Hydraulic Performance of Combined Flow Labyrinth Weir-Gate

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Abstract

Weirs are common structure to regulate water surface and flow control in water conveyance channel and hydraulic structure. One of effective and economical method to increase the efficiency of weirs is utilization of labyrinth weirs which length of weirs increase with modification of plan form and therefore flow discharge will be increase. Compared to the separate using of weir and gate structures, there are some advantages including the Simultaneous passage of floating substances (wood, ice, etc.) and sedimentation in using combined weir-gate structure. The Rectangular Labyrinth weir-gate is one of the combined models. In this research five physical models that discussion weirs height and effective length changes on discharge coefficient of flow over and under the combined Rectangular Labyrinth weir-gate. Tests were performed on Sari Agriculture Science and Natural Resources University's research flume with width of 0.50 (m) and length of 12 (m) and discharge in range of 10-90 (Lit/s). Comparisons have shown that upstream head water increasing the discharge coefficient reduced. Also discharge coefficient and passed discharge of Rectangular Labyrinth weir-gate are increasing with increase of weir’s height (P). Data analysis shows that increase of weir’s effective length till H/L (H; Total upstream head, L: Effective length) less than 0.03 lead to increasing in discharge coefficient of Rectangular Labyrinth weir-gate. we compared of Rectangular Labyrinth weir-gate with sharp crested weir-gate. The results have shown that till a boundary of current (H/L>0.4) amount of discharge coefficient of Rectangular Labyrinth weir-gate is almost equal to or more of discharge coefficient of sharp crested weir-gate.

Key words: Sharp crested weir, Discharge coefficient, Dimensional analysis, Flume

Introduction

In the last few decades, the presence of water in nature has been changed. This change is suspected due to the impact of climate change (Sulistiyowati, 2006; Dunne et al., 2008). Climate change is influenced by human activity. These changes increase the variability of climate on long period (Trenberth et al., 1995). Implications of climate change have resulted in instability of the atmosphere in the lower layers, especially near the surface of the earth (UNDP-Indonesia, 2007). Global warming causes climate change, which in turn, increases the frequency and intensity of extreme weather events. This condition triggers significant changes in physical systems and biologics such as, changes in rainfall patterns. Several observations and studies conducted in Australia showed that climate change has changed the pattern of rainfall and resulting in flooding (Deborah Abbs, 2011).

Flooding occurred in several regions in Indonesia and the surface water of reservoir was increased faster. Collapse of the Situ Gintung dam is due to an increase in the volume of the reservoir water (Triwidodo, 2009). In March of 2010, there has been an increase of the reservoir water of Jatiluhur dam as indicated by an increase of water level to +108.87 meter, beyond the limit of normal point of +107.00 meter (Ismoko Widjaya, 2010). This situation is alarming for many risks that may arise.

The flow of water entering the reservoir is uncertain. This is corresponding with the intensity of rainfall. If the rainfall intensity increased significantly, the reservoir water will rise quickly. This condition can cause overtopping and further endanger the dam. A survey conducted by the Corps of Engineers U.S. Army (USACE), which includes more than 80.000 dams, showed that approximately 36% of the existing dam is included in the category of unsafe due to various reasons. However, about 80% of insecurity is due to inadequate spillway. To increase the spillway capacity is often by additional construction of spillway. However, these efforts are often obstructed due to field conditions that do not support such option. In many cases, modification to the existing spillway may be a better alternative. This alternative was chosen.
because it can utilize the existing spillway and does not reduce volume capacity (Hay and Taylor, 1970; Lux, 1984; Tullis et al., 1995).

Increase of the reservoir water level is quite worrying and interested to be examined. Increased spillway capacity without reducing the reservoir volume is an alternative that is selected in this study. Experiment has been observed on Hydro Laboratory, Faculty of Engineering of Sebelas Maret University. The experiments were conducted by comparing the flow of water through Sharp crested weir and Rectangular Labyrinth weir (RLW). The prototype of Sharp crested weir and RLW was made of Plexi Glass.

