the other variables of a labyrinth weir and also in order to obtain the most convenient and economic design, site-specific limitations should be regarded.

In 2000s Crookston defined the aim of his study (2010) to develop a labyrinth weir design method for various orientations such as flush, rounded, inlet and projecting, and improve geometric design and hydraulic design methodology. Crookston tested 32 new hydraulic labyrinth weir models in Utah Water Research Laboratory (UWRL). The data were obtained for quarter-round labyrinth weirs. In the channel normal and inverse orientation were used and flush, rounded, inlet and projecting orientations were used in the reservoir for the model configurations. Crookston calculated the discharge by using the traditional weir equation. However, he used the centerline length of the weir (L_c) instead of the characteristic length. The discharge coefficient data were obtained for quarter-round and half round labyrinth weirs with side wall angles $6° \leq \alpha \leq 35°$. From this test, it was concluded that for the values of $H_T/P \leq 0.4$, the increase in efficiency, especially for the half-round crest shape could be seen clearly. In this study, cycle efficiency (ε') was mentioned. In the test results it could be seen that when α decreases ε' increases and the maximum ε' values occur at low H_T/P discharge per cycle.

Then, Crookston and Tullis (2011) conducted a study. The main purpose of the study was to develop the design and analyses of labyrinth weirs by using physical modeling, available data, and current design methods so as to examine the behavior of specific weir geometries.
In the study, the basic equation developed for linear weirs is proposed to demonstrate the head-discharge relationships of labyrinth weirs.

$$Q=2/3\, C_d L_c h^{1.5} \sqrt{2g} \qquad (2\text{-}2)$$

Where,
Q= Discharge over the weir (m^3/s)
C_d= Dimensionless discharge coefficient
L_c= Total centerline length of labyrinth weir (m)
g= Acceleration due to gravity (m/s^2)
h= Total head on the crest (m)

Cycle efficiency, ε', represents the relationship between the decrease in discharge efficiency and the increase in discharge. Decreasing α (sidewall angle) causes the reduction in discharge efficiency and the increase in the crest length which triggers the increase in the discharge.

The hydraulic performance of the normal, inverse, projecting, flush, rounded inlet, and arced orientations were investigated and then following results were obtained:

i. The discharge efficiency gains the greatest value with an arced labyrinth weir. (~10%-25%)
ii. It can be noticeably seen that rounded abutments ensure the hydraulic efficiency of the flush orientation.
iii. A performance difference between the orientations of normal and inverse was not determined.

Crookston, et al. (2012) introduced a study extending the H_T/P design range. It was aimed to evaluate the hydraulic performance of labyrinth weirs for greater H_T/P values than the maximum values which had been conducted in previous studies. Therefore, H_T/P design range could be extended. This study contained both physical and numerical modeling to supply further validation of the application of CFD algorithms in order to examine the discharge characteristics of the labyrinth weirs. In the physical modeling $\alpha=15°$ curve fit equation for quarter-round crest shape is prevailed. In the study, they concluded that CFD was a reasonable instrument to evaluate discharge performance of the labyrinth weirs. In addition, the conformation between the physical modeling and the numerical modeling was of 3% to 7%.

Later, Suprapto (2013) conducted an experiment so as to compare the Ogee type spillways and labyrinth sharp crested spillways (LSCS). Labyrinth sharp crest spillways consisted of trapezoid type, saws type and duck beak type. In order to calculate the spillway discharge, the classical equations of linear weir crest were used in the study. For various water thicknesses of spillways, flow observations of all types were determined. Moreover, the differences of discharges for all types of spillways were observed. It can be concluded from the observations that the smallest discharge capacity belongs to the Ogee type spillway, except in the flow thickness of less than 1.50 m. Furthermore, the greatest discharge capacity belongs to the trapezoidal types. The hydraulic performance of the traditional labyrinth weirs is well known since they have been studied for a long time. However, a generally accepted standard design procedure of the piano key weirs has not been developed yet, because of the lack of systematic experiments and existing data.

2.2 Piano Key Weirs

Figure 2-2 and Figure 2-3 shows the schematic view of piano key weirs. The main parameters are also defined in those figures.

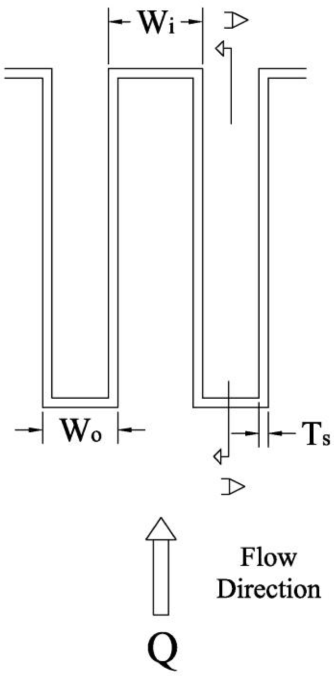


Figure 2-2 Piano Key Weir Schematic (Anderson and Tullis, 2011)

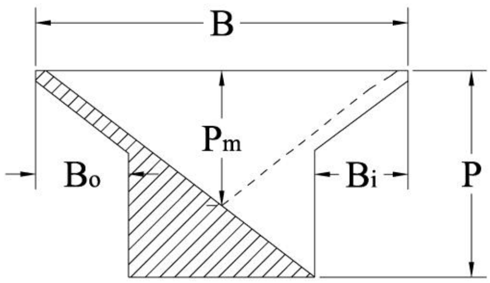


Figure 2-3 Cross Section A-A (Anderson and Tullis, 2011)

Definition of the terms in Figure 2-2 and 2-3

W_i= inlet cycle width

W_o= outlet cycle width

T_s= wall thickness

B_o= upstream overhang length

B_i= downstream overhang length

P_m= the weir wall height at the middle of the weir structure

P= weir height

N= number of cycles

B= length of side weir

After 2000, piano key weirs started to play a role in the studies of the increasing spillway capacity.

In the study of Lempérière and Quamane (2003) very simple longitudinal sections are preferred due to their cost efficiency. Two solutions are developed in this study. In solution A, there are similar upstream and downstream overhangs, enabling the use of precast concrete. In solution B, there is only an upstream overhang. Cost savings are approximately 10 % higher than the cost savings of solution A. Solution B does not support the use of precast concrete. In the study, they concluded that a piano key weir has four times more flow capacity than a traditional spillway. In addition, by using the piano key weir the cost could be reduced and the safety could be ensured.

Later, Lempérière (2009) explained the negative properties of vertical walls of labyrinth weirs:

- For large discharges, vertical walls are not suitable.
- The vertical walls need too much reinforcement.
- The typical gravity dam sections do not have the base area the piano key weirs have.

In the study, it was presented that the ratio of the developed plan length of wall to the overall spillway length should be close to 5. An increase of this ratio generally is not accepted as an economical way. It was recommended that, upstream head over the weir crest, h, ought to be between $0.4P_m$ and $2P_m$ (P_m= maximum height of the Piano key walls)

Lempérière proposed the following relationship for PK weir-head discharge:

$$q=4.3h\sqrt{P_m} \tag{2-3}$$

In which, h is the upstream head over weir crest.

Moreover, it was stated that if there is no restriction about the height of PK weir, increasing P_m is usually an economic method and using recommended properties rather than increasing the value of N ratio to develop hydraulic efficiency is also an economical way to increase P_m. In addition, Lempérière suggested that the ratio between the inlet cycle width ratio and the outlet cycle width ratio (a/b) ought to be close to 1.25.

Then, Anderson and Tullis (2011) revealed a study in order to discuss the 'h' parameter mentioned in the Lempérière's study (2009) and examine the sensitivity of the piano key weir by using three models in which a/b ratios are 1.25, 1.00, and 0.80. Equation (2-2) proposed by Lempérière did not explain the h parameter. Thus, it was not known whether h was the total head (H_t) or the water depth between maximum reservoir elevation and crest elevation (H). In this study, it was specified that using the water depth between maximum reservoir elevation and crest elevation (H) instead of the total head (H_t) was more correct. In the study, the sensitivity of the PK weir was examined by testing three models in which the "a/b" ratios were 1.25, 1.00 and 0.80. It was concluded that the most effective model is the one with a/b ratio of 1.25.

About the same times, Paxson, et al. (2012) gave information about the advantages and disadvantages of PK weirs, labyrinth weirs, and gated structures in channel applications and dam rehabilitation by considering economic, structural, and hydraulic issues. This study mentioned that the PK weirs were constructed in order to increase the discharge capacity similar to the labyrinth weirs. Nevertheless, a piano key weir has a smaller foundation footprint than a labyrinth weir, by the reason of their cantilevered apex geometry. Thus, this small footprint gives advantages where the footprint is limited. In the study, PK weir was compared with the labyrinth weir, and it appears that the construction cost of a PK weir is less than that of a labyrinth or a gated weir having similar hydraulic capacity. In addition, due to the reduction in the footprints of the foundation and weir, the concrete volume in a PK weir is 40% less than the one used in a labyrinth weir that have similar head-discharge characteristics. Moreover, it was stated that the estimated cost of the PK weir is 20% to 40% less than that of a labyrinth weir with similar hydraulic capacity, because of the ability of reducing the length of the training wall.

Then, in the paper of Machiels, et al. (2012) a preliminary design method based upon the previous experimental test results is presented. A preliminary design method for the piano key weirs is improved by using the results of former works. The method consists of four steps as (1) choosing a reference model (2) by using different number of PKW-units, determining the geometric and hydraulic characteristics of the reference model (3) isolation of the design which meets the project constraints. (4) optimization of the design considering structural, economic and hydraulic issues with regarding the project engineer's advances. It is stated that this method is used for different configurations in order to obtain a good final design for a large number of PKW-units.

Then, Ribeiro, et al. (2013) conducted a study. The objective of the study was to investigate the geometry of the different piano key models experimented a long time ago and to compare them to previous piano key weir prototypes.

In the study the relation between the ratios P_i/W_i and L/W, W_i/W_o and L/W, P_i/T_s and L/W were studied. According to the study they concluded:

i. If the ratio of P_i/W_i increases, the ratio of L/W usually increases.
ii. Generally, the value of W_i/W_o varies between 0.5 and 2.5. However, the optimal value of W_i/W_o is equal to 1.5.
iii. Discharge capacity is increasing by decreasing the thickness of the side walls and so increasing the ratio of P_i/T_s.

CHAPTER 3

GENERAL INFORMATION FOR LABYRINTH AND PIANO KEY WEIRS

In this chapter, firstly, the concepts of labyrinth weirs and piano key weirs are defined. Then, their hydraulic and geometric properties are illustrated. After doing these, their advantages and disadvantages are discussed.

