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EXPERIMENTAL STUDY OF ENERGY DISSIPATION IN A SINGLE STEP CONDITION OVER A BROAD CRESTED WEIR

[1*] Bashir Tanimu, [1]Aliyu Bamaiyi Usman, [1]Al-Amin Danladi Bello and [1]Sulaiman Jamilu Abdullahi

[1]Department of Water Resources and Environmental Engineering, Faculty of Engineering, Ahmadu Bello University, Zaria.
*Corresponding Author, email: bashirtanimu10@gmail.com

ABSTRACT

This research study the experimental performance of broad-crested weir with single-step by introducing U/S and D/S round-nose and analysing the parameters that have effect on the shape of the step and their effects on the flow characteristics and energy dissipation (E%) downstream (D/S) of the weir. Furthermore, empirical relations for *E%* and flow rate due to the influencing factors were derived. The results showed that the weir model with $\frac{R_2}{R_1} = 1.000$ gives a higher E% in comparison with other weir models. Flow regimes were observed i.e nappe flow for small discharges, transition flow for intermediate discharges and skimming flow for higher discharges. Two model equations were obtained, the first to dteremine the flow rate over the weir models and the second relation to estimate E% in terms of $\frac{h}{P_1}, \frac{R_2}{R_1}$ and Froude number Fr_2. The model ($\frac{R_2}{R_1} = 1.000$) can be used in the design of prototype weirs in terms of energy dissipation.

Keywords: Weirs, flow regimes, Energy dissipation, Upstream(U/S) and Downstream(D/S)

INTRODUCTION:

Weirs are hydraulic structures built across channels for measurement of discharge and also to raise the depth of water across irrigation channels. There are two types of weir shapes according to the crest namely broad crested and sharp crested weir. According to Altalid (2021) discharge rate and its coefficients in broad crested weir as well as the head loss are accurate with small error and can also be applied in flat slopes channel with the depth of flow at upstream not affected. The main purpose of using broad crested weir in open channels is for raising, measuring of flow controlling of upstream water level in fields. (Al Hashimi et al 2017)

A Stepped weir is a structure that has been used for energy dissipating, reducing water erosion, scour at the downstream slope and also reducing the length of stilling basin. The stepped weir also aids in water quality control. Stepped weirs are provided with steps from a small distance close to the crest down to the toe. These steps provided helps in increasing the energy dissipation rate that is taking place within the spillway surface (Tanimu, 2016).

Hussein et al (2009) study flow characteristics and energy dissipation over stepped round nosed broad-crested weirs. The authors vary the weir models by reducing the downstream height of the weir to provide a different performance. The height of the downstream step was vary several times, while length of the downstream step was fixed. The results obtained showed the energy dissipation rate increased by 46% with reduction in downstream height of the weir. Moreover, the discharge coefficient were also improved as the values obtained are higher compared with that of traditional weirs.

Hussein et al (2011) also investigated the effects of changing the step geometry on the flow characteristics and energy dissipation downstream of the stepped weir by changing the downstream step length and fixing downstream step height. The experimental results showed that when the ratio of the length of the downstream step (L_2) to the length of the weir (L_1) equals 0.5 gives higher energy dissipation and over single step weirs there are two parts of flow, in the first part the flow is gradually-varied flow while in the second part the flow is rapidly-varied flow. Guenther et al (2013) investigated flow aeration using stepped spillway, the authors concluded that smaller slopes performed better in flow aeration and energy dissipation. Gandhi and Mishra (2016) review studies on stepped weirs and spillways and influence of baffle blocks on dissipation of energy, they concluded the baffle blocks dissipated higher amount of energy and also plays a significant role in reducing length of the stilling basin.

Naderi (2014) investigated Dissipation of Energy in different types of stepped spillways geometry by Numerical method. He considers the following parameters such as discharge per unit width, step height and slopes of stepped spillway. He concluded that energy dissipation rate increases with increase in sill height. Jahad et al (2016) study Dissipation of energy and effects of varying geometry over stepped spillways, they fabricated four models in order to assess the significant of adding end sills with a quarter circle shapes at the step edges. They concluded that radius of endsills and number of steps have great impact on energy dissipation and also number of steps higher effect napped flow than step height.

Al-Hashim et al (2018) study "Determination of Discharge Coefficient of Rectangular Broad-Crested Weir by CFD" In their study, The performance of broad crested weir was assess by varying an upstream face slope from 90^0 to $23^{\mathbf{0}}$ degree in order to reduce the effect of flow separation. They concluded that the coefficient of discharge tends to increase with decrease in upstream weir slope. Thus weirs with upstream face slopes 90^0 have the smallest and 23^0 has largest discharge coefficient.

