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RESEARCH ON THE DISCHARGE CAPACITY THROUGH PIANO KEY WEIR CONSIDERING EFFECT OF DOWNSTREAM WATER LEVEL

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SUMMARY OF THE TECHNICAL DOCTORAL THESIS

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INTRODUCTION

1. Research rationale

Under the context of global climate change and the sudden increase of flood flow, flood discharge capacity enhancement is a key solution to ensure the reservoir safety and mitigate the downstream flood. The application of the piano key weir is one of progressive flood discharge solutions.

The piano key weir (PKW) - a modified labyrinth weir - has been developed over the past 20 years and considered as an "economic-technical" solution. There are various achievements in studying the weir geometry. However, the discharge capacity for both free and submerged flow conditions, hydraulic aspects and flow regime is still a complex problem. Especially, when the downstream water level changes and interacts with upstream flows, the discharge capacity and flow states through the PKW is significantly affected. The hydraulic aspects of the flow through the PKW are much different from the traditional weir, which have not been mentioned in any specific studies.

All the hydraulic works applying PKW method are entirely based on the research sample conducted before 2011. All the equations and graphs were applied in specific conditions. Until now, there is no publication comprehensively identifying the discharge capacity or the impacts of downstream water level on the standard-section PKW, revealing the economic optimum of discharge capacity, and basic design for different conditions. In this event, the "***Research on the discharge capacity through piano key weir considering impacts of downstream water level"*** is necessary.

2. Research objectives

- Identify the flow threshold affecting the discharge capacity based on the typical flow through the weir and connecting the PKW downstream;
- Develop the equations and graphs to determine the discharge capacity through PKW considering the free flow and under the impact of downstream conditions such as the weir bed elevation and downstream water level.

3. Research objects and scope

Object: Discharge capacity of standard PKW; rounded-wall crest

Scope: Flat problem, irregular stable flow; Ratio between water head and weir height: $H_0/P=0.17\div2.50$; Submergence ratio $h_n/H_n = -0.2\div0.98$; the PKW section with geometry ratio: $P/W_u=0.5\div1.3$; $W_i/W_o=1.2\div1.5$; $N=L/W=4\div6$.

4. Research methodology

The research methods include: Overview method; model experimentation: physical experimental model and 3D mathematical model; experimental data analysis; dimensional analysis: Buckingham method to determine experimental series and to establish experimental relationships.

5. Scientific and practical significance

Scientific significance: The thesis outcomes clarified and explained some typical features and hydraulic mode of the piano key weir; determined and quantified the flow state of the full outlet key, impact of downstream canal bed, overflow conditions; and develop the equations to identify the discharge capacity in different flow regime. All the outcomes has complemented the PKW studies and laid the foundation to further research on other aspects of this structure.

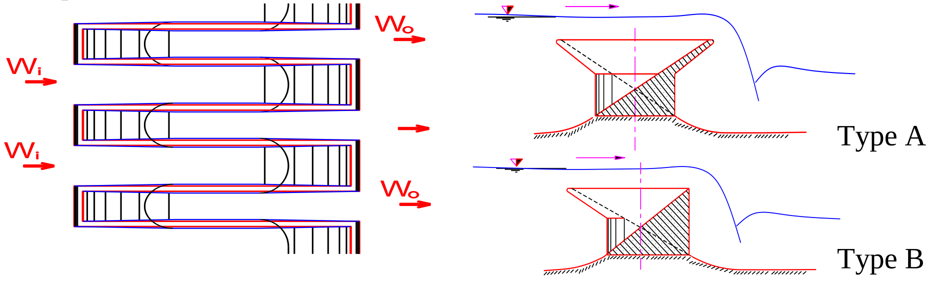
Practical significance: Thesis outcomes also identified the economic-technical effects of the piano section. The discharge capacity equations and charts are effective tools to reduce the design time and practically applied in reality. It also identified the hydraulic regions to select the active area, minimizing the risks in designing and operation of PKW.

Chapter 1 OVERVIEW OF PKW RESEARCH RESULTS

1.1 Introduction of Piano key weir

Piano key weir is a modified labyrinth weir that developed in 1930s with the zigzag weir line, the reduction of footprint and internal slopes in the alveoli, thus reducing the forces acting on the lateral walls and hence the structural cost.

The piano key weir consists of inlet water keys (W_i) and the outlet water keys (W_o). Depending on the inclined up- and downstream key floors, the PKW is divided into four main types: In type A, the up- and downstream overhangs are identical. Types B and C include only up- or downstream overhangs, respectively. Although type D has an inclined floor, it does not contain overhangs. Leading groups in this field are HydroCoop, French Electricity, Biskra University (Algeria), Roorkee University (India) that conducted studies in the period 1999 ÷ 2002.



Plan view Section

Figure 1.3 Scheme of PKW in channel

1.2 The features influence on discharge capacity of piano key weir

The discharge capacity of piano key weir is affected by geometry and flow features. The effects of weir geometry on the free flow weir including the weir shape, height P, width W (W), key length (B) or weir length (L) by dimensionless units: N = L/W; P/W; P/W_u and W_i/W_o. The geometry and flow features have great impact on discharge capacity through piano key weir.

1.2.1 Flow pressed close to the PKW

In case of a very small water head on the PKW ($H/P<0.15$), the flow follows the whole zigzag path, the water passes through the piano key weir walls that's similar to the sharp-crested weir. When H/P> (0.15 ÷ 0.2), flow through the spillway is a free flow. These shape and transformation bound have been researched in detail by authors as O. Machiels, Kabiri - Samani & Javaheri and A. Mehboudi. However, if the water head of the PKW continues to increase high, the shape, features and boundary changes of the flow are almost unpublished.

1.2.2 Free flow spillway – standard unit PKW

According to A. Noui and A. Ouamane (2003, 2011), the discharge capacity through the type B PKW is better than the type A with low water head $H/P<0.4$. When H increases, the discharge capacity is similar between Type A and B. The optimum ratio of the widths of inlet and outlet keys W_i/W_o varies from 1.2 to 1.5.

According to M. Leite Ribeiro et al. (2011), the discharge capacity of the PKW that width $N = L/W$ from 3 to 7, increase about 50% with $H/P=0.2$. When $H/P>1.2$, the discharge capacity of the PKW increase insignificantly. The ratio between inlet and outlet keys W_i/W_o should be in the range $1.0<W_i/W_o<1.6$.

According to O. Machiels, S. Erpicum et al. (2014), the factors such as weir height, width and keys length affected the discharge capacity in a descending order. + According to S. Erpicum et al. (2017) at the international workshop on PKW, the piano key weir with the ratio $P/W_u =0.5\div1.3$ will have optimal discharge capacity.