3.1 Labyrinth Weirs

A labyrinth weir is a linear weir which has been shaped in a zigzag form. The purpose of using labyrinth spillways is to increase the crest length for a given spillway width. Hence, the discharge capacity of the spillway can be increased for a given upstream head and spillway width. Figures 3-1, 3-2 and 3-3 show pictures of some labyrinth weirs used in practice.

The crest length can be increased around five times by using a labyrinth spillway instead of a standard spillway. Furthermore, the discharge capacity of a labyrinth spillway can be twice as much as that of a standard spillway.

Although there are many geometric configurations of labyrinth weirs, three of them are widely used: triangular, trapezoidal and rectangular. According to Crookston's study (2010), triangular and trapezoidal shaped labyrinth weirs are more effective than rectangular shaped labyrinth weirs per unit discharge, Figure 3-4.

Figure 3-1Ute Dam, New Mexico (Triangular Labyrinth Spillway) (Rhone, 1988)

Figure 3-2 Labyrinth Crest (Uncontrolled) Spillway, Ute Dam, New Mexico (A Bureau of Reclamation photographer)

Figure 3-3 River Brent: Osterley Lock Trapezoidal Labyrinth Weir (Geograph, 2013)

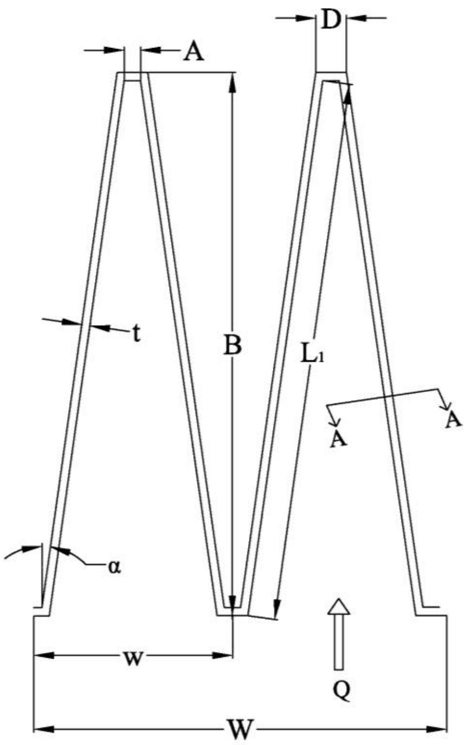


Figure 3-4 Labyrinth Weir Schematic for Two Cycles

Below the important parameters shown in Figures 3-4 and 3-5 are defined.

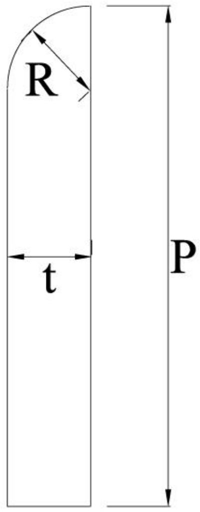


Figure 3-5 Cross Section A-A

t= wall thickness (m)

w= width of one cycle (m)

W= total width of labyrinth weir (m)

α= labyrinth angle (degree)

A= inside apex width (m)

D= outside apex width (m)

B= length of labyrinth apron (m)

P= weir height (m)

L_1= actual length of side length (m)

R= radius of crest curvature (m)

Next, some important parameters such as headwater ratio, cycle width ratio, number of labyrinth weir cycles, discharge coefficient and sidewall angle are explained in detail.

Headwater Ratio (H_T/P)

The headwater ratio is the ratio of the total head (H_T) to the weir height (P). According to the study conducted by Tullis et al. (1995), the upper limit of H_T/P is 0.9. Crookston (2010) also stated that for the values of $H_T/P \leq 0.4$ increases in the efficiency can be seen clearly. In addition to these, it is mentioned that the maximum cycle efficiency occurs at low H_T/P values. In the study, no data were used above $H_T/P= 0.9$ and below $H_T/P= 0.1$, since with increasing head labyrinth weirs become significantly ineffective. What is more, it is stated that finding value of the discharge coefficient (C_d) is very hard at $H_T/P <0.1$

Cycle Width Ratio (w/P)

Cycle width ratio is the ratio of the width of one cycle of a labyrinth weir (w) to the weir height (P).

Taylor (1968) suggested that the w/P ratio should be greater than 2 in order to avoid an important performance loss. Khode and Tembhurkar (2010) also recommended that the w/P ratio should not be less than 2 for trapezoidal shaped weirs and not be less than 2.5 for triangular shaped weirs.

According to the study conducted by Tullis et al. (1995), the limitation of $3\leq w/P \leq 4$ supplies an economical and hydraulically efficient design.

Number of labyrinth weir cycles (N)

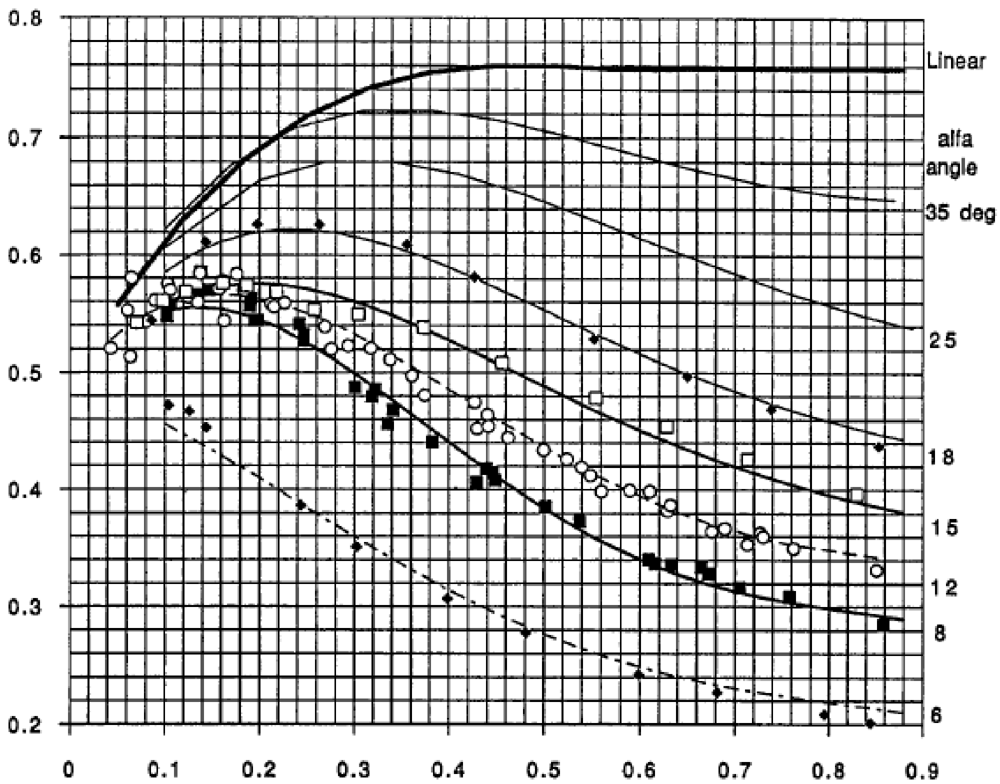
Number of labyrinth weir cycles (N) is another important parameter influencing the design and cost of the spillway. As regards the past test results, the number of labyrinth weir cycles do not influence the discharge coefficients. This situation eases the project design. However, using too little or too many number of labyrinth weir cycles supply a design that may not be cost effective and hydraulically efficient. For this reason, the width ratio should be between 3 and 4 to select available labyrinth weir length.

Discharge coefficient (C_d)

Another important parameter is the discharge coefficient (C_d). Crest shape, labyrinth angle, wall thickness, weir height, flow conditions influence the discharge coefficient. Accurate C_d values have a role in making correct design.

Tullis et al. (1995) demonstrated C_d in terms of H_T/P for trapezoidal labyrinth weirs for the range of $6° < \alpha < 35°$. Figure 3-6 is valid for the following expressions $t \leq A \leq 2t$, $H_T/P < 0.9$, $t = P/6$ and $R = P/12$ for a quarter-round crest shape.

C_d



H_T/P

Figure 3-6 Discharge Coefficients for Labyrinth Spillways (Tullis et al. 1995)

Sidewall angle (α)

The sidewall angle (α) has an effect on both performance and cost of the spillway. As regards previous works, the degrees between 7 and 16 are stated as the optimal value. The degrees under 7° and above 16° cause an increase in the spillway width. In addition to these, by increasing the angle, the length of the spillway decreases which results in decrease in discharge. According to the results obtained from past studies, small values of sidewall angle with low level reservoir provide a significant increase in the discharge capacity.

3.2 Piano Key Weirs

A piano key weir is an alternative to the traditional labyrinth weirs. The plan view of the piano key weir shape is rectangular. Even though the apex of the labyrinth weir is vertical, the apex of the piano key weir is not vertical but inclined. Due to this property, they have been named as "Piano Key Weirs". Figures 3-7 and 3-8 show some applications of piano key weirs in practice.

The footprint of the piano key weir is smaller than that of a labyrinth weir. This property brings an advantage to the piano key weirs since they can be easily inserted at the foundation even if there is not enough space. It is clear that the piano key weir is an economic and cost effective way to increase the spillway capacity.

Similar to the labyrinth weirs, the piano key weirs increase the discharge capacity with their longer crest lengths. This advantage will be lost if the upstream head increases. Therefore, the piano key weirs are designed for moderate heads so as to avoid any reduction in the discharge capacity.

Figure 3-7 Von Phong PK Spillway Under Construction (Vietnam) (Khanh, et al. 2011)

Figure 3-8 L'Etroit Dam PK-Weir (Limousin, France) (2nd Internatiol Workshop on Labyrinth and Piano Key Weirs, 2013)

The important geometric parameters in the design of the piano key weirs are the weir height (P), the weir wall height at the middle of the weir structure (P_m), effective length (L), total weir width (W), slope of the inlet and outlet cycle floors (S), number of cycles (N), inlet cycle width (W_i), outlet cycle width (W_o), upstream overhang length (B_o), downstream overhang length (B_i), and wall thickness (T_s) and these parameters are demonstrated in Figure 3-9 and Figure 3-10.