Altalib (2021) study Coefficient of Discharge for flow over Al-Shalalat stepped weir on Al-Khusr River. He uses the calculated discharge for daily rainstorm for the period of (2000-2018) data, then predicted a coefficient of discharge equation and predicted coefficient of discharge using statistical tools and compare the equation obtained with the previous studies available. The study shows there is good agreement between the their equation In the light of Hussein et al (2011), this study investigates the effects of changing the geometry of step on energy dissipation and flow characteristics of a single stepped weir by introducing two additional D/S round-noses before the step and after the step. This research is aimed at investigating the energy dissipation rate and characteristics of flow over step broad-crested weir with two additional D/S round-noses before and after the step.

The specific objectives of the study are to:

Examine the performance characteristics of each model on energy dissipation and get the most efficient and develop a mathematical equation that can be used to predict energy dissipated over such step weirs.

THEORETICAL ANALYSIS

Hussein et al (2011) tested seven weir models made from thermo-stone and painted to decrease the surface roughness. One of the weir models was a traditional round-nosed broad-crested weir, its length was 48 cm, 50 cm wide and 12 cm height with 6 cm radius of the round-nose. The other four models involved the above dimensions of the weir with D/S stepped height P_2= 6 cm and D/S lengths L_2 = 12, 18, 24 and 30 cm. While in the last two models the length of the weirs was increased to 54 and 60cm with D/S lengths 30 and 36 cm respectively.

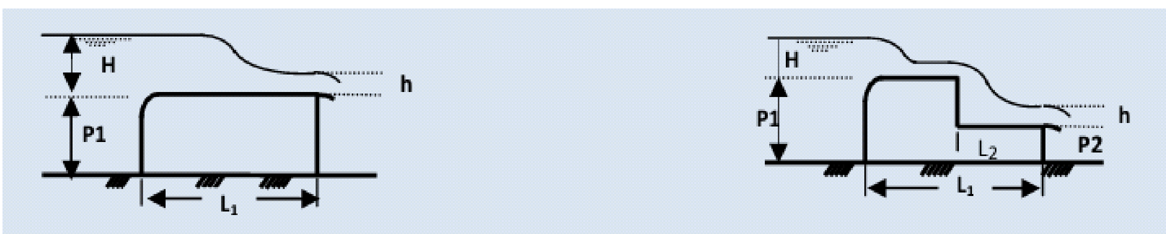

Figure 1 Free flow over Broad-crested weir: Traditional round-nosed weir (LEFT); Stepped weir (RIGHT) (Source: Hussein et al, 2011).

Energy Dissipation Percent, E%

Hussein et al, (2011) expressed the energy dissipation percent (E%) due to the change in D/S step geometry by Dimensional analysis as:

$$E\% = f_1\left(\frac{H}{P_1}, \frac{P_2}{P_1}, \frac{h}{P_1}, \frac{L_2}{L_1}, \frac{q^2}{gh^3}\right) \quad (1)$$

Since P_1 and P_2 were fixed and h value related to H and q^2/gh^3 is Froude number then Eqn. 1 became:

$$E\% = f_2\left(\frac{h}{P_1}, \frac{L_2}{P_1}, Fr_2\right) \quad (2)$$

Empirical Relation

Hussein et al, (2011) derived another empirical power relation based on Eqn. 2 for the variation of E% with $\left(\frac{h}{P_1}\right)$, $\left(\frac{L_2}{L_1}\right)$and $Fr_2$with correlation coefficient of 0.96.

$$E\% = 24.4\left(\frac{h}{P_1}\right)^{-0.57}\left(\frac{L_2}{L_1}\right)^{0.02} Fr_2^{-1.24} \quad (3)$$

Figure 2.09 shows the variation of the energy dissipation percent E% with the Froude number Fr_2 for different stepped weirs. It shows that E% increases as Fr_2 increases. On the other hand, Hussein et al, (2011) showed that the weir model with $\frac{L_2}{L_1}$= 0.5 gives a higher E% when compared with other models. Effect of the non-dimensional parameter $\frac{h}{P_1}$ on E% for different weir models were shown in Figure 1, it was observed that increase of value of $\frac{h}{P_1}$ makes E% to decreased gradually. Also, the E% for the traditional weir model ($\frac{L_2}{L_1}$= 1) almost remains constant with the increase of $\frac{h}{P_1}$. While E% of other weir models was decreased clearly. A comparison between E% values predicted by Eqn.3 and observed values experimentally is shown in Figure 2.1 and showing a good agreement (Hussein et al, 2011).