In short, the economic and optimal shape of PKW in terms of discharge capacity should contain the following geometry aspects: $P/W_u=0.5\div1.3$; $W_i/W_o=1.2\div1.5$; $N=L/W=4\div6$, which is called the standard piano key weir in this thesis.

1.2.3 Submerged-flow

Under the submergence condition, the discharge capacity will be impacted by flow parameters similarly to the traditional weir and with $h_n>0$. The researches on submerged flow are not as many as free flow. Few foreign researches is in this field, mainly conducted in Vietnam.

The research found out that discharge coefficient through the PKW under the submerged flow conditions is in the form of discrete curves $C_d\sim H_{n0}/H_0$ at each level q on the model; Some results could be applied in specific conditions for the PKW with a high submergence level $h_n/H_n>0.65$.

There is no publication mentioning about the transitional zone. When $h_n<0$, the piano key weir is in the submergence condition as stated in study of Rozanop on practical weir with vacuum. This is also confirmed the study findings in Ngan Truoi PKW conducted by the Ph.D. candidates and the research groups.

1.3 The equations determining PKW discharge capacity

The equations determining discharge capacity through the PKW included indirect calculation with increasing by ratio flow discharge increase according to the Ogee spillway $r=Q_P/Q_{TD}$; direct calculation determining the discharge coefficient C_{d1} according to the zigzag line of weir L and the recent studies focused on the equation of the traditional spillway, $Q=C_{d2}.W.\sqrt{2g}H^{3/2}$ (1.3)

The equations are the results of experimental studies on the influence of the quantity of dispersed and focus scope on the main geometrical quantities. So far, there is no specific publication on standard PKW. Some equations taken from Vietnamese studies such as (1.8) and from (1:12) to (1:15) were set up under the water head with boundary with dimension H = 2m, 3m.

However, the boudary determination is not based on the typical flow characteristics through the PKW. These equations were only applied for specific structure with high error. Equations determining the PKW discharge capacity for non-standard weir has high submergence level $h_n/H_n>0.65$ or $h_n/H_n>0.12\div0.33$; however, the σ_n is not relevant when h_n decreases. The transitional boundary state of flow through the PKW when downstream water level changing, hasn't not been taken into mentioned.

1.4 Conclusions of Chapter 1

After more than 20 years of studying, PKW is gradually completed in terms of geometry and discharge coefficiency. Accordingly, PKW optimum design will contain the following geometry parameters $P/W_u=0.5\div1.3$; $W_i/W_o=1.2\div1.5$; $N=L/W=4\div6$; is also known as standard PKW in this thesis.

With the standard PKW, different type of PKW types showed different discharge capacity if the water head is $H/P<0.3$ equivalent to $H/W_o<0.5$. When $H/P>0.3$, the shape and type of PKW has insignificant impacts on the disharge cpacity. This feature made PKW typical compared to traditional spillway. It reflected the interact boudary characteristic between the inlet and outlet key as well as the impacts of downstream flow on the PKW discharge but they haven't been mentioned in any publication on the flow regime boundary when Q through the weir is affected by both H and downstream water level.

In most of studies, the publiced equations were the experimental data results applied in specific conditions, narrow scope, dimensional structure or high error. Therefore, this thesis will focus on determining the PKW discharge capacity for standard section by identifying the hydrodymanic characteristics, states, and flow regimes through the PKW.

Chapter 2 SCIENTIFIC BASIC FOR DETERMINING PKW DISCHARGE CAPACITY

2.1 Methods determine PKW discharge capacity

With low water head, the flow follows the zigzag line and fall down outlet keys to downstream channel as thin wall spillway. With high water head, water covers the whole keys, PKW works as Ogee spillway. At this point, PKW will not be able to work as a broad-crested spillway, because it cannot meet the requirement of ratio between spillway crest length and total upstream water head B/H =3÷8.

In thesis, the PKW discharge coefficient is determined based on the experimental method. The physical model measures, determines the value of flow hydrodynamic features such as discharge capacity Q, upstream water head H, downstream flow depth h_h, water level, flow velocity, etc. Mathematical model (3D model) simulates velocity distribution, flow direction of inlet and outlet keys and downstream transitional.

2.2 The theory of experimental model

2.2.1 Similitude theory for the establishment of research model

Use the similitude theory also known as mathematical analysis or dimensional analysis of parameters that influences to research phenomena. The results obtained from the models will be used in reality based on similitude laws or similitude criteria.

2.2.2 Similitude criteria

The flow through the headwork is free flow, of which gravity force is the main force. The model was designed based on similitude criteria of Froude (Fr). Reynol Number (Re) on $R_{em} > R_{egh} = 5000 \div 10000$ to satisfy condition flow working in squared resistance (auto zone model). When the water head is small, the flow through the weir is affected by the external tension, the model needs to content with the Weber criteria (W_e), the minimum value W_e is greater than 54, or the small water depth H should ensure greater 0.03m.

2.2.3 The dimension theory, Pi theorem function

The Buckingham equation represents variable quantities and describes hydrodynamic phenomena that need to be researched in a function. From the parameters, select three basic dimensions namely time [T], length [L], and mass [M]. The independent variable parameters are (n-3) then becomes into a non-dimensional relation, a Pi function. Have function f $(\pi_1, \pi_2, \pi_3 \ldots.)$ = 0 (2.13).

2.2.4 Experimental zoning

Experimental data are synthesized and correlated closely between quantities: **Input → Dependence (experimental regression equation) → Output**. Thesis is based on the active method of experimental layout based on analysing, surveying, inheriting the existing research. Evaluate the compatibility of regression equation with experimental data by Fisher distribution (Sig.F) with a significance level of 5%. The experimental equations were verified by the Hold-out method, dividing the experimental dataset into two independent sets, is an equation preparation set and a test data set.