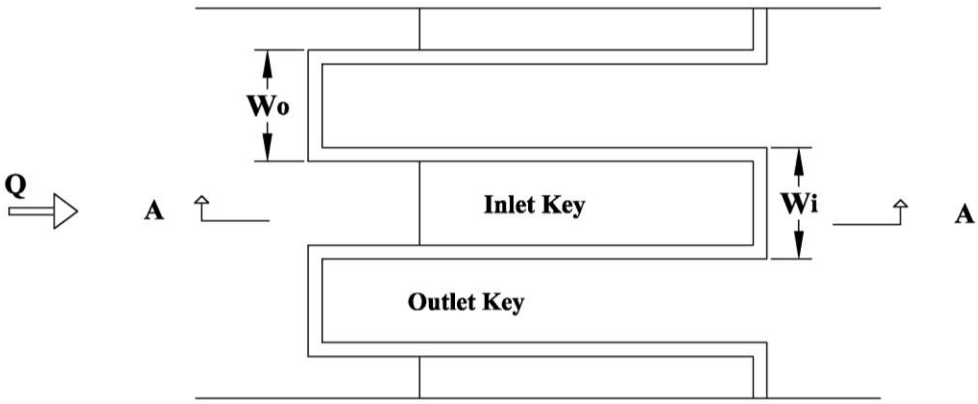


Figure 3-9 Plan (Paxson, et al., 2012)

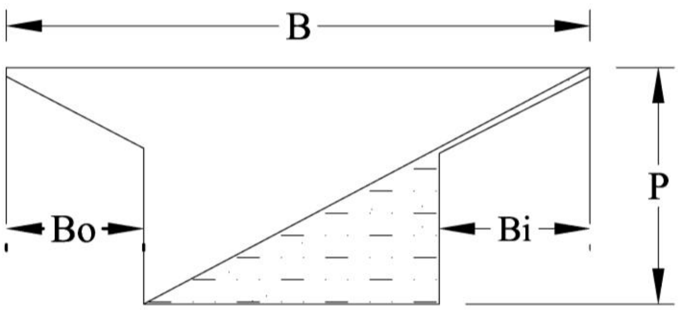


Figure 3-10 Section A-A (Inlet Key) (Paxson, et al., 2012)

In the study carried out by Paxson et al. (2012), a 2-cycle labyrinth weir with a 12° sidewall angle (α) and 4-key piano key weir with similar discharge characteristics are compared. It is stated that the foundation and the weir of the footprint of the piano key weir is less than that of the labyrinth weir.

In the study, the concrete volumes of the piano key weir and the labyrinth weir are determined by using the weir dimensions. These determined volumes are illustrated in Table 3-1 and Table 3-2.

Table 3-1 PK Weir Concrete Volumes (Paxson et al., 2012)

Element	Type of Concrete	Volume (cubic yards)
Base	Mass	195
Weir Walls	Reinforced	55
Overhangs	Reinforced	20
Training Walls	Reinforced	130
Slab	Reinforced	40
Total	Reinforced	245
Total	All	440

Table 3-2 Labyrinth Weir Reinforced Concrete Volumes (Paxson et al., 2012)

Element	Volume (cubic yards)
Weir	195
Slab	260
Training Walls	240
Total	695

By considering Tables 3-1 and 3-2, it can be seen that the labyrinth weir requires about 40% more concrete volume than the piano key weir for similar head-discharge characteristics with the labyrinth weir. The reason why the concrete volume of the piano key weir is less than the concrete volume of the labyrinth weir is that the foundation and the footprint of the piano key weir are smaller than that of the labyrinth weir.

In addition, cost estimation for the labyrinth and the piano key weir is made in this study and concrete costs are represented in Table 3.3. In accordance with the results in Table 3.3, it can be understood that the estimated cost of the piano key weir is 40% less than the estimated cost of the labyrinth weir which has similar hydraulic capacity to the piano key weir.

Table 3-3 Cost Estimates for PK Weir and Labyrinth Weir (Paxson et al., 2012)

Structure	Element/Type	Unit Cost (per cubic yard)	Concrete Cost
PK Weir	Base/Mass	$600	$117
	Weir and Overhangs/Reinforced	$1000	$75
	Slab and Training Walls/Reinforced	$800	$136
	Total	N/A	$328
Labyrinth	Slab/Reinforced	$700	$182
	Weir and Training Walls/Reinforced	$800	$348
	Total	N/A	$530

In the study of Anderson et al. (2011), 3 laboratory-scale sectional models of a PK weir with different W_i/W_o ratios of 1.25, 1.00 and 0.80 were constructed and tested. It can be concluded from the test results that the W_i/W_o=1.25 geometry is the most efficient of the three geometries.

CHAPTER 4

DESIGN PROCEDURE AND CASE STUDIES

4.1 Design Procedure for Labyrinth Weirs

A labyrinth weir is used to increase the effective crest length for a given spillway width. Discharge capacity of the spillway increases as a result of the increased crest length.

The basic equation developed for linear weirs is used to design a labyrinth weir, Eqn 2-1.

Figure 4-1 shows the labyrinth weir schematic. Figure 4-2 is giving the details of cross-section A-A in Figure 4-1.

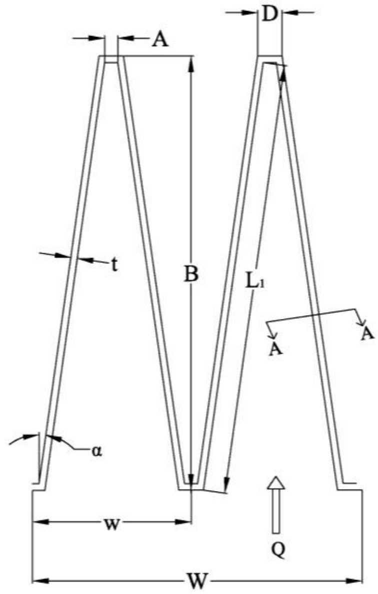


Figure 4-1 Labyrinth Weir Schematic

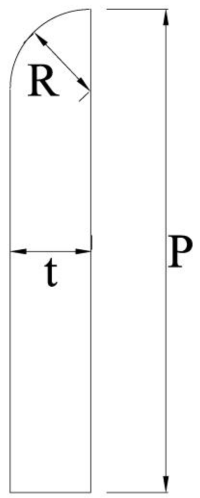


Figure 4-2 Cross Section A-A

t= wall thickness (m)

w= width of one cycle (m)

W= total width of labyrinth weir (m)

α= labyrinth angle (deg (°))

A= inside apex width (m)

D= outside apex width (m)

B= length of labyrinth apron (m)

P= weir height (m)

The discharge coefficients for a labyrinth weir, initially given in Figure 3.6, are illustrated once again in Figure 4-3 for labyrinth angle range of 6° and 35°. On the other hand, Fig 4-4 shows discharge coefficients for linear weirs.

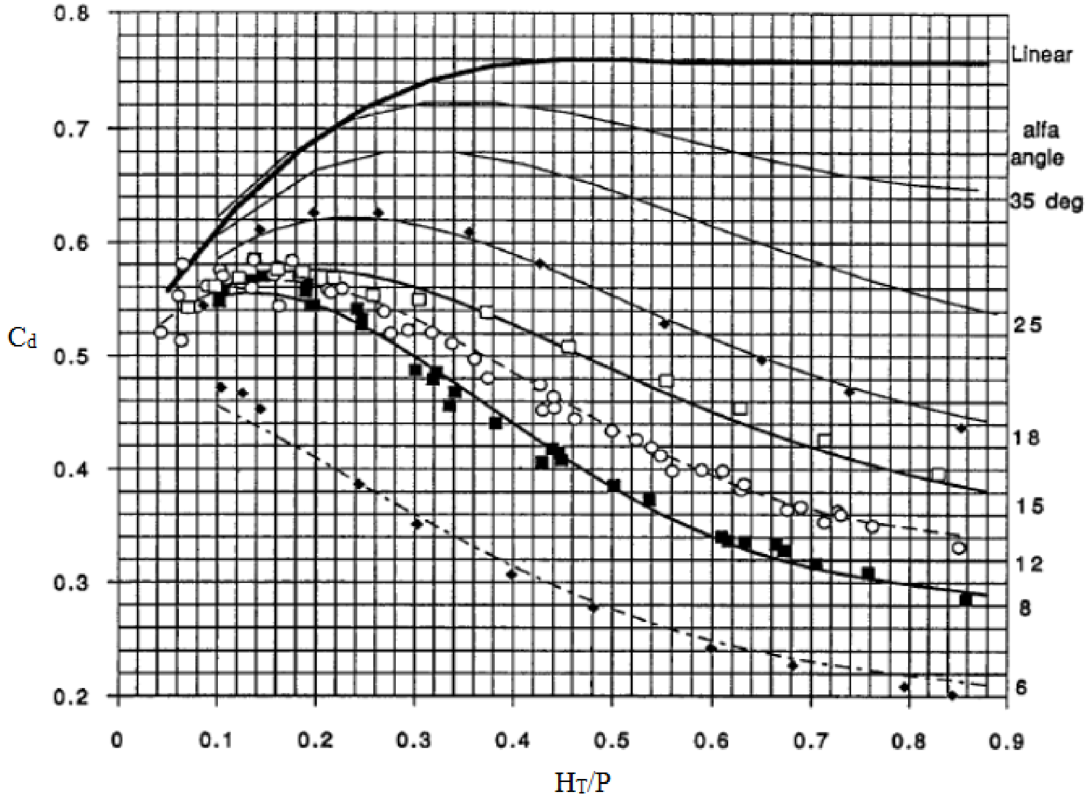


Figure 4-3 Discharge Coefficients for Labyrinth Weirs (Tullis et al. 1995)

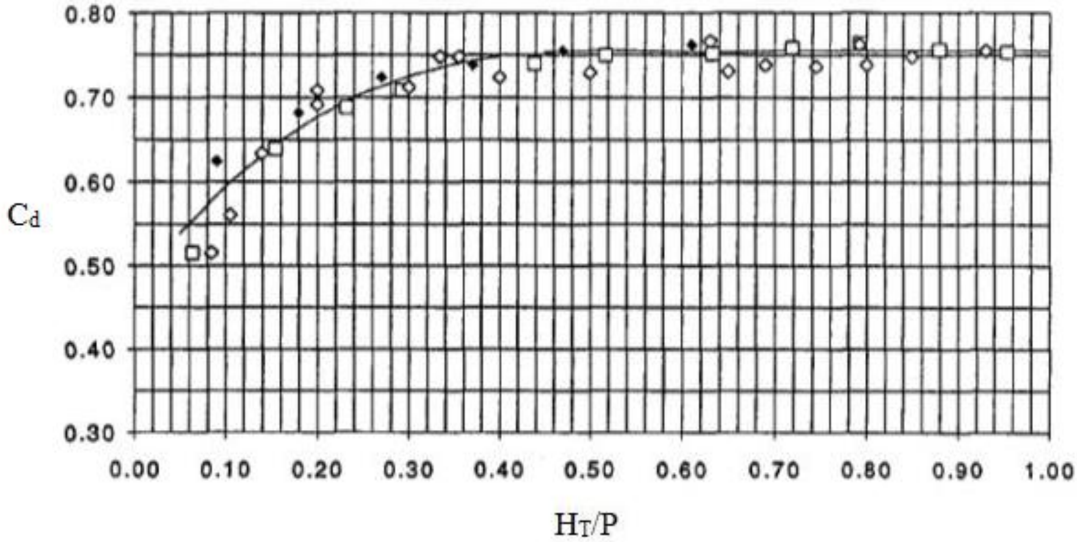


Figure 4-4 Discharge Coefficients for Linear Weirs (Tullis et al. 1995)

4.2 Design Procedure Steps for Labyrinth Weirs

1) Ensure that H_T / P is smaller than 0.9.

