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The proposed modeling and experimental design of a test section of a hydraulic jump in an open flow channel

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ABSTRACT
The determination of the exact location of the occurrence of hydraulic jump has remained a subject of much research in literature. Yet there are many disparities between experimental and predicted results. The work involves experimented design of a test section of a hydraulic jump in an open flow channel using the data generated in a laboratory channel. The experimental work was carried out in a 5 m-long horizontal glass-walled flume, having a rectangular 0.075 m wide and 0.15 m deep cross-section. The model weir was 0.257 m high by 0.06 m wide. The interchangeable crests of the model all have a thickness of 0.02 m and their lengths ranged from 0.06 m to 0.55 m. At different slopes, flow velocities, and variation of geometrical properties like Froude number, location of the jump, jump height, energy dissipation, and the length was measured. The Froude numbers from the post-hydraulic jump section within 0.37 to 0.41 ($0.37<Fr_3<0.41$), this shows that the flows are subcritical. The relationship between sequent depth ratio y_3/y_2 and velocity ratio v_2/v_3 is approximately -5024 +1.485 Fr_2 with R^2 =0.9957 indicating that as the sequent depth ratio and velocity ratio increases the inflow Froude number Fr_2 also increases. Accordingly, in the level-bedded constricted flume, the energy loss due to hydraulic jump ranged from -0.001 to 0.001 which shows some energy gain with an increase in the rate of discharge through the flume. The upstream of the flume, the Froude numbers range from 0.038 to 0.052 ($0.038 < Fr_1< 0.52$), showing that the flows were subcritical. For the weir configuration, the Froude numbers to the jump were within the range of 1.90 to 4.10 ($1.90 < F_{r1} <4.10$), which shows that the flows are supercritical.

Key words: Obstacle, Structures, Weirs, subcritical, supercritical downstream, upstream

INTRODUCTION

The primary objective of this study is to determine the exact location of the occurrence of hydraulic jump that has remained a subject of much research in literature. Yet there are many disparities between experimental and predicted results. Perhaps the model results have not been very satisfactory because of the negligence of some important factors such as bed friction effects, shear, and other factors in the modeling efforts. The location of the jump is required to enable the design of hydraulic structures with an adequate depth to avoid the spilling of water in the channel. In determining the jump location in a channel requires the jump equation along with the gradually-varied flow calculations. However, hydraulic jumps occur due to the transition of the supercritical flow into the subcritical flow in an open venturi channel according to [1-2]. These alterations help to accomplish the following, viz: stabilise the position of the jump, reduce the tailwater depth required for the jump to form, shorten the length of the jump and improve the characteristics of the downstream flow pattern [3].

The appurtenances as earlier said are of three distinct types, viz: chute blocks, end sills, and baffle blocks. Some of the importance of the hydraulic jump in hydraulic design engineering is as follows: To dissipate energy in water flowing over dams, weirs, and hydraulic structures and this helps to prevent scouring downstream from the structure. To increase the weight on an apron and this leads to uplift pressure under a masonry structure by raising the water depth on the apron. To mix chemicals used for purification.Lopez and Nistor [4] defined weirs as a hydraulic structure that represents a vital constituent of the infrastructure system assuming a relevant role as a life-sustaining element for the population. These structures impound water, wastewater, or other liquid substances upstream to serve various functions such as flood control, water supply, irrigation, water level control, etc. According to the Bureau of Reclamation of the United States, dams can be categorised based on three main aspects: use, hydraulic design, and material of construction.Similarly, [5] investigated to show the boundary layer effects in the hydraulic jump locations.

Moreso, [6] published a paper on the investigation on the design of a stilling basin for a hydraulic jump. Accordingly, [7] led a progression of investigations to consider the impact of roughened beds utilising consistently positioned solid shape obstructs that involved 10% of the bed surface. He found that the length of the hop was diminished by around 27 to 67% for the Froude number extended from 10 to 4, separately. The more decrease estimations of the pressure-driven jump length were for Froude number under 6.

The classification based on its hydraulic design defines two topologies: overflow and non-overflow structures [8]. Overflow or overtopping dams are defined as structures which are designed to discharge flow over their crests. This plan brings about structures which are flooded. The design of flood structures envelops a few profiles, for example, sharp-peaked, expansive peaked, ogee-formed, and so on Accepting a vertical downstream face, two sorts of stream systems related with overtopping pressure driven structures are depicted in Figure 1: free stream and lowered stream [8]. The tailwater level decides the stream system overseeing the release over the weir. Weirs and low-head dams have a place with the class of little dams. The International Commission of Large Dams gave nonexclusive rules to characterise little dams on an announcement zeroed in on this typology of structures [9]. The proposed characterisation characterises little dams as structures portrayed by a stature (estimated from the bed level to the most extreme peak level) inside the reach and fulfilling, where speaks to the capacity volume a huge number of cubic meters at the greatest level.