2.3 Equations for experimental study

General equation:

$$f\left[\frac{W_u}{H}, \frac{W_i}{H}, \frac{W_o}{H}, \frac{B}{H}, \frac{B_i}{H}, \frac{B_o}{H}, \frac{P}{H}, \frac{P_T}{H}, \frac{P_H}{H}, \frac{L_u}{H}, S_i, \frac{\mu H}{Q_u \rho}, \frac{H^5 g}{Q_u^2}, \frac{h_n}{H}, \frac{h_h}{H}, \frac{z}{H}\right] = 0 \quad (2.23)$$

Considering closed velocity, use short equation:

$$f\left[\frac{Q_u}{W_u\sqrt{2g}H^{3/2}},\frac{H_0}{P},\frac{H_0}{P_H},\frac{H_0}{W_u},\frac{H_0}{L_u},\frac{h_n}{H_0},\frac{z}{P}\right]=0 \qquad (2.24)$$

Or $$\frac{Q_u}{W_u\sqrt{2g}{H_0}^{3/2}}=f\left[\frac{H_0}{P},\frac{H_0}{P_H},\frac{H_0}{W_u},\frac{H_0}{L_u},\frac{h_n}{H_0},\frac{Z}{P}\right] \qquad (2.25)$$

Flow discharge through the weir was determined by this equation:

$$Q=m.L.\sqrt{2g}.{H_0}^{3/2}= m.N.W.\sqrt{2g}.{H_0}^{3/2} \qquad (2.26)$$

Set C_d=m.N, (2.26) to: $Q=C_d.W.\sqrt{2g}.{H_0}^{3/2}$

or $$Q_u=C_d.W_u.\sqrt{2g}.{H_0}^{3/2} \qquad (2.27)$$

thus $$C_d=\frac{Q_u}{W_u\sqrt{2g}{H_0}^{3/2}} \qquad (2.28)$$

Therfore, when using C_d = N.m, the equationapplied for PKW is similar to traditional spillway; C_d might be greater than 1.0 and Ogee spillway has m coefficient is smaller than 1.0.

Combine (2.25) and (2.28), we have:

$$C_d=f\left[\frac{H_0}{P},\frac{H_0}{P_H},\frac{H_0}{W_u},\frac{H_0}{L_u},\frac{h_n}{H_0},\frac{z}{P}\right] \qquad (2.29)$$

When the flow through PKW is free flow, the discharge capacity does not affected by the downstream water level, the equation (2.29) becomes:

$$C_d=f\left[\frac{H_0}{P},\frac{H_0}{P_H},\frac{H_0}{W_u},\frac{H_0}{L_u}\right] \qquad (2.30)$$

When discharge capacity through the weir does not affected by downstream channel bed, the equation (2.30) becomes:

$$C_d=f\left[\frac{H_0}{P},\frac{H_0}{W_u},\frac{H_0}{L_u}\right] \qquad (2.31)$$

When flow through PKW with small water head, the flow follow zigzag line same as through the sharp-crested weir, discharge capacity does not depend on key width, the equation (2.31) becomes:

$$C_d=f\left[\frac{H_0}{P},\frac{H_0}{L_u}\right] \qquad (2.32)$$

When the flow through the PKW is the submerged flow:

$$C_d=f\left[\frac{H_0}{P},\frac{H_0}{P_H},\frac{H_0}{W_u},\frac{H_0}{L_u},\frac{h_n}{H_0},\frac{z}{P}\right] \qquad (2.33)$$

2.4 Experimental model

2.4.1 Physical experimental model

Model was designed, conducted in a 0.5m wide, 22m long, and 1.0m deep rectangular tempered glass-walled flume. PKW headwork model was made with organic glass; Upstream, downstream channel with polished cementations plaster. Design, model building; arrangement of tools; evaluation model error; condition applicable in practice; test data and conformity assessment of experimental data. The experimental data includes nearly 150 data of thesis and more than 450 data from other researches as Figure 2.7.

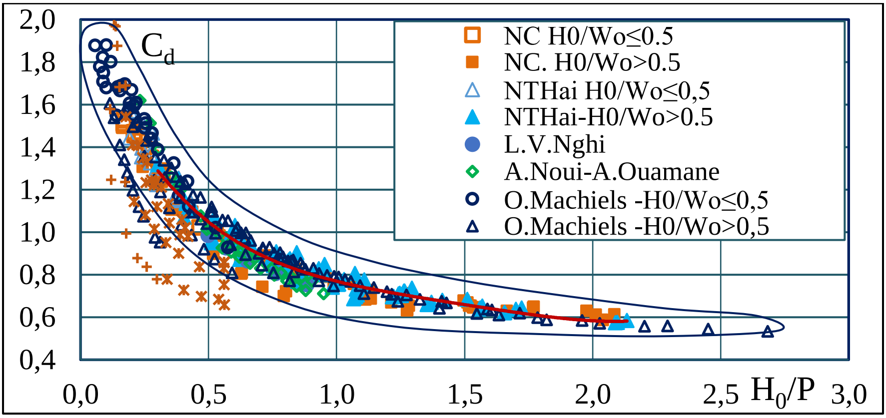


Figure 2.7 The suitability of the experimental data

2.4.2 Mathematical model

Thesis uses Flow 3D software to build a 3-D mathematical simulation of flow through the piano key weir. The PKW unit shape is similar to experimental model with ratio λ_l=20, P=3.6m; W=10m, W_u=4,7m; T_s= 0.3m; B=10m; The whole region is divided into five different grid sizes.

Mesh step: is the divisor of the geometry dimensions, symbolized in three dimensions, respectively Δx, Δy, Δz, is 0.05÷2.0m, rough in the canal area, smooth in the terminal area.

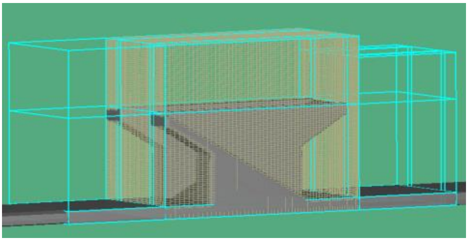


Figure 2.10 Simulated grid computing

2.5 Conclusions of Chapter 2

Base on the discharge capacity of the traditional spillway, the thesis explained and pointed out that the main parameters affecting the discharge capacity through PKW were P, P_H, W, W_o, L, H, h_n, h_h and z, according to the similar theory, the theory of dimensions and experimental model, the thesis established an experimental regression showing the correlation between discharge capacity and effect factors.

The thesis synthesized and analysed more than 450 key data on PKW published in recent years by local and foreign authors, since addition the experimented with nearly 150 experiments to determine discharge capacity, velocity distribution, water level line flow, flow direction. Research by dimensionless dimension, range $H_0/P=0.17÷2.09$; $H_0/W_o=0.31÷2.08$; $H_0/W_u=0.14÷0.92$; $P/W_u=0.44÷1.07$; $h_n/H_n=-0.2 ÷ 0.98$; $q=0.03÷0.32\ m^2/s$; is a combination of three cases of height of the PKW; two cases of downstream channel bed were equal/lower than the outlet key foot; Two flow modes were non- submerged and the submerged flow.

The experimental data was subject to objective evaluation and other research, providing the appropriate data sets, ensuring reliability.