2) Consider the criteria $3 \leq w/P \leq 4$. (4-2)

   By inserting the value of the weir height (P), the range of w (width of one cycle) can be obtained. After then, the number of cycles can be calculated.

3) The wall thickness (t) is equal to P/6. (Tullis, et al. 1995)

   $t = P/6$ (4-3)

4) Crest shape of the labyrinth weir is quarter-round and radius of crest curvature R is equal to P/12. (Tullis, et al. 1995)

   $R = P/12$ (4-4)

5) The value of inside apex width (A) is between t and 2t.

   $(t \leq A \leq 2t)$ (4-5)

6) Labyrinth angle is usually chosen from the range of alpha values of 8°-16°.

7) Outside apex width (D) is calculated from:

   $D = A + 2t \tan(45 - \alpha/2)$ (4-6)

8) Obtain L_1 (actual length of side length) by using α and w. Then calculate the effective length as follows:

$\sin \alpha = x / L_1$ (4-8)

Where,

$x = (w - D - A)/2$ (4-7)

$L = (D/2 + L_1 + A + L_1 + D/2)\, N$ (4-9)

9) Determine C_d from Figure 4-3.

10) Calculate the discharge over the labyrinth weir using Equation (4-1).

4.3 Case Studies for Labyrinth Weirs

4.3.1 Nilüfer Dam

Location: Bursa

Maximum reservoir water elevation: 762.40 m

Crest elevation: 760.00 m

Approach channel elevation: 758.00 m

Effective length of the linear weir = Total spillway width (W): 122.85 m

Approach channel elevation was reduced by 1 m from the original elevation in order to increase the weir height so to decrease H_T/P.

New approach channel elevation: 757.00 m

H_T= Total head

H_T= 2.4 m

P= Crest elevation-Approach channel elevation= 3 m

1) $H_T/P= 0.8 < 0.9$ OK.
2) $3\leq w/P\leq 4$ (Eqn 4-2)

   $3\leq\frac{w}{3}\leq 4$ thus $9\leq w\leq 12$

w=12 m, thus N=10. (Number of cycles=N= W/w)

3) The wall thickness (t) is equal to P/6.

   t=3/6=0.5m. (Eqn 4-3)
4) Crest shape of the labyrinth weir is quarter-round and radius of crest curvature R is equal to P/12. (Eqn 4-4)

   Therefore, R=3/12=0.25m.
5) The value of inside apex width (A) is between t and 2t.

   $t\leq A\leq 2t$ (Eqn. 4-5)

   $0.5\leq A\leq 1.0$

   Then, A= 1m.
6) Labyrinth angle is usually chosen from the range of alpha values of 8°-16°.

α is chosen as 8°.

7) $D= A+ 2t \tan(45-\alpha/2)$ (Eqn. 4-6)

$D= 1+ 2\ 0.5 (\tan 41)$

$D=1.87$ m.

8) Calculating L_1.

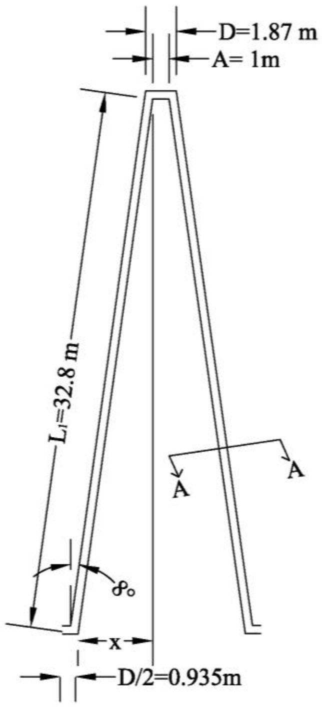


Figure 4-5 Schematic of L_1 Calculation

$x= (w-D-A)/2$ (Eqn. 4-7)

$x= (12-1.87-1)/2$

$x= 4.565$ m.

$\sin 8= 4.565 / L_1$ (Eqn. 4-8)

$L_1= 32.8$ m.

$L= (D/2 +L_1+ A+ L_1+ D/2)\ N$ (Eqn. 4-9)

$L= (D/2 + L1+ A+L_1+ D/2)\ 10+2.85$

L=687.55 m.

9)Determine C_d from Figure 4-3.

According to Figure 4-3, C_d= 0.3

10)Calculate the discharge over the labyrinth weir using Eqn. 4-1.

Q= $\frac{2}{3} C_d \, L \, \sqrt{2g} \, H_T^{3/2}$ (Eqn. 4-1)

Q= $\frac{2}{3}$ 0.3 687.55 $\sqrt{(2\ 9.81)}$ $2.4^{1.5}$

Q= 2264.65 m^3/s.

Discharge of the linear weir:

Q= $\frac{2}{3} C_d \, L \, \sqrt{2g} \, H_T^{3/2}$

L=122.85 m

$C_d = 0.75$ is obtained with H_T/P = 0.8, according to Figure 4-4.

Q= $\frac{2}{3}$ 0.75 122.85 $\sqrt{(2\ 9.81)}$ $2.4^{1.5}$

Q= 1011.61 m^3/s.

It can be seen in Table 4-1 that by using labyrinth weir instead of a linear weir, the effective length increases about 5 times and the discharge capacity increases about 2 times in this specific case.

Table 4-1 Labyrinth Weir Calculations for Nilüfer Dam

		Tool →	Eq. (4-2)		Eq.(4-3)	Eq.(4-4)	Eq.(4-5)
H_T	P	H_T/P	w	N	t	R	A
(m)	(m)	-	(m)	-	(m)	(m)	(m)
2.4	3	0.8	12	10	0.5	0.25	1
	Eq.(4-6)	Eq.(4-7)	Eq.(4-8)	Eq.(4-9)	Fig.(4-3)	Eq.(4-1)	Eq.(4-1)
α	D	x	L_1	L	C_d	$Q_{labyrinth}$	Q_{linear}
(deg.)	(m)	(m)	(m)	(m)	-	(m^3/s)	(m^3/s)
8	1.87	4.565	32.8	687.55	0.3	2264.65	1011.61

4.3.2 Aydınca Dam

Location: Amasya

Maximum reservoir water elevation: 828.69 m

Crest elevation: 827.25 m

Approach channel elevation: 826.50 m

Effective length of the linear weir = Total spillway width (W): 13 m

Approach channel elevation was reduced by 1.25 m from the original elevation in order to increase the weir height so to decrease H_T / P.

New approach channel elevation: 825.25 m

H_T= Total head= 1.44 m

P= Crest elevation-Approach channel elevation = 2 m

Computation steps are shown in Table 4-2.

Table 4-2 Labyrinth Weir Calculations for Aydınca Dam

		Tool →	Eq. (4-2)		Eq.(4-3)	Eq.(4-4)	Eq.(4-5)
H_T	P	H_T/P	w	N	t	R	A
(m)	(m)	-	(m)	-	(m)	(m)	(m)
1.44	2	0.72	6.5	2	0.333	0.167	0.5
	Eq.(4-6)	Eq.(4-7)	Eq.(4-8)	Eq.(4-9)	Fig.(4-3)	Eq.(4-1)	Eq.(4-1)
α	D	x	L_1	L	C_d	$Q_{labyrinth}$	Q_{linear}
(deg.)	(m)	(m)	(m)	(m)	-	(m^3/s)	(m^3/s)
8	1.07	2.465	17.7	73.94	0.31	116.96	49.75

Discharge of the linear weir:

$Q = \frac{2}{3} C_d \, L \, \sqrt{2g} \, H_T^{3/2}$

L=13 m

$C_d = 0.75$ is obtained with $H_T/P = 0.72$, according to Figure 4-4.

$Q = \frac{2}{3} \, 0.75 \; 13 \sqrt{(2 \; 9.81)} \; 1.44^{1.5}$

Q= 49.75 m³/s.

It can be seen that by using labyrinth weir instead of a linear weir, the effective length increases about 5 times and the discharge capacity increases about 2 times as in Nilüfer Dam.

4.3.3 Turhal Dam

Location: Tokat

Maximum reservoir water elevation: 859.59 m

Crest elevation: 857.77 m

Approach channel elevation: 854.27 m

Effective length of the linear weir = Total spillway width (W): 63 m

H_T= Total head

H_T= 1.82 m

P= Crest elevation-Approach channel elevation= 3.5 m

Computation steps are shown in Table 4-3.

Table 4-3 Labyrinth Weir Calculations for Turhal Dam

		Tool →	Eq. (4-2)		Eq.(4-3)	Eq.(4-4)	Eq.(4-5)
H_T	P	H_T/P	w	N	t	R	A
(m)	(m)	-	(m)	-	(m)	(m)	(m)
1.82	3.5	0.52	10.5	6	0.58	0.29	1
	Eq.(4-6)	Eq.(4-7)	Eq.(4-8)	Eq.(4-9)	Fig.(4-3)	Eq.(4-1)	Eq.(4-1)
α	D	x	L_1	L	C_d	$Q_{labyrinth}$	Q_{linear}
(deg.)	(m)	(m)	(m)	(m)	-	(m^3/s)	(m^3/s)
8	2	3.75	26.94	341.28	0.375	927.91	342.58

Discharge of the linear weir:

$Q=\frac{2}{3} C_d \, L \sqrt{2g} \, H_T{}^{3/2}$

L=63 m

$C_d = 0.75$ is obtained with $H_T/P = 0.52$, according to Figure 4-4.

$Q=\frac{2}{3} 0.75 \; 63 \sqrt{(2 \; 9.81)} \; 1.82^{1.5}$

Q= 342.58 m^3/s.

It can be seen that by using labyrinth weir instead of a linear weir, the effective length has increased about 5 times and the discharge capacity has increased about 2.7 times in this specific case.

4.3.4 Büyükkumla Dam

Location: Bursa

Maximum reservoir water elevation: 68.14 m

Crest elevation: 66.50 m

Approach channel elevation: 65.00 m

Effective length of the linear weir = Total spillway width (W): 50.00 m

Approach channel elevation was reduced by 0.5 m from the original elevation in order to increase the weir height so to decrease H_T / P.