Labyrinth weirs produce complex, three-dimensional flows that are not readily described analytically. As is commonly done with hydraulic structures, empirical relationships that utilize a discharge coefficient (ascertained experimentally) have been developed to determine the head-discharge relationship of labyrinth weirs. This study utilizes equation (1) to determine the head-discharge relationship (Crookston, 2010); \( Q \) is the labyrinth weir flow rate, \( C_d \) is a dimensionless discharge coefficient, \( L_c \) is the centerline length of the weir crest or effective length of crest, \( g \) is the acceleration constant of gravity, and \( H_r \) is the total upstream head defined as \( H_r = V^2 / 2g + h \). \( V \) is the average cross-sectional velocity and \( h \) is the piezometric head upstream of the weir relative to the weir crest elevation. \( C_d \) is a function of geometry (crest shape), weir height (\( P \)), cycle width (\( w \)), cycle depth (\( B \)), apex geometry, cycle orientation (i.e., linear, arced), approach flow conditions, nappe behaviour (aeration condition, nappe instability), local submergence, and tail water submergence.

\[
Q = \frac{2}{3} C_d \cdot L_c \cdot \sqrt{2g} \cdot H_r^{1.5}
\]  

Over the past 70 years, numerous research studies, case studies, and design methods have been published that have advanced hydraulic understanding of labyrinth weirs. Taylor (1968), Hay and Taylor (1970), Hinchliff and Houston (1984), Lux and Hinchliff (1985), Magalhães and Lorena (1989), Tullis et al. (1995), Melo et al. (2002), Tullis et al. (2007) are a selection of notable investigations conducted with physical models to quantify the hydraulic behaviours of labyrinth weirs, with emphasis on geometric and hydraulic influences on discharge capacity. Several dimensionless ratios are used to describe and quantify complex labyrinth flows and the influences of geometric parameters [e.g., headwater ratio (\( H_r / P \)), cycle width ratio (\( w / P \)), magnification ratio (\( L / W \)), cycle efficiency (\( \varepsilon \))]. Lopes et al. (2006, 2008), Wormleaton et al. (1998) and Emiroğlu et al. (2010) are examples of labyrinth weir research focused upon energy dissipation, downstream flow characteristics, and aeration. Recent research efforts have included numerical modelling to evaluate and validate the use of CFD algorithms as an additional design tool (Savage et al. 2004, Paxson and Savage, 2006).

Materials and Methods

Labyrinth weirs have indirect (broken) crest. Therefore weirs current lines are in different direction from crests of weirs and in fact this current is three dimensional in labyrinth weirs. Then mathematical models for labyrinth weirs are sufficiently complicated and when these weirs would have exploited with kinds of gates (in this study life gate) and in fact compounded synchronous current is on the weirs and gates then it will be added to complicated condition of current. Therefore physical model used for simulation. For physical model making must recognize effective factors on studied phenomena and then by dimensional analysis calculate the effective dimensionless parameters. With determination of dimensionless parameters and physical model making extraction steps of data begins and we extract the needed data with examination on physical model.

Dimensional analysis of current which passed from combined structure (weir-gate)

For quantity making of synchronous current hydraulically behavior which passed under of life gate and above rectangular labyrinth weirs ,geometrical and hydraulic parameters could put under study as effective factors on discharge coefficient for combined model Rectangular labyrinth weir-gate (\( C_d \)) as follow:

Geometrical parameters: height of weir with dimension [L] \( P \), effective length of crest [L] \( L_w \), width of flume [L] \( w \), thickness of weir’s wall [L] \( t \), height of gate [L] \( a \), width of gate [L] \( b \).

Hydraulic parameters: discharge of passed current from structures [L³T⁻¹] \( Q \), height of water over weir at upstream of structure [L] \( h \), speed of water that passed from weir [LT⁻¹] \( v \).

The parameters that defined fluid and conditions: acceleration due to gravity [LT⁻²] \( g \), adhesion [MT²] \( \sigma \) ,dynamical viscosity of fluid [ML⁻¹T⁻¹] \( \mu \), especial mass of fluid [ML⁻¹] \( \rho \).

Since discharge could be written as multiplication of velocity and area thus we didn’t use of it in dimensional analysis. Dimensional analysis is reduction of effective variables number in a physical phenomena and turning them into less numbers of without dimension groups of the same variables that there is several method for it. In this research first we use of Buckingham method for dimensionless parameters determination .Then we investigate Buckingham dimensionless parameters by matrix method. The results show that both methods yield same dimensionless parameters. We chose speed, density and height of upstream as repetitious variables that dimensionless parameters presented in equation (2) earned:

\[
Q = \frac{2}{3} C_d \cdot L_c \cdot \sqrt{2g} \cdot H_r^{1.5}
\]
If the current on combined structure wasn’t as laminar (Streamline flow) could relinquish of viscosity effect in fluid behavior according to above relation. Then Reynolds dimensionless number eliminate in above relation. As well as, if the waters height be less on structure then adhesion of water will have effect on current behavior. According to this if observe at least amount bond of water height on combined weir structure (3 cm) then could eliminate adhesion effect. Then Weber number eliminated from above relation. Therefore according to above discussion we could write relation (3) as follow:

\[
f\left(\text{Fr}, \text{h} \frac{h}{h}, h \frac{h}{h}, \frac{h}{h}, C_d\right) = 0
\]  