Chapter 3 PKW DISCHARGE CAPACITY FEATURES

3.1 Hydrodynamic features, transition states and serial flow through piano key weir

The flow through PKW is divided into three parts corresponding to the zigzag surrounding the keys as shown in Figure 3.1, namely Part 1 - flow through the upstream wall of outlet key, Part 2 - flow through the side wall and Part 3 - flow through the downstream wall of inlet water key.

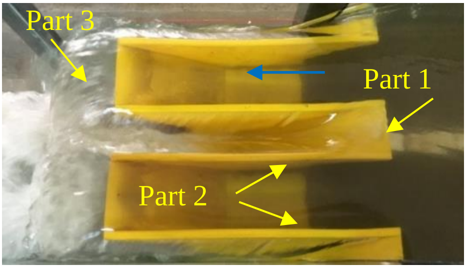


Figure 3.1 The parts of the flow through PKW

3.1.1 Flow on inlet key

When the water head increase, the water level line changes from horizontal ($H_0/W_o \leq 0.5$) to wavy ($0.5 < H_0/W_o \leq 1.7$) and is lowered from upstream to downstream ($H_0/W_o > 1.7$)

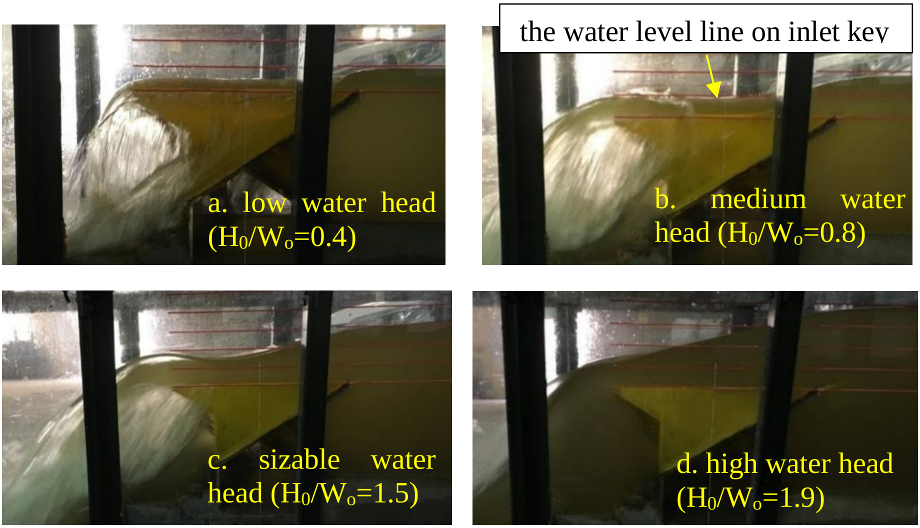


Figure 3.2 The process of changing the water level line shape on the spillway

* *Flow direction and velocity distribution:* When increasing H, the direction of flow on the inlet key is less change. Direction of the bottom flow parallel to the bottom of the key, the slope of the direction decreases when the line up to the surface, the direction of the surface flow similar to the water level line

3.1.2 Flow on outlet key

The outlet key consists flow through upstream wall and flow through side wall, which account for the bulk of flow total through the piano key weir.

The water shape through the upstream wall was less change, similar to the flow on the slope. Flow through the side wall down the outlet key contains two symmetrical lines. The water line shape is limited by the water head and width of outlet key that switch through the various states.

The flow is perpendicular to the side wall ($H_0/W_o \leq 0.5$) and the oblique angle. Shape of the water level line along outlet key that has wavy shape

(0.5<H_0/W_o≤1.7) switch to the lower shape and evenly distributed on horizontal sections of the keys, similar to the flow on the inlet water key (H_0/W_o>1.7).

H/W_o=0.34	H/W_o=1.0	H/W_o=1.6	H/W_o=2.1

Figure 3.6 The flow character on outlet keys when water head increase

* *Flow direction and velocity distribution:* When water head H increases, the flow through the side wall changes significantly, the area has a large velocity travels from the upper third to the end of the key, the flow direction of gradually transition from perpendicular to oblique. Direction of the bottom flow parallel to the bottom of the key

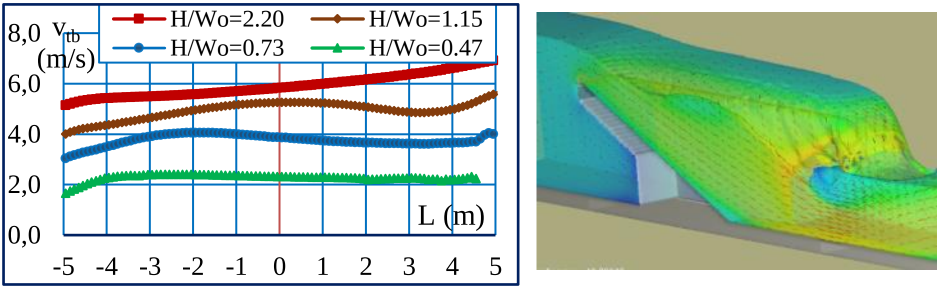


Figure 3.8 The flow direction and velocity distribution on outlet key when H increase

3.1.3 The downstream transitional flow

Along inlet and outlet keys, the downstream sequence is different, distributed unevenly on the horizontal section. When transitional flow is swift flowing, unit discharge, the depth of the water layer, the velocity of the flow that along the inlet key is bigger than ones on the outlet key. When downstream is submerged, downstream of the weir that has two whirlpools areas clearly, including the whirlpools at the foot of the structure and the jumping water behind narrow position that is same as the traditional weir.

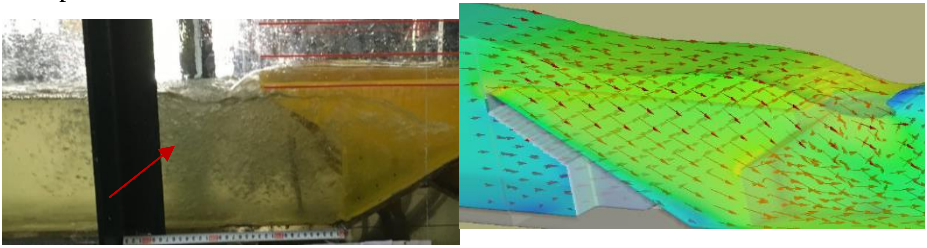


Figure 3.11 Transition and distribution of the flow in the weir downstream when H, h_h changes

3.1.4 Influence of downstream whirlpools to discharge capacity of piano key weir

The whirlpools is under piano key rolls reduce the flow area at the PKW foot. When the water head is large or downstream channel bed upraises, the whirlpools intensifies, increasing of the influence decreases to discharge capacity.