New approach channel elevation: 64.50 m

H_T= Total head = 1.64 m

P= Crest elevation-Approach spillway elevation = 2 m

Computation steps are shown in Table 4-4.

Table 4-4 Labyrinth Weir Calculations for Büyükkumla Dam

		Tool →	Eq. (4-2)		Eq.(4-3)	Eq.(4-4)	Eq.(4-5)
H_T	P	H_T/P	w	N	t	R	A
(m)	(m)	-	(m)	-	(m)	(m)	(m)
1.64	2	0.82	8	6	0.333	0.167	0.5
	Eq.(4-6)	Eq.(4-7)	Eq.(4-8)	Eq.(4-9)	Fig.(4-3)	Eq.(4-1)	Eq.(4-1)
α	D	x	L_1	L	C_d	$Q_{labyrinth}$	Q_{linear}
(deg.)	(m)	(m)	(m)	(m)	-	(m^3/s)	(m^3/s)
8	1.07	3.215	23.1	288.62	0.28	501.2	232.57

Discharge of the linear weir:

$$Q= \frac{2}{3} C_d \, L \, \sqrt{2g} \, H_T^{3/2}$$

L=50 m

$C_d = 0.75$ is obtained with H_T/P = 0.82, according to Figure 4-4.

$$Q= \frac{2}{3} \, 0.75 \; 50 \, \sqrt{(2 \; 9.81)} \; 1.64^{1.5}$$

Q= 232.57 m^3/s.

4.3.5 Yavrudoğan Dam

Location: Antalya

Maximum reservoir water elevation: 131.92 m

Crest elevation: 130.57 m

Approach channel elevation: 129.57 m

Effective length of the linear weir = Total spillway width (W): 58.00 m

Approach channel elevation was reduced by 1 m from the original elevation in order to increase the weir height so to decrease H_T / P.

New approach channel elevation: 128.57 m

H_T= Total head

H_T= 1.35 m

P= Crest elevation-Approach channel elevation = 2m

Computation steps are shown in Table 4-5.

Table 4-5 Labyrinth Weir Calculations for Yavrudoğan Dam

		Tool →	Eq. (4-2)		Eq.(4-3)	Eq.(4-4)	Eq.(4-5)
H_T	P	H_T/P	w	N	t	R	A
(m)	(m)	-	(m)	-	(m)	(m)	(m)
1.35	2	0.675	7	8	0.333	0.167	0.5
	Eq.(4-6)	Eq.(4-7)	Eq.(4-8)	Eq.(4-9)	Fig.(4-3)	Eq.(4-1)	Eq.(4-1)
α	D	x	L_1	L	C_d	$Q_{labyrinth}$	Q_{linear}
(deg.)	(m)	(m)	(m)	(m)	-	(m^3/s)	(m^3/s)
8	1.07	2.71	19.474	324.218	0.32	483.523	173.696

Discharge of the linear weir:

$Q = \frac{2}{3} C_d L \sqrt{2g} H_T^{3/2}$

L=58 m

$C_d = 0.75$ is obtained with $H_T/P = 0.675$, according to Figure 4-4.

$Q = \frac{2}{3} 0.75\ 50 \sqrt{(2\ 9.81)}\ 1.35^{1.5}$

Q= 173.696 m^3/s

Table 4-6 summarizes the results of five case studies used for labyrinth weirs.

Table 4-6 Labyrinth Weir Calculations for Five Dams

			Tool →	(4-2)		(4-3)	(4-4)	(4-5)
Dam Name	H_T (m)	P (m)	H_T/P	w (m)	N	t (m)	R (m)	A (m)
Nilüfer Dam	2.400	3.000	0.800	8.000	10.000	0.500	0.250	1.000
Aydınca Dam	1.440	2.000	0.720	6.500	2.000	0.333	0.167	0.500
Turhal Dam	1.820	3.500	0.520	10.500	6.000	0.580	0.290	1.000
Büyükkumla Dam	1.640	2.000	0.820	8.000	6.000	0.333	0.167	0.500
Yavrudoğan Dam	1.350	2.000	0.675	7.000	8.000	0.333	0.167	0.500

		(4-6)	(4-7)	(4-8)	(4-9)	Fig. (4-3)	(4-1)
Dam Name	α°	D (m)	x (m)	L_1 (m)	L (m)	C_d	Q (m^3/s)
Nilüfer Dam	8.000	1.870	4.565	32.800	687.550	0.300	2264.650
Aydınca Dam	8.000	1.070	2.465	17.700	73.940	0.310	116.960
Turhal Dam	8.000	2.000	3.750	26.940	341.280	0.375	927.910
Büyükkumla Dam	8.000	1.070	3.215	23.100	288.620	0.280	501.200
Yavrudoğan Dam	8.000	1.070	2.710	19.474	324.218	0.320	483.523

4.4 Design Procedure for Piano Key Weirs

A Piano Key Weir is an alternative to the traditional labyrinth weirs. Similar to the labyrinth weirs, the piano key weirs increase the discharge capacity with their longer crest lengths. Figures 4-6 and 4-7 show important parameters of these weirs.

The basic equation developed for linear weirs is used to design a piano key weir.

$$Q= \frac{2}{3} C_d \, L \sqrt{2g} \, {H_T}^{3/2} \tag{4-1}$$

Where,

Q= Discharge over the weir (m^3/s)

C_d= Dimensionless discharge coefficient

L= Effective length of the weir (m)

g= Acceleration due to gravity (m/s^2)

H_T= Total head over the crest (m)

4.5 Design Procedure Steps for Piano Key Weirs

1) Determine P_m. (P_m= P/2)
2) Optimal value of W_i/W_o is around 1.25. (Hydrocoop, 2013)
   Specify W_i and W_o by considering this ratio.
3) For a cost effective design, following expressions are suggested $W_i = P_m$, W_o= 0.8 P_m and B= 3.6 P_m, and also B_o= B_i= 0.9 P_m (Hydrocoop, 2013)

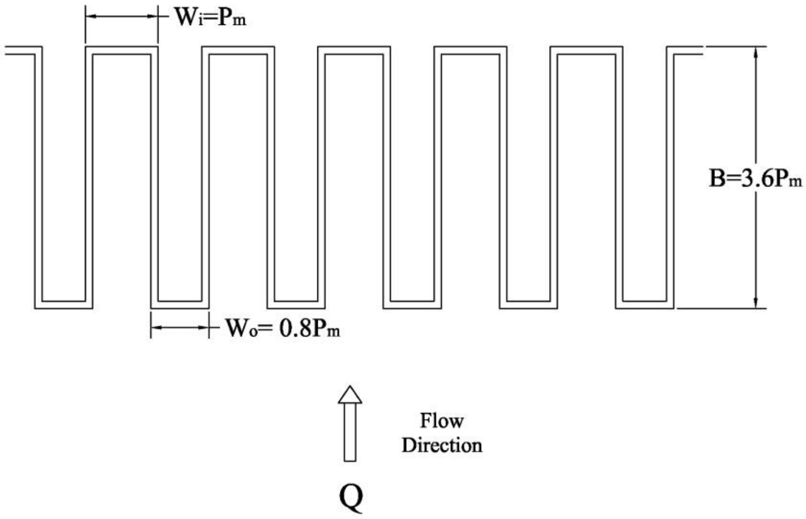


Figure 4-6 Piano Key Weir Schematic, Plan View

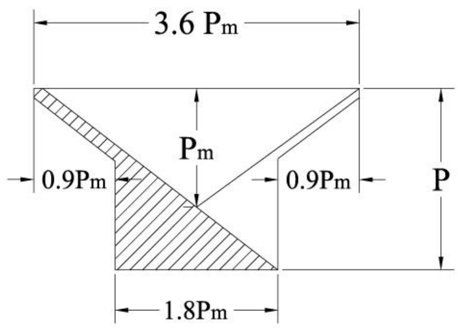


Figure 4-7 Piano Key Weir Schematic, Cross-Section View

4) P_i= the height of the walls

   Specify that $P_i = 1.5P_m$.

5) After calculating P_i, specify T_s by considering that $10<P_i/T_s<22$. (Ribeiro et al. ,2013)

6) Determine width of one cycle (w), Figure 4-8.

   $w= 2 (W_i/2 - T_s) + W_o$

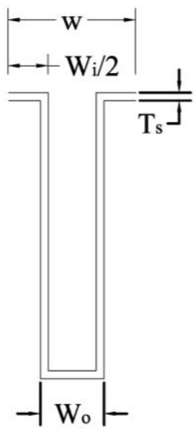


Figure 4-8 Schematic of w Calculation

7) Find number of cycles (N).
8) Find L.

   $L= N [(W_i/2-T_s+ B-T_s) 2 +W_o] +2.85$

9) Specify C_d in accordance with Figure 4-9.

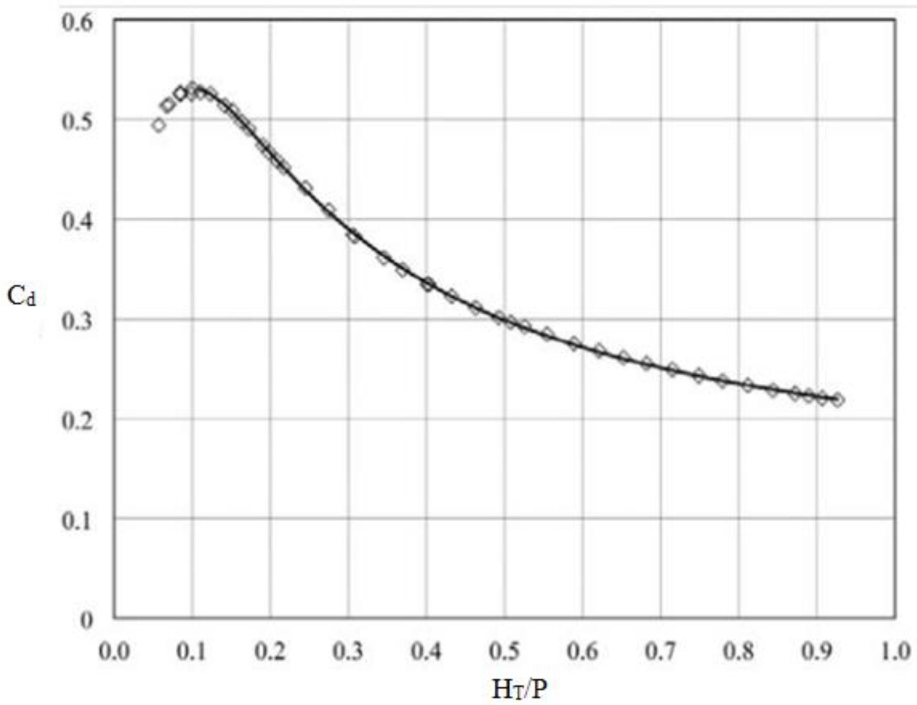


Figure 4-9 C_d vs. H_T/P for PK Weir with 1.25 W_i/W_o =1.25 (Anderson and Tullis, 2011)

10) Calculate the discharge over the PK weir.