Consequently combined flow rectangular weir–gate discharge coefficient is a function of dimensionless parameters of relation (4). In laboratory with changing in these parameters some relations presenting for discharge coefficient.

\[
C_d = f\left(\text{Fr}, \frac{h}{h}, \frac{h}{h}, \frac{h}{h}, \frac{h}{h}, \frac{h}{h}, \frac{h}{h}, \frac{h}{h} \right)
\]

Laboratory equipments
Examinations had done in laboratory flume, sloppy and rectangular form at Sari’s Agriculture and Natural Resource University by 12 (m)*0.5 (m) area and 0.8 (m) height by glass wall and floor. Discharge of flume provided by three pumps by overall 90 lit/s and measured by 90 degree triangular weir (Fig. 1). For measure of current waters depth in flume we use of stage gauge by ±0.1 mm attention. Fig. 2 shows schematic of flume from above. Triangular weir calibrated as volume calibration and then Q-H curve (Rating Curve) calculated (Before examinations started). Then passed discharge from flume evaluated by measuring of upstream water depth in triangular weir. If at least height of physical model in labyrinth weir be 0.15 (m) and ratio of \(H_t/P\) at least 0.3 (m) Then may relinquish of adhesions force. Then in this study at least labyrinth weir has chose 0.15 (m). In our study the number of labyrinth weirs made as even cycle and according to width of laboratory flume and induction of adhesion force chose 2 cycles for wall of rectangular labyrinth weir.

In this research we used of five Plexi Glass rectangular labyrinth weir physical model and one Plexi Glass sharp crested weir. All made weirs have two life gates with 90 degree shaped crest and with 10 (mm) thickness wall. Fig. 3 and 4 showed a samples of made combined model for rectangular labyrinth weir–gate for each examination in this research models set in 4 (m) upstream of output. Examination had done at 10 till 90 (lit/s) discharge that height and speed (v) of water calculated in one meter upstream at labyrinth weir set place. All models sizes have shown in table 1.
In this research as what have done before combined models we used of one discharge coefficient for passed current for combined model of weir–gate and didn’t separated weir or gate’s discharge coefficient. Discharge coefficient for combined model rectangular labyrinth weir–gate calculated from equation (5).

\[ C_d^{eq} = \frac{Q}{\frac{1}{2} \sqrt{g} \sqrt{H} (L_t + \sqrt{H})^2 + a} \]  

(5)

In this equation a is size of openings gates (m), b width of gates (m), H is depth of upstream gate current (m), Q passed discharge of combined model (weir–gate) (m³/s), \( C_d \) is discharge coefficient for combined model (weir–gate), \( L_t \) is effective length of labyrinth weir or sum of all labyrinth weir length (broken crest) (m), \( H \) is total head of water on weir and \( g \) is acceleration due to gravity (m/s²). In this research we use of above equation for all of earned results too. Also in discharge result calculation of combined model (Sharpe crested weir–gate) we use of same equation.

Results and Discussion

Change of effective length (\( L_t \)) and height of Rectangular Labyrinth weir–gate

In table 2 shows some of examination results on All models (RL₁, RL₂ and RL₃) with 8 (cm) opening height of gate.

<table>
<thead>
<tr>
<th>Model</th>
<th>( H ) (mm)</th>
<th>Q (L/min)</th>
<th>( C_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL₁</td>
<td>100</td>
<td>58</td>
<td>0.34</td>
</tr>
<tr>
<td>RL₂</td>
<td>100</td>
<td>53</td>
<td>0.31</td>
</tr>
<tr>
<td>RL₃</td>
<td>100</td>
<td>47</td>
<td>0.27</td>
</tr>
<tr>
<td>RL₄</td>
<td>71</td>
<td>43</td>
<td>0.41</td>
</tr>
<tr>
<td>RL₅</td>
<td>71</td>
<td>38</td>
<td>0.35</td>
</tr>
<tr>
<td>RL₆</td>
<td>71</td>
<td>32</td>
<td>0.31</td>
</tr>
</tbody>
</table>

According to table 2 could say that comparisons have shown that in all discussed geometry with upstream head water (\( H \)) increasing the discharge coefficient (\( C_d \)) reduced. Also discharge coefficient and passed discharge of combined model rectangular labyrinth weir–gate are increasing with increase of weir’s height (P).

\[ P_{RL₁} > P_{RL₂} > P_{RL₃} \rightarrow C_{d(RL₁)} > C_{d(RL₂)} > C_{d(RL₃)} \rightarrow Q_{RL₁} > Q_{RL₂} > Q_{RL₃} \]

In table 3 shows some of examination results on All models (RL₁, RL₄ and RL₅) with 8 (cm) opening height of gate. Fig. 5 shows discharge coefficient All models (RL₁, RL₄ and RL₅) with opening gate of height 8 (cm) against dimensionless parameters the ratio of total upstream head to weir height (\( H/P \)).