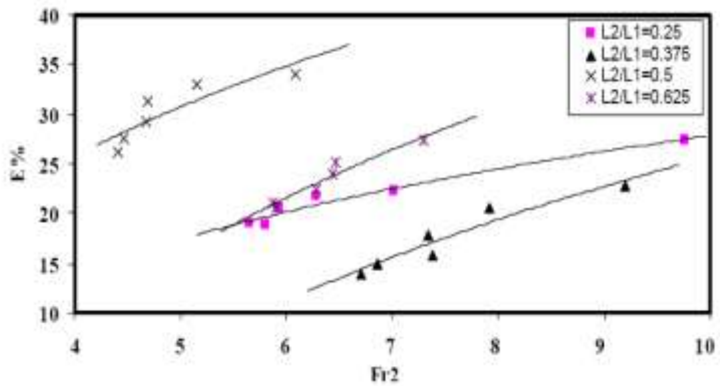

Figure 2. Variation of E% with Fr_2 for different step weirs.
(Source: Hussein et al, 2011)

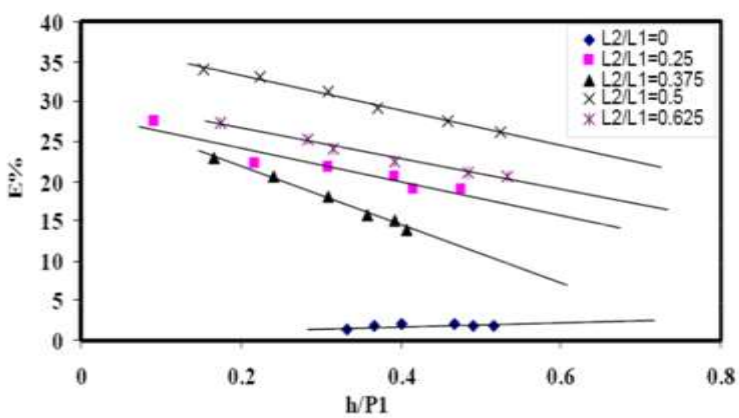

Figure 3. Dimensionless water surface profile for all weir models
(Source: Hussein et al, 2011).

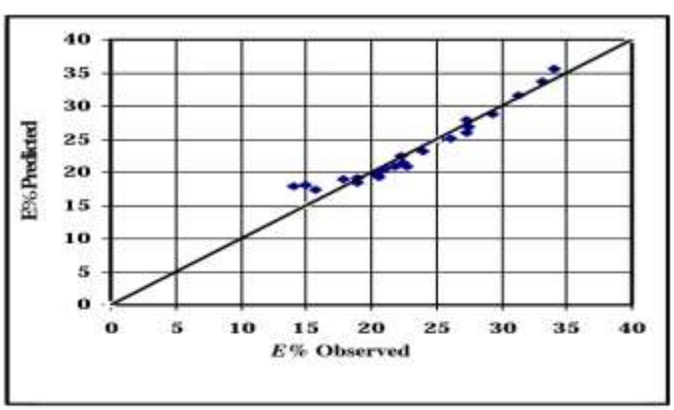

Figure 4. Variation of predicted values of C_d with the observed ones for all models (Source: Hussein et al, 2011).

Hussein et al, (2011) based on their results and analysis, they concluded that the weir model when $\frac{L_2}{L_1}$= 0.5 when compare with other weir models. So this model geometry can be used for the design of prototype weirs over single step. There basically two flow path, i.e the gradually flow and the rapidly varied flow.

MATERIALS AND METHODS

EXPERIMENTAL MODELS

Seven weir models were made from wood, they were painted to avoid swelling and reduction in surface roughness. One of the weir models was a (Block) traditional round nose broad crested weir, its length (L_1) 30cm, 30cm wide (b) and 20cm high (P_1) with 6cm radius (R) of the round-nose. The other six models have the below dimensions of the weir with downstream, D/S stepped height (P_2) = 10cm;according to Hussein et al, (2009), $\frac{P_2}{P_1}$ = 0.5, downstream, D/S stepped length (L_2)= 15cm; according to Hussein et al, (2011), $\frac{L_2}{L_1}$ = 0.5 and the introduction of two additional round-noses of radius (R_1)= 6cm and radius (R_2)= 6, 5, 4, 3, 2, 1cm before and after the step respectively. *See* ***Table 1.*** for summary of the geometries of the weir models tested.

Figure 5: Schematic diagram of block and step broad-crested weir models (with round-noses)

Model No.	L_1 (cm)	L_2 (cm)	P_1 (cm)	P_2 (cm)	R (cm)	R_1 (cm)	R_2 (cm)	$\frac{R_2}{R_1}$
1	30	—	20	—	6	—	—	—
2	30	15	20	10	6	6	6	1.000
3	30	15	20	10	6	6	5	0.833
4	30	15	20	10	6	6	4	0.667
5	30	15	20	10	6	6	3	0.500
6	30	15	20	10	6	6	2	0.333
7	30	15	20	10	6	6	1	0.167

Table 1. Dimensions of weir models tested.

EXPERIMENTAL SET UP AND PROCEDURE

The experiment was conducted in the Department of Water Resources and Environmental Engineering, Hydraulic laboratory ABU Zaria.