3.2 Boundary of the flowing states through piano key weir

3.2.1 Boundary of "the full flow regime of outlet key"

When the interferometry position of the two lane that drops from side wall is lower crest of the PKW, the flow shape through the side wall is unchanged, called the "*not full flow regime of outlet key*" When H increases, this interferometry position upraises, which is higher crest of the PKW, the flow shape through the side wall is changing, raises up that makes to decrease discharge capacity through the PKW, is called the "*full flow regime of outlet key*". The boundary value of these states is H_0/W_o=0.5.

3.2.2 Boundary of "the submerged flow regime"

PKW is submerged flow when it satisfies two conditions:

(1). Downstream water level influence on discharge capacity. Thus, the regimes are determined: + the complete free flow regime when $h_n/H_n<-0.2$. + The complete submerged flow regime when $h_n/H_n>0$; Boundary of the submerged flow or transition area from the free flow to the submerged flow is $-0.2<h_n/H_n\leq0$.

(2). Downstream transition flow of the PKW is submerged. The thesis determine the condition $(z/P_H)<(z/P_H)_{pg}$; Z_{pg} is determined by experimental result:

$$z_{pg} = 0.974.\left(\frac{H}{P}\right)^{0.977}.P_H \tag{3.2}$$

3.2.3 Boundary of the influence by downstream channel bed

Researching, determining of the influence of downstream channel bed (P_H) with two limit cases of P_H: that does not influence to discharge capacity and has influence with channel bed level highest that on the elevation with outlet key foot; and each case there are 3 cases of the PKW height P, respectively. The total of research cases is 06.

The experimental results show that: + When $H_0/P_H<0.7$, flow discharge through PKW was not influenced by downstream channel bed. + When $H_0/P_H\geq0.7$, discharge capacity of PKW was influenced to reduce. The influence is significant when water head of PKW increases, within the research scope the maximum decreasing discharge capacity is 4%.

3.2.4 Analysis of influence of flowing state to discharge capacity through the piano key weir

+ When the flow on PKW is incomplete flow regime of outlet key, $H/W_o\leq0.5$, all flow parts of PKW work as the sharp-crested weir, the discharge length is the zigzag line L, which $L=(4\div6)W=(8\div15)\sum W_o$. Thus influence on the flow that through PKW by L parameter is much higher than H_0, so the piano key weir has different form and structure then the discharge capacity through PKW is significantly different.

+ With the full flow regime of outlet key, $H_0/W_o>0.5$, the width of the flow of PKW is W, which $W=\sum(W_i+W_o)= (2.2\div2.5)\sum W_o$. So, the influence on Q by W compare to H is negligible, or the discharge capacity of the PKW that has different structure then not significant difference. When the PKW has a water head $H/W_o>2.0$, the geometry of the piano key weir almost does not influence to discharge capacity

3.3 Establishing experimental equations determine discharge capacity through piano key weir

The experimental data were evaluated with two sets: (1) Independent sets of thesis; (2) Combined dataset includes data from thesis and other authors. Each set of data is divided into two arrays: the establishing array the test array. The establishing array includes the data of the standard unit PKW. The test array includes the data of the standard unit PKW and non-standard.

Establishing the equations determines Q through PKW, in the form of the traditional spillway. When there is the influence of the downstream water level and downstream channel bed:

$$Q = m.k_H.\sigma_n.L\sqrt{2g}H_0^{\frac{3}{2}} = k_H.\sigma_n.m.N.W.\sqrt{2g}H_0^{3/2} = k_H.\sigma_n.C_{d0}.W.\sqrt{2g}H_0^{3/2} \quad (3.4)$$

Set up C_{d0}=m*N that is discharge coefficient of piano key weir when there is not influence by downstream water level and downstream condition.

To determine C_{d0}, use equation (2.31), the features, flow states showed in part 3.1, part 3.2, establishing the experimental equation of C_{d0} follow two states that are the full and incomplete flow state of outlet key.

1. When $H_0/W_o \le 0.5$, determining C_{d0} is the same as for the sharp-crested weir, free flow, the multinomial linear function of the quantities H_0, weir height P. For PKW there is also the influence of the weir length L_u, so (2.31) is written:

$$C_{d0} = a + b.\frac{H_0}{P} + c.\frac{H_0}{L_u} \quad (3.7)$$

2. When $H_0/W_o > 0.5$, $C_{d0,}$ the function follows the variables H_0/P, $H_0/W_{u,}$ H_0/L_u. However, the quantity L_u does not significant influence to discharge through PKW. Thus, determining the function type C_{d0} follow the main variables H_0/P, $H_0/W_{u.}$

To select the appropriate equation, the type of linear, nonlinear or exponential linear forms are used and linearized by analytic mathematics. The coefficients of the experimental equation are determined by the linear regression method, the least squares error.

Correlation analysis between C_{d0} and water head ratio H_0/P, the survey and experiment showed the exponential form for best result. Accordingly, the discharge coefficient C_{d0} is the correlation function indicates in (3.8):

$$C_{d0}=a_0\left(\frac{H_0}{P}\right)^{a_1}\left(\frac{H_0}{W_u}\right)^{a_2} \quad (3.8)$$

The coefficients of experimental equation (3.7), (3.8) were determined by 02 data sets: independent dataset of thesis and combined dataset. The experimental equations have a good relationship. Coefficient of correlation is R = 0.952 ÷ 0.988. The standard error is S = 0.023 ÷ 0.080.

The difference between the calculated result and the experimental results is in the independent dataset and the combined data are similar. The average absolute error of the constructional set is small, under 5%, the maximum absolute error of 7 ÷ 8%. The average absolute error of the test set is 6 ÷ 7% and the maximum absolute error is 12.6%.

The thesis equations were developed based on the data set of N=5. However, the calculation results of these equations showed smaller error than the results of experimental data. It is because of the author select the typical flow state of PKW. In this case, the equation scope can be extended to PKW with N=4÷6. The thesis used the equations developed from the independent data set to continue the calculation in the coming steps.