<table>
<thead>
<tr>
<th>Model</th>
<th>( H/L )</th>
<th>Q (Lit/s)</th>
<th>( C_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL₁</td>
<td>0.021</td>
<td>43</td>
<td>0.411</td>
</tr>
<tr>
<td>RL₄</td>
<td>0.021</td>
<td>36</td>
<td>0.406</td>
</tr>
<tr>
<td>RL₅</td>
<td>0.021</td>
<td>30</td>
<td>0.401</td>
</tr>
<tr>
<td>RL₁</td>
<td>0.030</td>
<td>49</td>
<td>0.387</td>
</tr>
<tr>
<td>RL₄</td>
<td>0.030</td>
<td>43</td>
<td>0.387</td>
</tr>
<tr>
<td>RL₅</td>
<td>0.030</td>
<td>36</td>
<td>0.385</td>
</tr>
<tr>
<td>RL₁</td>
<td>0.032</td>
<td>51</td>
<td>0.379</td>
</tr>
<tr>
<td>RL₄</td>
<td>0.032</td>
<td>42</td>
<td>0.381</td>
</tr>
<tr>
<td>RL₅</td>
<td>0.032</td>
<td>37</td>
<td>0.382</td>
</tr>
</tbody>
</table>

According to table 3 and Fig. 5 could say that increase of weir’s effective length till \( H/L \) less than 0.03 lead to increasing in discharge coefficient of combined model rectangular labyrinth weir–gate. But above of this boundary increasing in effective length lead to decrease of discharge coefficient in combined model and increasing of effective length cause to increase of passed discharge of combined model for every boundary of current.
Le(RL1) > Le(RL4) > Le(RL5) \rightarrow C_{RL1} > C_{RL4} > C_{RL5} \rightarrow Q_{RL1} > Q_{RL4} > Q_{RL5} \quad (H/P < 0.03)

Le(RL1) < Le(RL4) < Le(RL5) \rightarrow C_{RL1} < C_{RL4} < C_{RL5} \rightarrow Q_{RL1} < Q_{RL4} < Q_{RL5} \quad (H/P > 0.03)

Figure 5. Discharge coefficient for All Types (RL1, RL4 and RL5) with 8 (cm) opening height of gate.

**Compare Sharp crested weir-gate with Rectangular Labyrinth weir-gate**

In this section passed current and discharge coefficient investigate at a combined model (Sharp crested weir-gate and Rectangular Labyrinth weir-gate). These combined model made with opening height 8 (cm), its data shown in table 1 and examination have done on it separately.

For comparing this model with combined model rectangular labyrinth weir-gate all its characters as weir height, wall thickness, gates height and width are equal in all combined model. Therefore could investigate correctly current amount and its coefficient in each model. Then changes that creates in passed current and current coefficient linked only to weir shape changing from labyrinth to sharp. Examinations result for SH weir and OG weir with opening height 8 (cm) of gate compare with model LR3 results with opening height of gate 8 (cm) because all models have 15 (cm) height. Fig. 6 and 7 shows discharge coefficient and discharge model RL3 and SH (both with opening gate of height 8 cm) against dimensionless parameters the ratio of upstream total head water to weir height (H/P) respectively. With attention to Fig. 6 and 7 could reach to following results:

Discharge coefficient for combined model sharp crested weir-gate increase with increasing of water height in upstream that reported in previous researches. Whereas discharge coefficient in rectangular labyrinth weir-gate decreased with upstream water increasing.

Within the boundary H/P<0.4 the amount of discharge coefficient of combined model rectangular labyrinth weir-gate almost is equal to or more of discharge coefficient of combined model sharp weir-gate. Because in this boundary we have at most cavitation and least interference of waves. In fact this leads to labyrinth weir in small amount of water limitation have better operation than hydraulics. Effective length of labyrinth weir is more than sharp crested weir. Therefore maximum discharge differences for these two model belonged to this boundary.