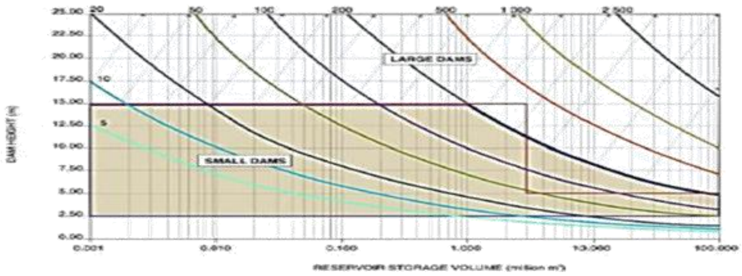

Fig. 1 Classification of small and large dams (Source: Committee on Small Dams [9]

Heat loss will be small in the case of the broad crested weir. These are constructed only in a rectangular shape and are suitable for the larger flows.

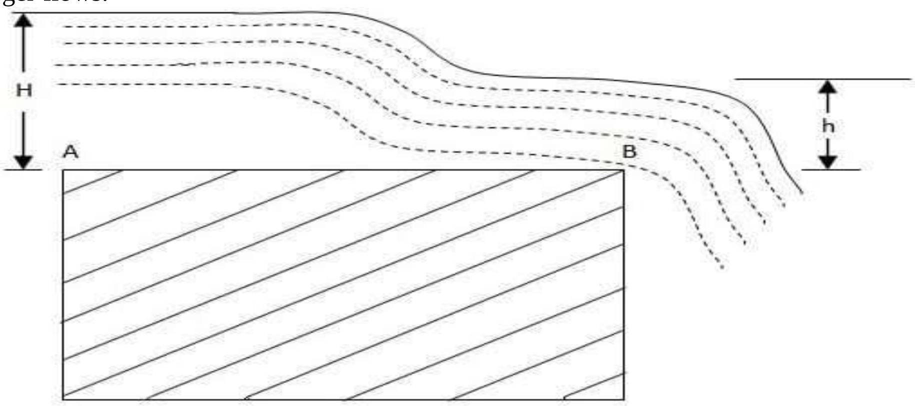

Fig. 2 An overview of broad-crested weir [10]

The release over the thin peaked weir is like release over the rectangular weir, it is like a rectangular weir with a limited formed peak at the top. Stream over ogee weir is additionally like stream over the rectangular weir. The peak of the ogee weir is somewhat risen and falls into explanatory structure, by and large, ogee formed weirs are accommodated the spillway of a capacity dam.

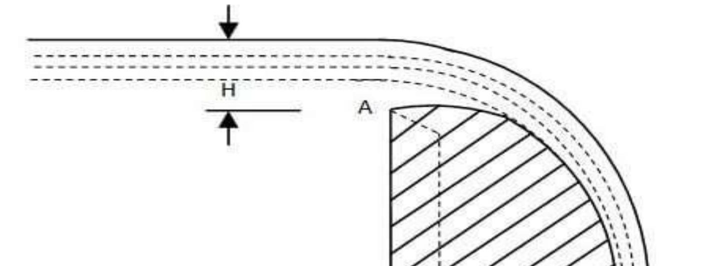

Fig. 3 Ogee-shaped weir [10]

In a contracted weir head loss will happen, the peak is cut as the indent, and afterward it is like the rectangular weir. The peak is stumbling into the channel so the head loss will be immaterial. Carollo et al. [11] contemplated the impact of bed unpleasantness on the sequent depth proportion and the roller length. Chanson [12] had built up the ongoing advances in violent water powered jumps. Afzal et al., [13] had explored the streamflow of a tempestuous water driven bounce in a rough rectangular channel bed. Carollo et al. [14] had examined the qualities of old style bounce and B-hops on smooth beds. Wang and Chanson [15] had led the analyses to examine the change of Froude numbers (3.8 <F1< 8.5) and Reynold's number (2.1 × 104 < R < 1.6 × 105). As of late, Egbe and Agunwamba [16], they proposed design and inference of numerical technique for displaying of water driven jump in a wide peaked weir in an open channel stream.

MATERIALS AND METHOD

All experimental works were performed in the Water Resources /Hydraulic Laboratory of the Cross River University of Technology, Calabar, Nigeria. The experimental work was carried out in a 5 m-long horizontal glass-walled flume, having a rectangular (0.075 m wide and 0.15 m deep) cross-section. The model weir was 0.257 m high by 0.06 m wide. The interchangeable crests of the model all have a thickness of 0.02 m and their lengths ranged from 0.06 m to 0.55 m. At different slopes, flow velocities, and variation of geometrical properties like Froude number, location of the jump, jump height, energy dissipation, and the length was measured.