The rectangular flume was leveled horizontally and then the weir model set at right angle to the direction of flow was installed at 3m from the inlet channel as suggested by Munta, (2010) for uniform flow and glued within the walls of the flume in order to prevent leakage of water at the walls of the flume. Water from the flume storage tank was then pumped to the flume main channel by a centrifugal pump through a pipe of 150mm which was regulated by a valve. As water overflows the weir model's crest, it was allowed to flow till the flow became steady before any measurement was taken. At steady state, the upstream, U/S water head above the weir crest (H) and downstream, D/S water head (h) were measured using the point gauge; also the mass flow rate passing over the model was determined using the weighing scale and the stop-watch; Seven different discharges were passed over each model and the heights of water over specific grid points were measured in order to determine the upstream surface profile. The above procedure was then repeated for the rest of the weir models (Seven weir models were tested in total). See Plates below

Plate I: side view of the Tilting Flume

Plate II: Block Model

Plate III: Model with R_2 = 1cm

Plate IV: Model with R_2= 2cm

Plate V: Model with R_2= 3cm

Plate VII: Model with R_2 = 4cm

Plate VII: Model with R_2 = 5cm

Plate VIII: Model with R_2 = 6cm

DETERMINATION OF WEIR DISCHARGE EQUATION

Since the physical models are considered to belong to the rectangular broad crested weir, the proposed theoretical equation for the step broad-crested weirs was initially assumed to be the basic equation developed for the linear weirs according to Chow (1959), expressed as Eqn (4).

the general form of the discharge equation for rectangular broad-crested weir is given as:

$$Q = C_d \frac{2}{3} Hb\sqrt{\frac{2}{3}gH} \quad (4)$$

Where Q is the actual discharge of the weir model, that is Q_{act}.

$Q = KH^{\frac{3}{2}}$ where, $K = \frac{2}{3}C_d\, b\sqrt{\frac{2}{3}g}$ and n $=\frac{3}{2}$, then the above Eqn. 3.05 becomes

$$Q = KH^n \quad (5)$$

Taking log of both sides, then it becomes

$$\log Q = \log K + n\log H \quad (6)$$

Plotting a graph of log Q against log H, n is the slope and log K is the intercept.

ENERGY DISSIPATION, E%

Flow energy loss (ΔE) is the difference between the flow energy (E_1) at the upstream, U/S of the weir model and the flow energy (E_2) at the downstream, D/S of the weir model. Based on energy relationships, the general relationship for the flow energy dissipation is given as:

Applying energy equations between section (1) and (2)

$$E_1 = P_1 + H + \frac{v_1^2}{2g} \quad (7)$$

$$E_2 = P_2 + h + \frac{V_2^2}{2g} \quad (8)$$

$$E\% = \frac{E_1 - E_2}{E_1} * 100\% \quad (9)$$

(Source: Hussein et al, 2009)

DIMENSIONAL ANALYSIS

Energy Dissipation, E%

The energy dissipation rate percentage (E %) due to the variation in the geometry of the weir models can be expressed by the functional relationship:

E%= f_1(q, H, h, P_1, P_2, L_1, L_2, R, R_1, R_2, g) (10)

The dependent variable is E% which is the ratio of energy loss between upstream and downstream of the weir models to the amount of energy in upstream of the weir.

Using Buckingham dimensional analysis method,

$$E\% = f_2\left(\frac{H}{P_1}, \frac{h}{P_1}, \frac{P_2}{P_1}, \frac{L_1}{L_2}, \frac{R_2}{R_1}, \frac{q^2}{gh^3}\right) \quad (11)$$

Since, P_1, P_2, L_1, L_2 are fixed and q^2/gh^3 is expression for Froude number at the downstream, then Eqn. 3.12 can be expressed as:

$$E\% = \boldsymbol{f_3}\left(\frac{\boldsymbol{h}}{\boldsymbol{P_1}}, \frac{\boldsymbol{R_2}}{\boldsymbol{R_1}}, \boldsymbol{Fr_2}\right) \quad (12)$$

COMPUTATION OF WATER SURFACE PROFILE

Water surface profile is defined as the measurement of flow depth as the depth of flow changes longitudinally. Over the weirs models, there are two flow paths. In the upstream path the flow is gradually-varied flow while in the downstream path the flow is rapidly-varied flow (Hussein et al, 2011).

The classic differential equation for gradually-varied flow in open channels as given by Chow, (1959) and Venutelli, (2004) is given below:

$$\frac{dy}{dx} = \frac{S_o - S_f}{1 - \alpha Q^2 T/gA^3} \quad (13)$$

MATHEMATICAL MODELLING OF FLOW RATE "Q" AND ENERGY DISSIPATION "E%"

From the following expressions below:

$$Q = kH^n \quad (14)$$

$$E\% = \phi\left(\frac{\boldsymbol{h}}{\boldsymbol{P_1}}\right)^{\alpha}\left(\frac{\boldsymbol{R_2}}{\boldsymbol{R_1}}\right)^{\beta}\boldsymbol{Fr_2}^{\gamma} \quad (15)$$

Equation 15 shows the non-linear variation of E% with $\frac{\boldsymbol{h}}{\boldsymbol{P_1}}$, $\frac{R_2}{R_1}$andFr_2 which can be used to determine the energy dissipation percent of any of the step broad-crested weir models.