+ Under free flow conditions that not affected by downstream channel bed, $C_d=C_{d0}$, discharge capacity Q_{TD} is calculated according to equation (3.9).

$$Q = C_{d0}.W.\sqrt{2g}H_0^{3/2} \text{ hay } q = C_{d0}.\sqrt{2g}H_0^{3/2} \quad (3.9)$$

Of which:

- When $H_0/W_o \le 0.5$, $C_{d0} = 1.885\text{-}1.768\frac{H_0}{P}\text{-}1.215\frac{H_0}{L_u}$ (3.10)

- When $H_0/W_o > 0.5$, $C_{d0}=0.705\left(\frac{H_0}{P}\right)^{-0.306}\left(\frac{H_0}{W_u}\right)^{-0.150}$ (3.11)

+ When discharge of PKW was influenced by downstream channel bed, discharge coefficient through the weir adjusted by the topographic characteristic coefficient k_H. To determine k_H, according to equations (2.30) and (3.4):

$$C_d = f\left[\frac{H_0}{P}, \frac{H_0}{P_H}, \frac{H_0}{W_u}, \frac{H_0}{L_u}\right] = f\left[\frac{H_0}{P_H}, C_{d0}\right] = k_H.C_{d0} \text{ hay } k_H = f\left[\frac{H_0}{P_H}\right]. \quad (3.12)$$

From the experimental result of the thesis, it was determined:

- When $H_0/P_H<0.7$: $k_H=1.0$;
- When $H_0/P_H\geq0.7$: $k_H=1.051-0.086\frac{H_0}{P_H}$ (3.13)

+ When the flow of PKW is submerged flow: $Q_n=\sigma_n.Q_{TD}$ (3.14)

Equations determine σ_n that was built from the data of thesis.

$$\sigma_n=0.974\left(\frac{Z}{P}\right)^{0.052}\left(1-\frac{h_n}{H_{n0}}\right)^{0.045}\left(\frac{H_{n0}}{W_u}\right)^{-0.043} \quad (3.15)$$

The experimental equation (3.15) has a good relationship. Coefficient of correlation was R = 0.883. The standard error is S = 0.034. The difference between the equation and experimental result is small, the average error of 3% and the absolute error of 7%. The range of formula is $-0.2<h_n/H_{n0}\leq0.9$.

3.4 Suitability of experimental equation

Equations were tested with over 450 experimental data of 4 different studies for PKW that has standard section and compared with PKW that has non-standard sections show that:

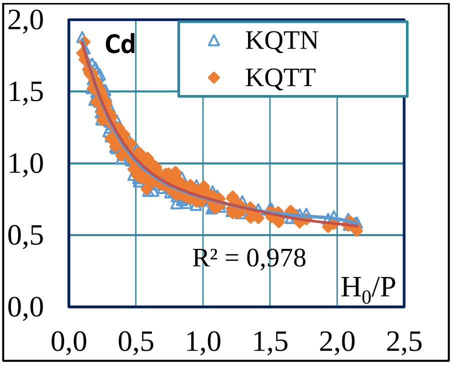


Figure 3.30 Compared between the equations (3.10, 3.11) results and experimental data

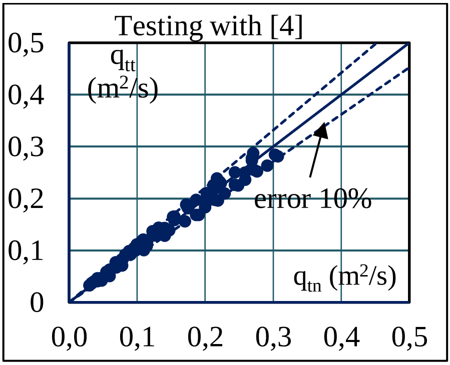


Figure 3.31 Compared between the equation q_{tt} (3.9) and the experimental data of thesis, q_{tn}

Results from the equations (from 3.9 to 3.15) are consistent in terms of distribution, and with small error when compared to experimental data. The average error of about 5% is small compared to the error of published equations, ranging from 10% to 27%.

The thesis equations are also suitable for PKW type B with the average error of 7.2%, the maximum absolute error of 13.5%.

Considering Q of the traditional spillway with W length or $m_p=C_d/N$, the result shows that: When the PKW works with low H, the maximum coefficient m_p is about $m_p=0.25\div0.36$. When H increases, m_p decreases rapidly, Q decreases rapidly. If calculate the unit flow on the zigzag line is equal, with H/P=1.0, the discharge coefficient per length unit is $m_p=C_d/N\approx0.12\div0.18$, (Figure 3.37).

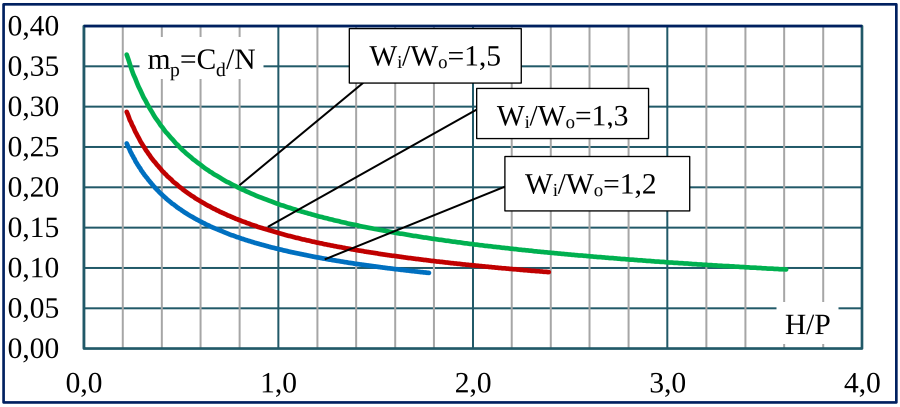


Figure 3.37 The graph m_p ~H/P of the piano key weir

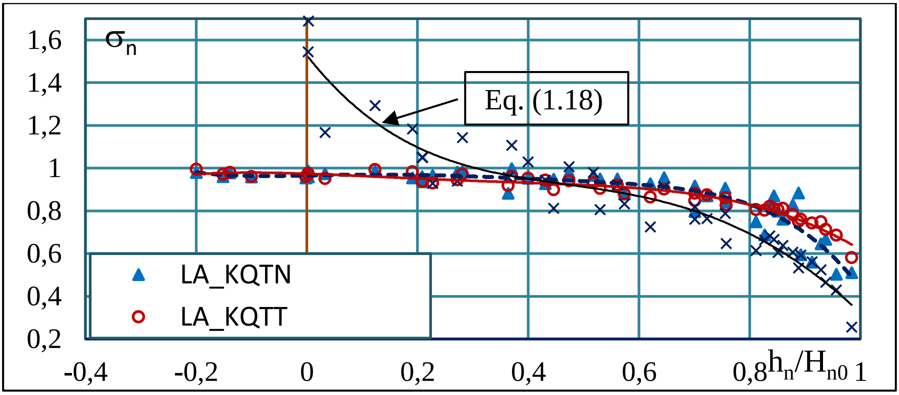


Figure 3.38 Compare the relationship between σ_n ~ h_n/H_{n0} according to equations (3.15) and (1.18)

3.5 Conclusions of Chapter 3

+ The thesis determined the hydrodynamic features of flow on the PKW and downstream transition flow of the keys, creating the specific flow states that are significant difference compared to the traditional weir. + It is determined the two states “non-full flow of outlet key” and “full flow of outlet key” with boundary value H_0/W_o=0.5; the boundary of the influence by downstream channel bed is H_0/P_H=0.7; determine to the boundary of the complete free flow regime, the complete submerged flow regime and the transition regime area from the free flow to the submerged flow is $h_n/H_{n=}$-0.2÷0, as well as analysis of the influence of these flow states to discharge capacity of PKW.