4.6 Case Studies for Piano Key Weirs

4.6.1 Nilüfer Dam

Location: Bursa

Maximum reservoir water elevation: 762.40 m

Crest elevation: 760.00 m

Approach channel elevation: 758.00 m

Effective length of the linear weir = Total spillway width (W): 122.85 m

Approach channel elevation was reduced by 1 m from the original elevation in order to increase the weir height so to decrease H_T/ P.

New approach channel elevation: 757.00 m

H_T= Total head = 2.4 m

P= Crest elevation-Approach channel elevation = 3 m

1) Determine P_m. (P_m= P/2) (4-10)

P_m= 1.5 m.

2) W_i/W_o=1.25

3) For a cost effective design;

$W_i = P_m = 1.5$m (4-11)

$W_o = 0.8P_m = 1.2$ m (4-12)

B= 3.6 P_m = 5.4 m (4-13)

B_o=B_i = 0.9 P_m= 1.35 m. (4-14)

4) $P_i = 1.5P_m = 2.25$ m. (4-15)

5) Determine T_s, by considering that $10<P_i/T_s<22$ (4-16)

$10 < P_i/T_s < 22$

$10 < 2.25/T_s < 22$

$0.225 > T_s > 0.102$

T_s is chosen as 0.15 m.

6) Calculate width of one cycle

$$w = 2\left(\frac{W_i}{2} - T_s\right) + W_o \qquad (4\text{-}17)$$

w= (2 0.6) + 1.2

w= 2.4 m.

7) Determine number of cycles (N)

N is selected as 50.

Total labyrinth width: 122.85 m

122.85= (50 2.4) + 2.85

8) Find L.

$$L = N\left[\left(\frac{W_i}{2} - T_s + B - T_s\right) 2 + W_o\right] \qquad (4\text{-}18)$$

L= 647.85 m.

9)Specify C_d from Figure 4.9 for $H_T/P=0.8$.

C_d= 0.24 (According to Figure 4-9)

10)Calculate the discharge over the PK weir

$$Q = \frac{2}{3} C_d\, L \sqrt{2g}\, H_T^{3/2} \qquad (4\text{-}1)$$

$$Q = \frac{2}{3}\ 0.24\ 647.85 \sqrt{(2 * 9.81)}\ 2.4^{3/2}$$

Q= 1707.11 m^3/s.

Computation steps are shown in Table 4-7.

Table 4-7 Piano Key Weir Calculations for Nilüfer Dam

Tool →	Eq. (4-10)	Eq. (4-11)	Eq. (4-12)	Eq. (4-13)	Eq. (4-14)	Eq. (4-15)
P	P_m	W_i	W_o	B	B_o=B_i	P_i
(m)	(m)	(m)	(m)	(m)	(m)	(m)
3	1.5	1.5	1.2	5.4	1.35	2.25
Eq.(4-16)	Eq.(4-17)		Eq.(4-18)	Fig.(4-9)	Eq.(4-1)	Eq.(4-1)
T_s	w	N	L	C_d	Q_{PKW}	Q_{linear}
(m)	(m)	-	(m)	-	(m^3/s)	(m^3/s)
0.15	2.4	50	647.85	0.24	1701.11	1011.61

Discharge of the linear weir: 1011.61 m^3/s.

It can be seen that by using piano key weir instead of a linear weir, the effective length increases about 5 times and the discharge capacity increases about 1.7 times in this specific case.

4.6.2 Aydınca Dam

Location: Amasya

Maximum reservoir water elevation: 828.69 m

Crest elevation: 827.25 m

Approach channel elevation: 826.50 m

Effective length of the linear weir = Total spillway width (W): 13 m

Approach channel elevation was reduced by 1.25 m from the original elevation in order to increase the weir height so to decrease H_T / P.

New approach channel elevation: 825.25 m

H_T = Total head= 1.44 m

P= Crest elevation-Approach channel elevation= 2 m

Computation steps are shown in Table 4-8.

Table 4-8 Piano Key Weir Calculations for Aydınca Dam

Tool →	Eq. (4-10)	Eq. (4-11)	Eq. (4-12)	Eq. (4-13)	Eq. (4-14)	Eq. (4-15)
P	P_m	W_i	W_o	B	B_o=B_i	P_i
(m)	(m)	(m)	(m)	(m)	(m)	(m)
2	1	1	0.8	3.6	0.9	1.5
Eq.(4-16)	Eq.(4-17)		Eq.(4-18)	Fig.(4-9)	Eq.(4-1)	Eq.(4-1)
T_s	w	N	L	C_d	Q_{PKW}	Q_{linear}
(m)	(m)	-	(m)	-	(m^3/s)	(m^3/s)
0.1	1.6	8	69	0.26	91.54	49.75

Discharge of the linear weir: 49.75 m^3/s.

It can be seen that by using piano key weir instead of a linear weir, the effective length increases about 5 times and the discharge capacity increases about 1.8 times as in Nilüfer Dam.

4.6.3 Turhal Dam

Location: Tokat

Maximum reservoir water elevation: 859.59 m

Crest elevation: 857.77 m

Approach channel elevation: 854.27 m

Effective length of the linear weir = Total spillway width (W): 63 m

H_T = Total head= 1.82 m

P= Crest elevation-Approach channel elevation= 3.5 m

Computation steps are shown in Table 4-9.

Table 4-9 Piano Key Weir Calculations for Turhal Dam

Tool →	Eq. (4-10)	Eq. (4-11)	Eq. (4-12)	Eq. (4-13)	Eq. (4-14)	Eq. (4-15)
P	P_m	W_i	W_o	B	B_o=B_i	P_i
(m)	(m)	(m)	(m)	(m)	(m)	(m)
3.5	1.75	1.75	1.4	6.3	1.575	2.625
Eq.(4-16)	Eq.(4-17)		Eq.(4-18)	Fig.(4-9)	Eq.(4-1)	Eq.(4-1)
T_s	w	N	L	C_d	Q_{PKW}	Q_{linear}
(m)	(m)	-	(m)	-	(m^3/s)	(m^3/s)
0.2	2.75	22	63	0.295	708.83	342.58

Discharge of the linear weir: 342.58 m^3/s.

It can be seen that by using piano key weir instead of a linear weir, the effective length has increased about 5 times and the discharge capacity has increased about 2 times in this specific case.

4.6.4 Büyükkumla Dam

Location: Bursa

Maximum reservoir water elevation: 68.14 m

Crest elevation: 66.50 m

Approach channel elevation: 65.00 m

Effective length of the linear weir = Total spillway width (W): 50.00 m

Approach channel elevation was reduced by 0.5 m from the original elevation in order to increase the weir height so to decrease H_T / P.

New approach channel elevation: 64.50 m

H_T = Maximum reservoir elevation- Crest elevation

H_T = 1.64 m

P= Crest elevation-Approach channel elevation = 2 m

Computation steps are shown in Table 4-10.

Table 4-10 Piano Key Weir Calculations for Büyükkumla Dam

Tool →	Eq. (4-10)	Eq. (4-11)	Eq. (4-12)	Eq. (4-13)	Eq. (4-14)	Eq. (4-15)
P	P_m	W_i	W_o	B	B_o=B_i	P_i
(m)	(m)	(m)	(m)	(m)	(m)	(m)
2	1	1	0.8	3.6	0.9	1.5
Eq.(4-16)	Eq.(4-17)		Eq.(4-18)	Fig.(4-9)	Eq.(4-1)	Eq.(4-1)
T_s	w	N	L	C_d	Q_{PKW}	Q_{linear}
(m)	(m)	-	(m)	-	(m^3/s)	(m^3/s)
0.1	1.6	30	260	0.25	403.123	232.57

Discharge of the linear weir: 232.57 m^3/s.

4.6.5 Yavrudoğan Dam

Location: Antalya

Maximum reservoir water elevation: 131.92 m

Crest elevation: 130.57 m

Approach channel elevation: 129.57 m

Effective length of the linear weir = Total spillway width (W): 58.00 m

Approach channel elevation was reduced by 1 m from the original elevation in order to increase the weir height so to decrease H_T / P.

New approach channel elevation: 128.57 m

H_T = Maximum reservoir elevation- Crest elevation

H_T = 1.35 m

P= Crest elevation-Approach channel elevation= 2 m

Computation steps are shown in Table 4-11.

Table 4-11 Piano Key Weir Calculations for Yavrudoğan Dam

Tool →	Eq. (4-10)	Eq. (4-11)	Eq. (4-12)	Eq. (4-13)	Eq. (4-14)	Eq. (4-15)
P	P_m	W_i	W_o	B	B_o=B_i	P_i
(m)	(m)	(m)	(m)	(m)	(m)	(m)
2	1	1	0.8	3.6	0.9	1.5
Eq.(4-16)	Eq.(4-17)		Eq.(4-18)	Fig.(4-9)	Eq.(4-1)	Eq.(4-1)
T_s	w	N	L	C_d	Q_{PKW}	Q_{linear}
(m)	(m)	-	(m)	-	(m^3/s)	(m^3/s)
0.1	1.6	36	310	0.275	394.896	173.696

Discharge of the linear weir: 173.696 m^3/s

Table 4-12 summarizes the results of five case studies used for piano key weirs.

Table 4-12 Piano Key Weir Calculations for Five Dams

	Tool→	(4-10)	(4-11)	(4-12)	(4-13)	(4-14)
Dam Name	P (m)	P_m (m)	W_i (m)	W_o (m)	B (m)	Bo=Bi (m)
Nilüfer Dam	3.000	1.500	1.500	1.200	5.400	1.350
Aydınca Dam	2.000	1.000	1.000	0.800	3.600	0.900
Turhal Dam	3.500	1.750	1.750	1.400	6.300	1.575
Büyükkumla Dam	2.000	1.000	1.000	0.800	3.600	0.900
Yavrudoğan Dam	2.000	1.000	1.000	0.800	3.600	0.900

	(4-15)	(4-16)	(4-17)		(4-18)	Fig. (4-9)	(4-19)
Dam Name	P_i (m)	T_s (m)	w (m)	N	L (m)	C_d	Q_{PKW} (m^3/s)
Nilüfer Dam	2.250	0.150	2.400	50.000	647.850	0.240	1707.110
Aydınca Dam	1.500	1.000	1.600	8.000	69.000	0.260	91.540
Turhal Dam	2.625	0.200	2.750	22.000	63.000	0.295	708.830
Büyükkumla Dam	1.500	1.000	1.600	30.000	260.000	0.250	403.123
Yavrudoğan Dam	1.500	1.000	1.600	36.000	310.000	0.275	394.896

CHAPTER 5

DISCUSSIONS

In this chapter, effects of the labyrinth angle, number of cycles and H_T/P ratio on the discharge of the labyrinth weirs and effects of the H_T/P ratio and W_i/W_o on the discharge of the piano key weir weirs are given.