The parameters of the above equations that is k and n in eqn.14, α, β and γ in eqn.15 were determined using regression analysis. At the end of the regression analysis, the values of these parameters were found

RESULTS AND DISCUSSION

Forty-nine experiments were conducted in the hydraulics laboratory of Ahmadu Bello University, Zaria to determine the flow parameters namely water surface profile, U/S water head above the weir crest "H", D/S water head "h", actual discharge Q_{act}, theoretical discharge Q_{theo}, discharge coefficient C_d and energy dissipation percent E%.

WATER SURFACE PROFILE

Figure 6 illustrates the water surface profile upstream of the weir using the measured water depth for seven various discharges Q_1toQ_7 (5.42 to 11.63litres per second).The abscissa of the graph represents the distance from the weir while the ordinate represents the water height from the bottom of the channel. As can be seen from the graph, the water surface is almost uniform after 50cm from the weir, in order to be on the safe side, the point gauge was located 60cm upstream from the weir.

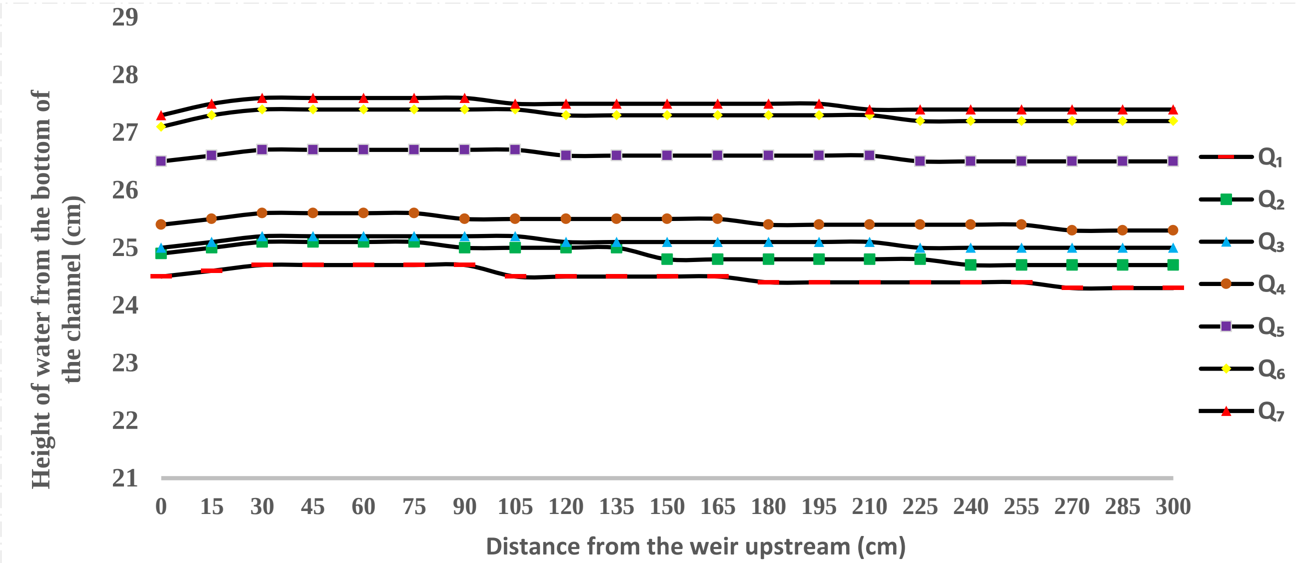

Figure 6: Water Surface Profile for various Discharges

FLOW REGIMES

The three flow regimes namely Nappe flow, Transition flow and Skimming flow were all observed during the experimental work. At smaller discharges where the step height is higher than depth of flow a free falling napped was observed. Transition flow occur at intermediate discharges where the depth of flow is close to step height, no free falling of flow and the water surface is rising and undulating. While for Skimming flow at higher discharges, the depth of flow is higher than the step height so the step has submerged (immerse completely) below strong current.

ENERGY DISSIPATION, "E%"

Table 4.2 to 4.5 show variation of E% with h/P_1 for the Block model and the stepped models with R_2 = 1cm, 2cm 3cm, 4cm, 5cm 6cm. Hence, the following were observed from the graphs below.