+ From the experimental data, the thesis established equations determining PKW discharge capacity in free and submerged flow conditions. The flow through PKW is based on the equations of the Ogee spillway, simple, easy to use by establishing data set and test set of the PKW has standard weir unit, for small error when compared to abundant experimental data, for appropriate correlation tendencies and wider application range than existing equations.

Chapter 4 SELECTION OF THE RIGHT SIZE AND CALCULATION OF DISCHARGE CAPACITY FOR THE ACTUAL PIANO STRUCTURE

The order of determining, arranging geometry elements with decreasing influence to discharge capacity in design, calculation the piano key weir: (1): Selection of the weir type; (2): Selection of the weir height and key width with the ratio P/W_u; (3): When there is W_u, select the ratio of W_i/W_o and lateral wall thickness, T_s; (4): When there is P, select the length L by coefficient N, as same as the slope of the key bottom S_i, S_o; (5): Preliminary draw of the PKW section.

4.1 Selection of the low water head structure, the low downstream channel bed – the Xuan Minh spillway

Xuan Minh spillway was designed and operated by Power Engineering Consulting Joint Stock Company 1 (PECC1) using the design sample of Van Phong PKW and was experienced on section model (known as structural experimental results). The discharge capacity for Xuan Minh PKW under free and submerged flow conditions was determined by using the thesis equations and findings of other authors (1.14, 1.15), compare to the structural experimental data and regulating results of the design consultants as described in Figure 4.5

The outcomes show that the thesis equations are consistent with the experimental results and more appropriate than the results calculated in other equations. Compared to the experimental results, the thesis equation's maximum error is 10%. When applying the ministerial project equations and the consultant design, the error is 20% and 15.4% respectively. With submerged flow, the error of the experimental result is 7% and the equations of other author is 13%.

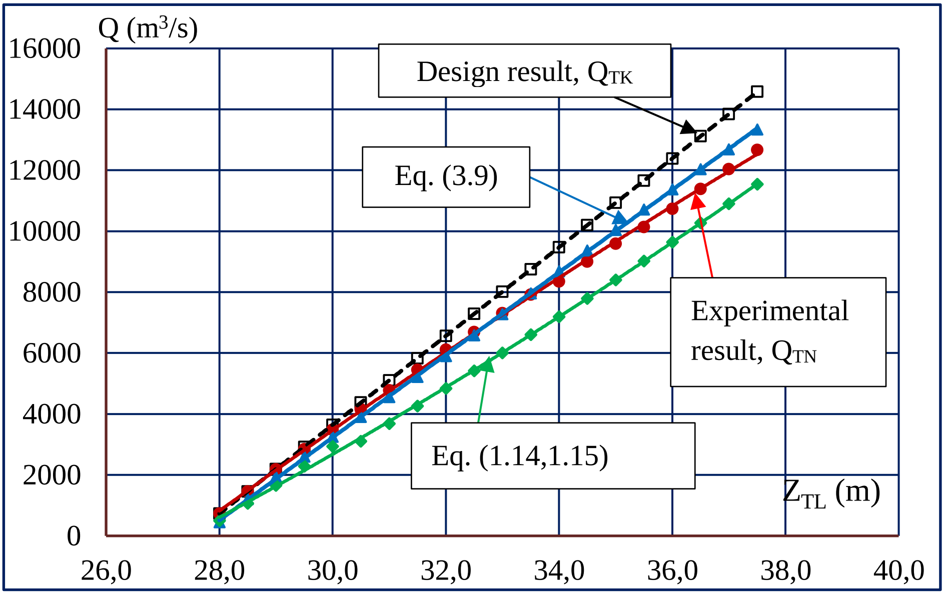


Figure 4.5 Compare results among Eq. (3.9), design, experimental investigation and equations (1.14), (1.15) under free flow conditions

4.2 Apply for the structure that has same elevation for downstream channel bed and outlet key– the Ngan Truoi PKW

The calculation error of Ngan Truoi PKW discharge capacity is smaller than the experimental result. The maximum absolute error was 3.8% for the free flow and 5.2% for the submerged flow. According to the Eq. (3.13), the discharge capacity was affected by the downstream channel bed when the water level is higher than the design water level (H_{TK}). With H_{TK} = 3.5m, the discharge efficiency decreased by 1.5%. The submerged coefficient reached σ_n= 0.94, when submerged water head is the largest h_n/H_{n0}=0.38.

4.3 Conclusions of chapter 4

1. The thesis introduced diagrams, equations, the application of the geometric parameters selection of piano key weir, that provide the designers general and specific views, select standard sections for the PKW that has economic optimum for discharge capacity

2. The thesis calculated and applied for actual structures, not only Type A, N=5 but also Type B, N = 6. The results of the thesis equations are consistent with the results of the experiment and more appropriate than the existing equations. The maximum error for the Ngan Truoi weir is 3.6% under the free flow condition and 5.2% for submerged flow and the Hoi Xuan weir is 7%. When calculated according to the equations of other authors, the error is 19% and 25%.

CONCLUSIONS AND RECOMMENDATIONS

I. CONCLUSIONS

1. General conclusions of the thesis

Piano key weir is an innovative spillway type, being researched and applied widely in hydraulic engineering. PKW increases the total effective crest length, thereby increasing the discharge capacity. PKW also has many different hydraulic modes and downstream transition compared to traditional weir. Thesis has helped to clarify and enrich the understanding of PKW shapes, hydraulics, flow modes, creating favourable conditions for engineering design and operation. The thesis completed its objectives and achieved the expected outcomes.