Till H/P<0.6 boundary, discharge of passed from rectangular labyrinth weir combined model-gate is definitely more than combined model sharp crested weir-gate. Because with increasing of discharge, labyrinth weir act like sharp weir. With discharge increasing, labyrinth weir drowned (Submerged flow) and water’s jet don’t aeration and in fact in H/P>0.6 boundary, discharge of labyrinth weir and sharp crested weir act like each other.

Figure 6. Comparison of discharge of RL3 with that of the SH
In table 4 and 5 shows some of examination results on model 3 with 8 (cm) opening height of gate and sharp crested weir with 8 (cm) opening height of gate.

Table 4. Comparison of discharge of RL3 with that of the SH against H/P

<table>
<thead>
<tr>
<th>Model</th>
<th>H/P</th>
<th>Q (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL3</td>
<td>0.3837</td>
<td>0.02893</td>
</tr>
<tr>
<td>SH</td>
<td>0.3824</td>
<td>0.02032</td>
</tr>
<tr>
<td>RL3</td>
<td>0.5177</td>
<td>0.03570</td>
</tr>
<tr>
<td>SH</td>
<td>0.0510</td>
<td>0.03417</td>
</tr>
<tr>
<td>RL3</td>
<td>0.5943</td>
<td>0.04012</td>
</tr>
<tr>
<td>SH</td>
<td>0.5912</td>
<td>0.04008</td>
</tr>
</tbody>
</table>

Table 5. Comparison of discharge of RL3 with that of the SH against H

<table>
<thead>
<tr>
<th>Model</th>
<th>H (mm)</th>
<th>Q (m³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RL3</td>
<td>52.0</td>
<td>0.02692</td>
</tr>
<tr>
<td>SH</td>
<td>64.5</td>
<td>0.02601</td>
</tr>
<tr>
<td>RL3</td>
<td>80.5</td>
<td>0.03772</td>
</tr>
<tr>
<td>SH</td>
<td>82.5</td>
<td>0.03718</td>
</tr>
</tbody>
</table>

According to table 4 at H/P<0.6, discharge of rectangular labyrinth weir-gate always is more than model sharp crested weir-gate. Passed discharge from labyrinth weir at this boundary in minimum is equal and in maximum is 1.021 times than sharp crested weir. According to table 5 could say that at a constant discharge, upstream water’s height of combined model sharp crested weir-gate at least is equal and at most is 1.24 times than combined model rectangular labyrinth weir-gate.

In higher discharges, combined model rectangular labyrinth weir-gate almost act like combined model sharp crested weir-gate that is conform to research about rectangular labyrinth weir and sharp without gate. Therefore combined model rectangular labyrinth weir-gate for cases that there is limitation for upstream water depth need less upstream head than sharp crest weir for same amount transformation. In such cases use of combined model rectangular labyrinth weir-gate recommended. In fact one of the combined model labyrinth weir-gate advantages to combined model sharp crested weir-gate is that flooding of upstream lands in labyrinth weirs is lesser (Floodplain is lesser). And in fact with less upstream water’s height passed the same current which passed from sharp crested weir that is its benefits.

Conclusion

Labyrinth weirs with rectangular, triangular, trapezoidal and etc. geometric plan are useful tools for regulation and evacuation of current in a limited width. In this research we investigate hydraulic operation of rectangular labyrinth weirs with two life gate in front of current with different dimensions of weir height and effective length at different slope of flume at laboratory condition. Comparisons have shown that in all discussed geometry plans with upstream head water increasing the discharge coefficient reduced. Also discharge coefficient and passed discharge of combined model rectangular labyrinth weir-gate are increasing with increase of weir’s height (P). Data analysis shows that increase of weir’s effective length till H/L less than 0.03 lead to increasing in discharge coefficient of combined model rectangular labyrinth weir-gate. But above of this boundary increasing in effective length lead to decrease of discharge coefficient in combined model and increasing of effective length cause to increase of passed discharge of combined model for every boundary of current. Experiment results for different flume slope shows that discharge coefficient of combined model when more inclining increased. In a part of this research we compared combined model of rectangular labyrinth weir-gate...
with combined model sharp crested weir-gate. The results have shown that till a boundary of current H/P<0.4, amount of discharge coefficient of combined model rectangular labyrinth weir-gate is almost equal to or more of discharge coefficient of combined model sharp crested weir-gate. Because in this boundary exist maximum cavitation and minimum interference of waves. In fact this shows that labyrinth weirs in less depth waters have better hydraulic operation.

References