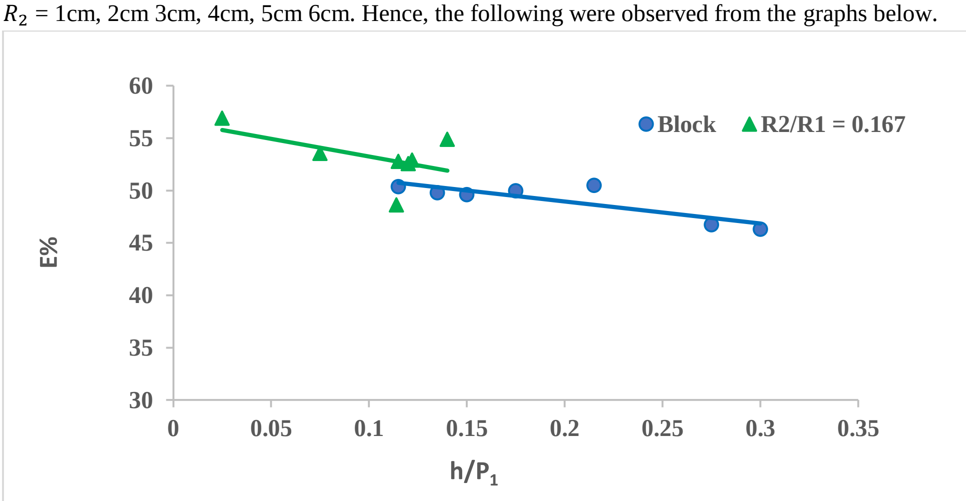

Figure 7: Variation of E% with $\frac{h}{P_1}$ for Block Model and Step Broad crested weir (R_2=1cm)

From the above figure 7, the Energy dissipation percent of the step broad-crested weir (R_2 = 1cm) are higher than those of the Block model, which is technically due to the step introduced which reduces the free falling energy of the water at the downstream. Also the introduction of the round-noses also reduces the free falling energy of the water at the downstream, making the water to flow over the weir model smoothly as a result of the round-noses curvature.

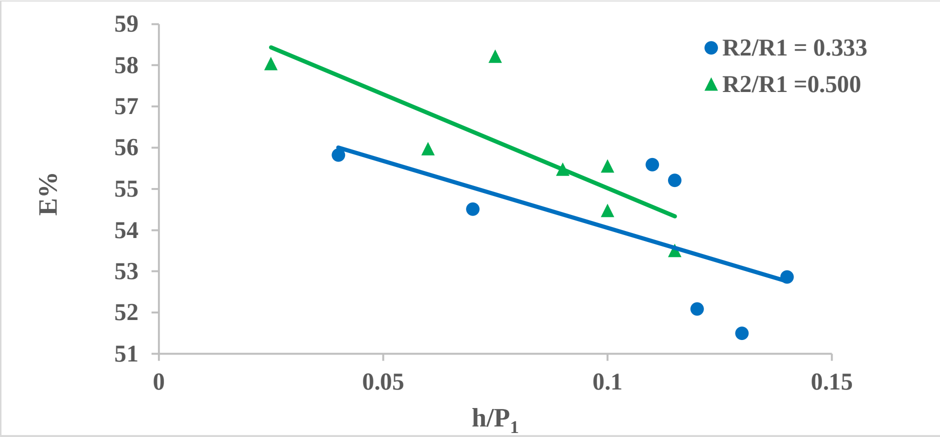

Figure 8: Variation of E% with $\frac{h}{P_1}$ *for Models (*R_2*= 2cm and 3cm)*

From the figure 8, the Energy dissipation percent, E% of the model (R_2= 3cm) are higher than those of model (R_2 = 2cm). As it was also observed from their respective $E\%_{avg}$; 55.90% and 53.94%. This is technical due to the fact that the model with R_2 = 3cm has higher surface area of flow at the D/S round-nose, making the friction between the fluid and the surface more pronounced, hence causing reduction of energy of the flow at downstream. As result of that the model with R_2 = 3cm is said to have higher E%. From the figure below, the energy dissipation percent of the model (R_2= 6cm) are higher than those of the model (R_2 = 4cm and R_2 = 5cm). As it was also observed from their respective $E\%_{avg}$; 55.53%, 55.99%, 57.75%. This is also due to the fact that the model with R_2 = 6cm has higher surface area of flow at the D/S round-nose, making the friction between the fluid and the surface more pronounced, hence, causing reduction of energy of the flow at the downstream. As result of that the model with R_2 = 6cm is said to have the highest E%.