1. Summarize the publicized findings on PKW. All the studies are successful in determining the geometry effects on discharge capacity:

+ PKW included 20 geometry parameters with only 09 main parameters and 03 specific parameters that have the largest influence to discharge capacity such as the weir height, key width and key length. The PKW shape and the geometric dimension ratios only have a significant influence with the water head H/P = 0.2÷0.4.

+ Shortcomings of the studies: No specific analysis or determination of the typical flow state and regime through PKW when
H/P > 0.2. They didn't consider the impacts of downstream conditions when the canal bed has same elevation with PKW outlet key; Not identifying the impacts of downstream water level and h_n<0 on the discharge capacity; No standards or fomulars applied for PKW design; Narrow scope, only applied for small water head, specific structure, high error.

2. The thesis adopted similitude theory, dimensional theory and model, physical experimental model, 3D mathematical model to establish experimental regression equation. The experiments were arranged logically. The data experimental analysis was conducted using available commercial software and experimental regression tools.

3. The science results

+ Thesis determined the PKW standard section by analysing existing studies. The optimal and economic discharge capacity has the following geometric parameters: P/W_u=0.5÷1.3; W_i/W_o=1.2÷1.5; N=L/W=4÷6.

+ The PKW discharge depends on the followings parameters: weir height P, channel width W, widths of upstream apex Wo, total weir crest length; Under the submergence condition, the discharge also depends on the flow parameters H_0, h_h, h_n and z.

+ Provide findings and detailed description of the weir flow and downstream flow. The features of inlet and outlet keys are different, making the typical state compared to traditional weir.

+ Establish equations determining discharge capacity according to the flow states of "not full flow of outlet key" and "full flow of outlet key" with the boundary of H_0/W_o=0.5; flow under the impact and not under the impact of downstream canal bed with the boundary of H_0/P_H=0.7; free and submerged flow with the transitional boundary of $h_n/H_{n=}$-0.2÷0.

+ Discharge capacity of the standard PKW was determined by the equations of Ogee-shaped weir. The free flow discharge was determined by the equations (3.5), the coefficient discharge C_{d0} is determined by the equations (3.10), (3.11), and k_H was determined by the equation (3.13). The maximum average error is of equation with the build set is 2.9%, with the test set of 6.9%. The surface tension σ_n was determined by the equation (3.15). The maximum average error is 3%, the maximum absolute error is 7%. The boundary water head z_{pg} was determined by the equation (3.2). These equations were used for PKW type A, N = 5 but the application scope are expanded and can be applied to standard weir; The range of water head of the PKW is $H_0/P=0.17 \div 2.5$; submergence level is $-0.2<h_n/H_{n0}\leq 0.9$. The wall crest is rounded; the equations is also suitable for the PKW type B, with the maximum error of 7.2%.

The equations determining the flow through PKW in free and submerged flow conditions are simpler, more general with low error than the published equations. They are more suitable and convenient when applying for computation and PKW design in different conditions.

2. New contributions of the thesis

(1). The thesis determined the boundary states to delimit the flow regimes through piano key weir, include: + Boundary of the two states “not-full flow of outlet key” and “full flow of outlet key” with boundary value $H_0/W_o=0.5$; + Boundary of the influence by downstream channel bed is $H_0/P_H=0.7$; + Boundary of the complete free flow regime, the complete submerged flow regime and the transition regime area from the free flow to the submerged flow is $h_n/H_{n=}-0.2\div 0$.

(2). The thesis developed equations determining discharge coefficient of the PKW under free flow conditions (3.4) using the equations ((3.10), and (3.11); the coefficient affected by downstream channel bed can be determined by the equation (3.13); submerged coefficient can be obtained through the equation (3.15); the value of boundary water head that determine submerged transition in the PKW downstream can be determined by the equation (3.2).

II. SHORTCOMINGS AND LIMITATIONS

+ The thesis results only conducted for flat problem. In reality, the transition upstream and downstream flow is affected by both vertical and horizontal factors. In this case, the author will consider to calculate or conduct the experiment in the total model if necessary, to ensure discharge capacity of the structure.

+ Equations from (3.9) to (3.15) were established for the standard weir, type A PKW; Verified according to the type A and type B data, the maximum absolute error for the Type B PKW was 16%, higher than the Type A PKW(only 8%). Not calculated and tested for the type C and D PKW.

+ The appropriate range of equation is: H_0/P =0.2÷2.5; P/W_u=0.5÷1.3; W_i/W_o=1.2÷1.5; N=4÷6; The weir crest is round.

III. RECOMMENDATIONS

+ Use the standard PKW unit for future study and apply for PKW design.

+ Using the experimental data, the relationship curve, the thesis equations determining the discharge capacity, the hydrodynamic feature through the piano key weir in free and submerged flow conditions and with the impact of downstream channel bed.

IV. FURTHER RESEARCHES

+ Continue studying and conduct a test for piano key weir type C and type D.

+ Change the key shape to increase the not-full flow key area (expanding to the downstream) in order to increase water head area with larger discharge capacity.

+ Expand the research scope to the transitional upstream and downstream of the weir; conduct research determining the sedimentation range, discharge drift, floating object in order to identify discharge capacity through piano key weir under the contraction impact, for better results when applied in the design area;

+ Conduct more detailed studies for flow velocity distribution, dynamic pressure, energy dissipation possibility of the PKW downstream flow.

+ Conduct more detailed studies to explain the formation of the water line level, the flow transition in the outlet key.

PUBLICATIONS

1. Le Van Nghi**,** Doan Thi Minh Yen, Determine the influence of the submerged level, narrow side to discharge capacity of the piano key weir by research experimental, *Journal of Water Resources Science and Technology*, No. 23, pp. 09÷16, October 2014;
2. Doan Thi Minh Yen**,** Le Van Nghi**,** Discharge capacity through the piano key weir type A - the free flow, *Collection of Water Resources Science and Technology Vietnam, 2016*, pp. 74-85, Hanoi 2016;
3. Doan Thi Minh Yen, Analysis the influence of the geometry features to discharge capacity and choose the standard section for piano key weir, *Journal of Water Resources Science and Technology*, No. 41, pp.62-70, November 2017;
4. Doan Thi Minh Yen**,** The shape feature and transition of the flow through piano key weir, *Collection of reports of research results of young scientists at KLORCE*, Hanoi, November 2017;
5. LE VAN NGHI, DOAN THI MINH YEN**,** Discharge capacity on piano key weirs, Journal of Applied Water Engineering and Research (JAWER), February 2017 (submitted, waiting review).
6. Doan Thi Minh Yen**,** Research determine the boundary and submerged coefficient of the piano key weir, *Journal of Water Resources Science and Technology*, May 2018 (submitted, waiting review);