5.1 Discharge Variation for Labyrinth Weirs with Different Labyrinth Angles

In part 4.3.1, labyrinth angle was selected as 8° for Nilüfer Dam. Then, the results given in Table 5-1 were obtained.

Table 5-1 Labyrinth Weir Calculations for α=8°

		Tool →	Eq. (4-2)		Eq.(4-3)	Eq.(4-4)	Eq.(4-5)
H_T	P	H_T/P	w	N	t	R	A
(m)	(m)	-	(m)	-	(m)	(m)	(m)
2.4	3	0.8	12	10	0.5	0.25	1
	Eq.(4-6)	Eq.(4-7)	Eq.(4-8)	Eq.(4-9)	Fig.(4-3)	Eq.(4-1)	Eq.(4-1)
α	D	x	L_1	L	C_d	$Q_{labyrinth}$	Q_{linear}
(deg.)	(m)	(m)	(m)	(m)	-	(m^3/s)	(m^3/s)
8	1.87	4.565	32.8	687.55	0.3	2264.65	1011.61

In order to observe changes in discharge capacity, α=15° and α=25° are used and effective lengths and the discharge capacities are calculated by using these labyrinth angles, Tables 5-2 and 5-3. Table 5-4 shows the angle effect in discharge capacity.

Table 5-2 Labyrinth Weir Calculations for α=15°

		Tool →	Eq. (4-2)		Eq.(4-3)	Eq.(4-4)	Eq.(4-5)
H_T	P	H_T/P	w	N	t	R	A
(m)	(m)	-	(m)	-	(m)	(m)	(m)
2.4	3	0.8	12	10	0.5	0.25	1
	Eq.(4-6)	Eq.(4-7)	Eq.(4-8)	Eq.(4-9)	Fig.(4-3)	Eq.(4-1)	Eq.(4-1)
α	D	x	L_1	L	C_d	$Q_{labyrinth}$	Q_{linear}
(deg.)	(m)	(m)	(m)	(m)	-	(m^3/s)	(m^3/s)
15	1.77	4.615	17.83	387.15	0.395	1679.0	1011.61

Table 5-3 Labyrinth Weir Calculations for α=25°

		Tool →	Eq. (4-2)		Eq.(4-3)	Eq.(4-4)	Eq.(4-5)
H_T	P	H_T/P	w	N	t	R	A
(m)	(m)	-	(m)	-	(m)	(m)	(m)
2.4	3	0.8	12	10	0.5	0.25	1
	Eq.(4-6)	Eq.(4-7)	Eq.(4-8)	Eq.(4-9)	Fig.(4-3)	Eq.(4-1)	Eq.(4-1)
α	D	x	L_1	L	C_d	$Q_{labyrinth}$	Q_{linear}
(deg.)	(m)	(m)	(m)	(m)	-	(m^3/s)	(m^3/s)
25	1.64	4.68	11.07	250.65	0.56	1541.1	1011.61

Table 5-4 Influence of Different Labyrinth Angles on the Discharge Capacity

Labyrinth angle(α°)	Discharge Coefficient (C_d)	Effective Length (m)	Discharge Capacity (m^3/s)
8	0.300	687.55	2264.65
15	0.395	387.15	1679.00
25	0.560	250.65	1541.10

It can be concluded from Table 5-4 that when α increases, C_d increases and the effective length decreases. The decrease in the effective length is more dominant than the increase in the discharge coefficient. Consequently, when α increases, the discharge capacity decreases significantly. In order to obtain a greater discharge capacity, low values of labyrinth angles should be selected.

Although the effective crest lengths of labyrinth weir (α=8°) and the piano key weir are close, discharge capacities are not close due to effect of discharge coefficients. When the head increases, discharge coefficient of a piano key weir is more sensitive than that of a labyrinth weir. Table 5-5, based on previous computations, gives a useful table to compare linear, labyrinth (with various angles of α) and piano key weirs.

Table 5-5 Comparison of Discharge Capacity and Discharge Coefficient of Different Types of Weirs for Nilüfer Dam

Weir Type	Effective Length(m)	Discharge Coefficient(C_d)	Discharge Capacity(m^3/s)
Linear Weir	122.85	0.750	1011.61
Labyrinth Weir with α=25°	250.65	0.560	1541.10
Labyrinth Weir with α=15°	387.15	0.395	1679.00
Piano Key Weir	647.85	0.240	1707.11
Labyrinth Weir with α=8°	687.55	0.300	2264.65

5.2 Discharge Variation for Labyrinth Weirs with Different Number of Cycles

Table 5-6 emphasizes the effect of number of cycles on discharge capacity.

Table 5-6 Influence of Number of Cycles on Discharge Capacity

Number of cycles N	Width of one cycle w (m)	Effective Length (m)	Discharge Capacity (m^3/s)
10	12	687.55	2264.65
8	15	723.41	2382.76
6	20	758.07	2496.93

According to Table 5-6, it can be seen that as number of cycles N decreases, effective length and discharge capacity increase. However, the data show that decreasing N has little effect on the effective length and discharge capacity.

In order to obtain both hydraulically efficient and cost effective design, the criterion of $3 \leq w/P \leq 4$ is recommended. (Tullis, et al. 1995)

5.3 Discharge Variation for Labyrinth Weirs with Different H_T/P Ratios

In accordance with the previous studies, the ratio of the total head to the weir height (H_T/P) should be less than 0.9. Because, when the ration of H_T/P increases, C_d starts to decrease and the spillway capacity will reach the capacity of linear weir in the end.

In Büyükkumla Dam study, approach channel elevation was reduced by 0.5 m from the original elevation. In order to observe changes in the discharge capacity, approach channel elevation is reduced by 1.5 and 2.5 m instead of 0.5 m from the original elevation to decrease H_T/P, and computations are shown in Table 5-7 and 5-8, respectively. Table 5-9 shows summary of the results.

Table 5-7 Labyrinth Weir Calculations When Approach Channel Elevation is Reduced by 1.5 m

		Tool →	Eq. (4-2)		Eq.(4-3)	Eq.(4-4)	Eq.(4-5)
H_T	P	H_T/P	w	N	t	R	A
(m)	(m)	-	(m)	-	(m)	(m)	(m)
1.64	3	0.55	10	5	0.5	0.25	1
	Eq.(4-6)	Eq.(4-7)	Eq.(4-8)	Eq.(4-9)	Fig.(4-3)	Eq.(4-1)	Eq.(4-1)
α	D	x	L_1	L	C_d	$Q_{labyrinth}$	Q_{linear}
(deg.)	(m)	(m)	(m)	(m)	-	(m^3/s)	(m^3/s)
8	1.87	3.565	25.6	270.35	0.36	603.6	232.57

Table 5-8 Labyrinth Weir Calculations When Approach Channel Elevation is Reduced by 2.5 m

		Tool →	Eq. (4-2)		Eq.(4-3)	Eq.(4-4)	Eq.(4-5)
H_T	P	H_T/P	w	N	t	R	A
(m)	(m)	-	(m)	-	(m)	(m)	(m)
1.64	4	0.41	12	4	0.667	0.333	1
	Eq.(4-6)	Eq.(4-7)	Eq.(4-8)	Eq.(4-9)	Fig.(4-3)	Eq.(4-1)	Eq.(4-1)
α	D	x	L_1	L	C_d	$Q_{labyrinth}$	Q_{linear}
(deg.)	(m)	(m)	(m)	(m)	-	(m^3/s)	(m^3/s)
8	2.16	4.42	31.8	267.04	0.43	712.1	232.57

Table 5.9 Comparison of Discharge Capacity and Discharge Coefficient for Various Ratios of H_T/ P Ratios for Labyrinth Weirs

H_T/ P	Effective Length(m)	Discharge Coefficient(C_d)	Discharge Capacity(m^3/s)
0.82	288.62	0.28	501.20
0.55	270.35	0.36	603.60
0.41	267.04	0.43	712.10

It can be concluded from the above table that as H_T/ P decreases, C_d continues to increase and effective length continues to decrease. However, the increase in the discharge coefficient C_d is more dominant than the decrease in the effective length (L). Therefore, discharge capacity increases with decreasing effective length and increasing discharge coefficient.

5.4 Discharge Variation for Piano Key Weirs with Different H_T/P Ratios

In order to observe the effect of H_T/P ratio on the flow rate Q_{PKW}/Q_{linear} ratios are calculated by using different H_T values. The calculated results are shown in Table 5-10.

Table 5.10 Influence of H_T/P Ratios on Discharge Capacity

1	2	3	4	5
H_T	H_T/P	Q_{PKW}	Q_{linear}	Q_{PKW}/Q_{linear}
0.50	0.14	179.92	41.438	4.34
1.00	0.29	371.87	133.946	2.78
1.50	0.43	575.30	256.329	2.24
1.82	0.52	708.83	342.584	2.07
2.00	0.57	775.02	394.644	1.96
2.50	0.71	967.08	551.531	1.75

If the values of first and third columns are used to plot, Figure 5-1 is obtained. As seen in Figure 5-1, as total head increases discharge over the weir increases. However, although the discharge over the weir seems to increase by increasing total head the ratio of PK weir discharge to linear weir discharge decreases, as shown in Table 5-10 in column 5, and also explicitly in Figure 5-2.