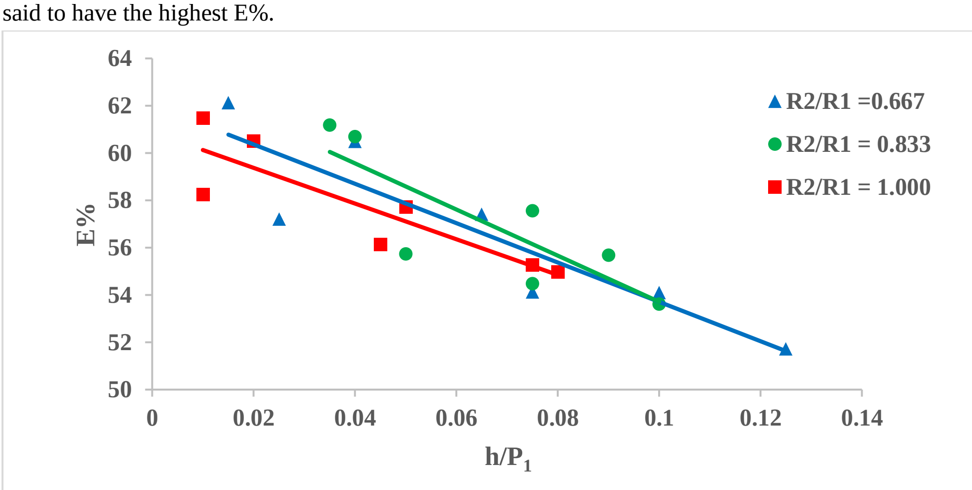

Figure 9: Variation of E% with $\frac{h}{P_1}$ *for Models (*R_2*= 4cm, 5cm, 6cm)*

From the figure 10 showing a combined variation of E% with $\frac{h}{P_1}$ for all the weir models, it was deduced that the energy dissipation percent "E%" decreases with increase in $\frac{h}{P_1}$, in this case, the E% increases as $\frac{R_2}{R_1}$ increases, that is, as radius of the D/S round-nose (R_2) increases.

As stated earlier, this is technically due to the fact that as $\frac{R_2}{R_1}$ increases, the surface area of flow at the D/S round-nose is also increasing, hence, the friction between the fluid and surface at the D/S round-nose increases. Thus, increasing the energy dissipation rate percentage "E%".

The energy dissipation percent "E%" achieved were higher than those achieved by Hussein *et al* (2011) in their investigation by 45.04%. Also the E% values obtained were higher than the E%values of the traditional (Block) broad-crested weir by 15.05%. This is to say that introduction of round-noses at U/S and D/S of the step broad-crested weir will improve the energy dissipation percent, "E%" of the weir.

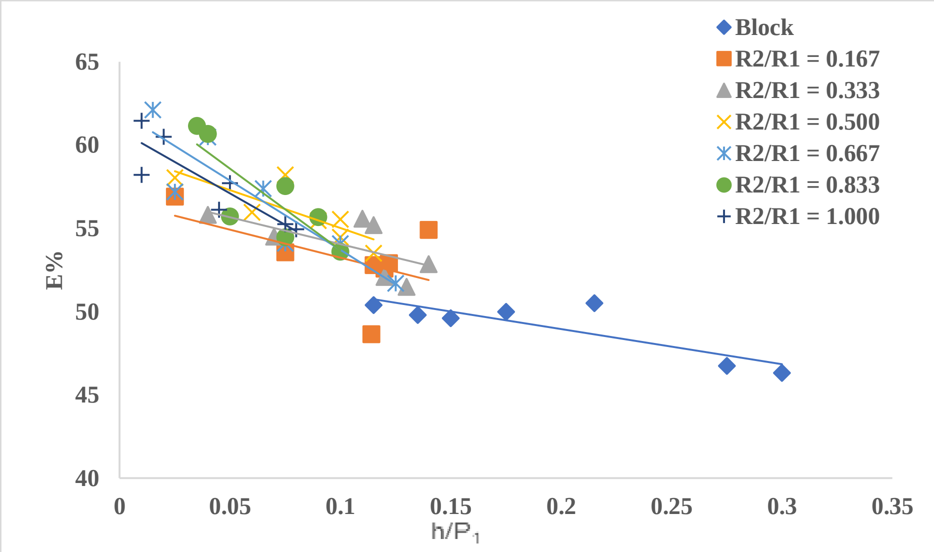

Figure 10: Variation of E% with $\frac{h}{P_1}$ for all the weir models

The Developed Model Equations

The parameters of equations (14) and (15) were obtained by multiple non-linear regression analysis. Correlation coefficient (R^2) is an indicator of how reliable the regression model is. For instance, Eqn.14 has R^2 of 0.788, this means that 78.8% of the variation in the observed values of the dependent variable(E%) is explained by the model, and 21.2% of these differences remain unexplained in the error (residual) term. Similarly, the same thing applies to Eqn. 15 which has R^2 of 0.928 with maximum error of 0.072 is more reliable in predicting the energy dissipation percent.

$$Q = 0.462H^{1.284} \tag{16}$$

Equation (16) is the discharge-head relationship which can be used to calculate the flow rate over the step broad-crested weir. Based on eqn. 15, multiple non-linear regression analysis was also used to correlate E% with both $\frac{h}{P_1}$, $\frac{R_2}{R_1}$ and Fr_2 in an empirical power relation.

$$E\% = 59.4566\left(\frac{h}{P_1}\right)^{0.0691} Fr_2^{\,0.0358} \tag{17}$$

with a correlation coefficient of 0.928.

In the above Eqn. 17 the $\frac{R_2}{R_1}$ term of the equation reduces to zero because the value of the parameter β = 0.000A comparison between E% values predicted by eqn. 17 and observed values experimentally is shown in figure 11 and showing a good agreement.

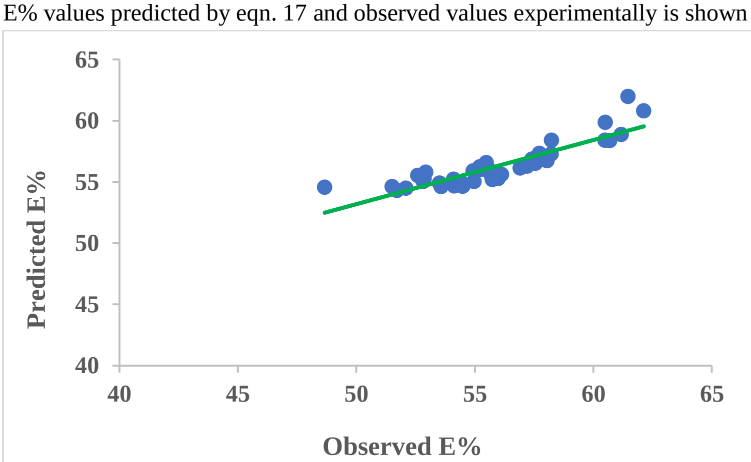

Figure 11: Variation of predicted values of E% with the observed ones for all weir models.

CONCLUSIONS

Within the limits of the results and analysis of this study the following conclusions are summarized

Stepping and introducing round-nose at U/S and D/S of the broad–crested weirs will improve the energy dissipation; the values of E% were higher than those of the traditional weir by 15.05%. More over the values of E% obtained were higher than those of Hussein *et al* (2011) by 45.04% due to the introduction of round-noses. Also the energy dissipation percent E% increase as $\frac{R_2}{R_1}$increases, so the weir model $\frac{R_2}{R_1} = 1.000$ gives a higher E% in comparison with the other weir models. Hence, it is said to be the most efficient model with respect to energy dissipation. Finally,three types of flow regimes were observed, nappe flow at small discharges, transition flow at intermediate discharges and skimming flow at large discharge.

REFERENCES

Al-Hashimi,S.M, Madhloom, H.M, Khalaf R.M, Nahi T.N and Al-Ansari, N.A(2017) "Flow over Broad Crested weirs: Comparison of 2D and 3D Models" Journal of CivilEngineering and Architecture 11 (2017) 769-779

Altalid, A(2021) " Discharge coefficient of flow over Al-Shalalat stepped weir on Al-Khusr River" Journal of Water Applied science.

Chow, V. T., 1959, *Open-channel Hydraulics*, McGraw-Hill, New York.

Hussein, H. H., Juma, I. A., and Shareef, S. J., 2009, "Flow characteristics and energy dissipation over stepped round–nosed broad–crested weirs", accepted in *Journal of Al-Rafidain Engineering*., Mosul University.

Hussein, H. H., Juma, I. A., and Shareef, S. J., 2011, "Improving the Hydraulic Performance of Single Step Broad-Crested Weirs", accepted in *Journal of Al-Rafidain Engineering*., Mosul University.

Hussein, H. H., Juma, I. A., and Shareef, S. J., 2011, "Improving the Hydraulic Performance of Single Step Broad-Crested Weirs", accepted in *Journal of Al-Rafidain Engineering*., Mosul University.

Jahad, U.A , Al-Ameri, R and Das,S. (2016) "Energy dissipation and geometry effects over stepped spillways" International Journal of Civil Engineering and Technology (IJCIET) Volume 7, Issue 4, July-August 2016, pp. 188–198 Article ID: IJCIET_07_04_015 ISSN Print: 0976-6308 and ISSN Online: 0976-6316 © IAEME Publication

Muhammad, M. M (2012); "Experimental study of flow characteristics over compound crested weir" M.sc Thesis, Department of Water Resources and Environmental Engineering, Ahmadu Bello University, Zaria.

Munta. S.K(2010) "evaluation study of energy dissipation over stepped spillway models" M.Sc thesis, Department of Water Resources and Environmental Engineering, Ahmadu Bello University Zaria.

Naderi I.R,(2014)"An Investigation of Energy Dissipation in Various Types of Stepped Spillways including Inclined Steps and Steps with End Sills by Numerical Model" International scientific publication and consulting services. cacsa-00030, 12 Pages doi:10.5899/2014

Tanimu, B (2016) "Study of Energy dissipation on stepped chute of different geometry" M.Sc thesis, Department of Water Resources and Environmental Engineering, Ahmadu Bello University Zaria.