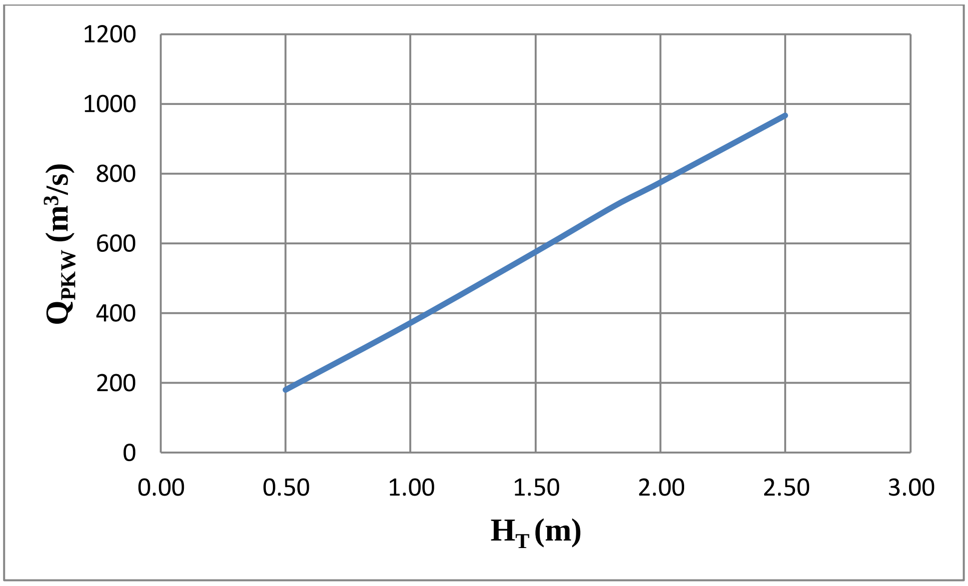


Figure 5-1 H_T versus Q Graph

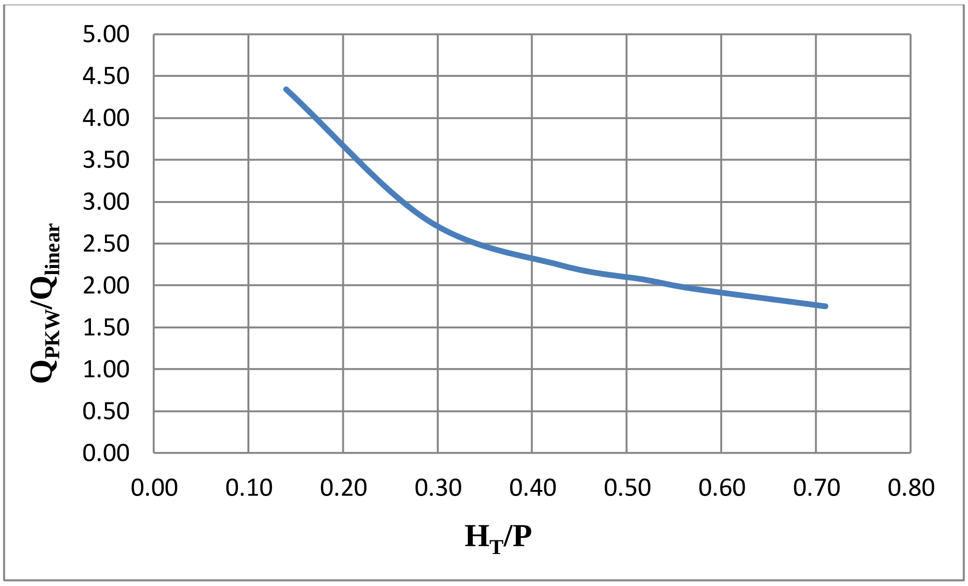


Figure 5-2 H_T/P versus Q_{PKW}/Q_{linear} Graph

Figure 5-2 shows that piano key weirs are more effective at low heads. A PKW provides increase in discharge with its longer crest length but this advantage gets lost with increasing upstream head.

5.5 Discharge Variation for Piano Key Weirs with Different W_i/W_o Ratios

In order to observe the most efficient W_i/W_o geometry, Q_{PKW}/Q_{linear} ratios are calculated by using different W_i/W_o ratios. The calculated results are shown in Table 5-11-a, Table 5-11-b and Table 5-11-c for W_i/W_o values of 1.25, 1.00 and 0.80 respectively.

Table 5-11-a Influence of W_i/W_o=1.25 Geometry on Discharge Capacity

H_T	H_T/P	Q_{PKW}	Q_{linear}	Q_{PKW}/ Q_{linear}
0.50	0.14	179.92	41.438	4.34
1.00	0.29	371.87	133.946	2.78
1.50	0.43	575.30	256.329	2.24
1.82	0.52	708.83	342.584	2.07
2.00	0.57	775.02	394.644	1.96
2.50	0.71	967.08	551.531	1.75

Table 5-11-b Influence of W_i/W_o=1.00 Geometry on Discharge Capacity

H_T	H_T/P	Q_{PKW}	Q_{linear}	Q_{PKW}/ Q_{linear}
0.50	0.14	166.67	41.438	4.02
1.00	0.29	344.49	133.946	2.57
1.50	0.43	532.95	256.329	2.08
1.82	0.52	656.64	342.584	1.92
2.00	0.57	717.96	394.644	1.82
2.50	0.71	895.87	551.531	1.62

Table 5-11-c Influence of W_i/W_o=0.80 Geometry on Discharge Capacity

H_T	H_T/P	Q_{PKW}	Q_{linear}	Q_{PKW}/Q_{linear}
0.50	0.14	146.78	41.438	3.54
1.00	0.29	303.38	133.946	2.26
1.50	0.43	469.34	256.329	1.83
1.82	0.52	578.27	342.584	1.69
2.00	0.57	632.27	394.644	1.60
2.50	0.71	788.95	551.531	1.43

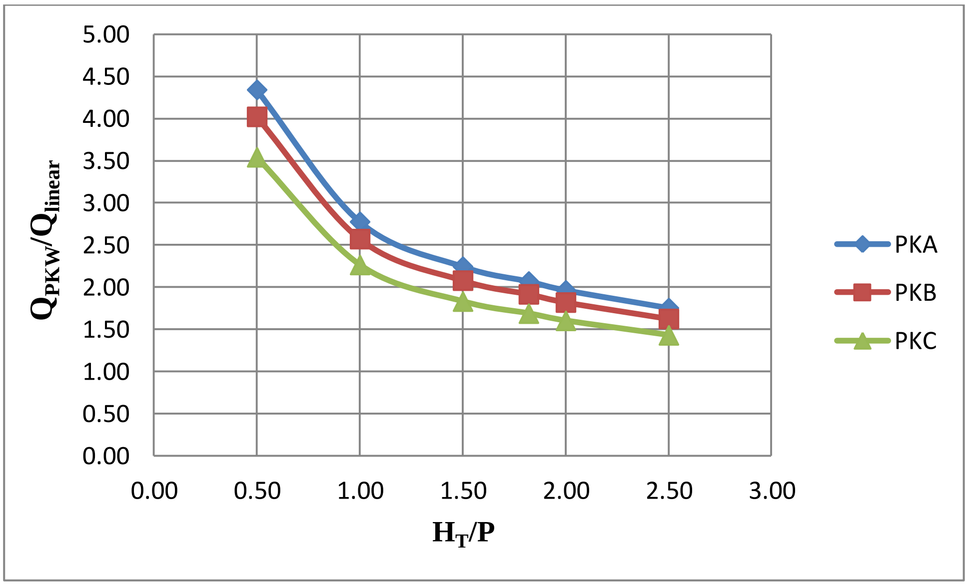


Figure 5.3 H_T/P versus Q_{PKW}/Q_{linear} with Different W_i/W_o Ratios

Figure 5.3 above demonstrates that the W_i/W_o=1.25 geometry (PKA) is the most efficient of three geometries, followed by the W_i/W_o=1.00 (PKB) and W_i/W_o=0.80 (PKC). It can be clearly seen that at constant H_T/P, the W_i/W_o=1.25 geometry (PKA) has the highest Q_{PKW}/Q_{linear} ratio.

CHAPTER 6

CONCLUSIONS

6.1 Summary and Conclusions

The main goal of this study is to investigate the methods in increasing the spillway capacity of the dams and focus was on the labyrinth weirs and piano key weirs as two ways of increasing spillway capacity. The crest length and the discharge capacity of the spillway can be increased by using labyrinth weirs and piano key weirs.

Labyrinth weirs supply an increase of crest length for a given spillway width. Therefore, they increase the flow capacity for a given water head. The capacity of a labyrinth spillway is a function of the total head H_T, the crest length L, and discharge coefficient C_d. Discharge coefficient C_d depends on total head H_T, weir heigth P, crest shape and labyrinth angle α.

In design procedure, different labyrinth angles α, H_T/P ratios and number of cycles N were used to observe changes in the discharge capacity. In light of these studies, the following conclusions are obtained:

- When the ratio of H_T/P increases in labyrinth spillways, discharge coefficient C_d starts to decrease and the benefits gained by using a labyrinth spillway is lost. Therefore, there is a limitation for H_T/P ratio of 0.9 for a successful design of a labyrinth spillway.
- When labyrinth angle α increases, discharge coefficient C_d increases and the effective length L decreases. The decrease in the effective length is more dominant than the increase in the discharge coefficient. Consequently, when

labyrinth angle increases, the discharge capacity decreases significantly. In order to obtain a greater discharge capacity, low values of labyrinth angles should be selected. Commonly, a value of 8° for α is used.

- As number of cycles N decreases, effective length L and discharge capacity increase. However, increasing N has little effect on the effective length and discharge capacity. In order to obtain both hydraulically efficient and cost effective design, the criterion of $3 \leq w/P \leq 4$ is recommended. (Tullis, et al., 1995)

A piano key (PK) weir is an alternative to the traditional labyrinth weirs. Similar to the labyrinth weirs, the piano key weirs increase the discharge capacity with their longer crest lengths.

In practice, the piano key weir has been developed to imitate the function of labyrinth weirs on smaller footprints of foundations. This situation can be explained that apart from the hydraulic advantages, the piano key weirs are effective and economic due to the fact that the piano key weirs can be easily placed at a very limited foundation. (Lempérière and Ouamane, 2003)

In design procedure, different total heads, H_T/P ratios and W_i/W_o ratios were used to observe changes in the discharge capacity. The following conclusions were reached based on the results from this study.

- Piano key weirs are more effective at low heads. A piano key weir provides increase in discharge with its longer crest length but this advantage gets lost with increasing upstream head.
- In order to observe the most efficient W_i/W_o geometry, Q_{PKW}/Q_{linear} ratios were calculated by three geometries in which the W_i/W_o ratios were 1.25, 1.00 and 0.80. It is concluded that the W_i/W_o=1.25 geometry is the most efficient of three geometries, followed by the W_i/W_o=1.00 and W_i/W_o=0.80.

In this study, it can be concluded that using a piano key weir or a labyrinth weir design engineers can increase both effective length and discharge capacity of a dam, if the conditions for their application are suitable. Labyrinth weirs with small sidewall angle (α) ensure more discharge capacity. Although the discharge capacity of a labyrinth weir with $\alpha=8°$ is greater than that of the piano key weir, by increasing the sidewall angle of a labyrinth weir, discharge capacity decreases and using piano key weir starts to be more appropriate.

In addition to these, the footprint of the piano key weir is smaller than that of a labyrinth weir for a given spillway width. This property brings an advantage to the piano key weirs that they can be easily inserted at the foundation even if there is not enough space. It can be concluded that the piano key weir is an economic and cost effective way to increase the spillway capacity.

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