Hydraulic jump parameter measurement

The exploratory assessments were done in a variable inclination open channel pressure-driven (VSOCPD) which we revamped and organized in the Civil Engineering Water Resources/Hydraulic Research Center, of the Cross River University of Technology, Calabar. The materials that were used to patch up the VSOCPD is showed up in Figure 4, including the going with: barrel-shaped metal with a rectangular profile, 0.075 cm wide and 5 m long, to create the base; pressure has driven jack to change the grades of the VSOCPD; acrylic sheets to fabricate the dividers and the base of the channel; two stands worked with three pieces of gets ready of 3 inches (80 mm) width to help the weight of the channel; a volumetric tank that serves not similarly as "reference model" to favor Q and as a store "water utilization" for the scattering of the stream rate (Q) into the VSOCPD; 3 HP fuel direct with 2 inches (50.8 mm) estimation of respect drive water from the repository "water confirmation" to VSOCPD and to circle the stream in a shut structure.

We input four distinctive stream rates (Q) through it. Each Q had an optional addition and decrease of Q to keep up a key good way from authentic inclinations in the length of the jump check, while the entryway opening "a" remained moderate. We evaluated the stream rates (Q) with the volumetric technique, using the scattering tank of the VSOCPD which was as of late adjusted.

The Manning "n" utilized is 0.009 (acrylic), and distinctive changed slants. We estimated the accompanying factors straightforwardly in the trial model: Length (L), pre-bounce profundity (y_1), and post-hop profundity (y_2), which gave the information to compute Froude's numbers: Fr_1 and Fr_2.

The point by point drawings of the test flume was drawn and the embellishments were gathered as portrayed in figure 4.

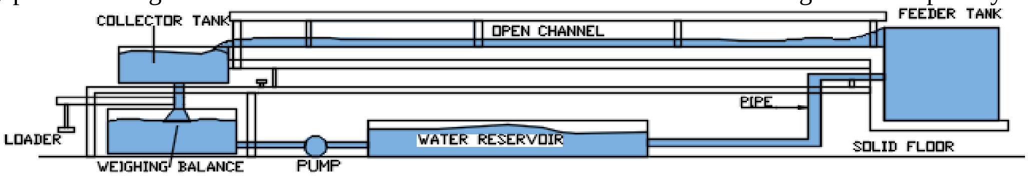

Fig. 4 Experimental setup of the Flume

Proposed Design

To locate the position of a hydraulic jump in the rectangular channel of width B, it is important to consider input parameters that govern the position of the jump. Figure4 shows the definition sketch of a hydraulic jump in a rectangular channel with a horizontal slope.

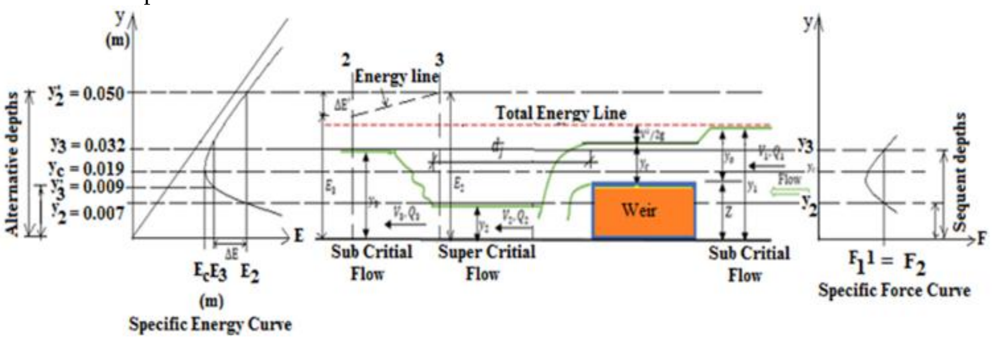

Fig. 5 The proposed definition design of the hydraulic jump in a rectangular channel

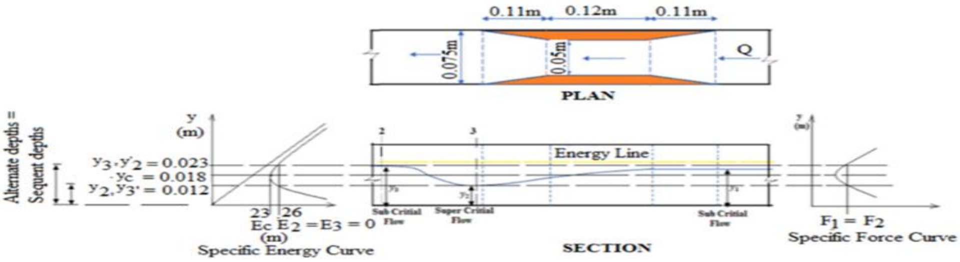

Fig. 6 The Proposed experimental design of the test section of the channel

Nevertheless, the following are the factors affecting hydraulic jump are total head-on upstream of sluice gate (H), pre-jump depth (y_1), post jump depth (y_2), crest height of weir (y'), head over weir crest (h), and tailwater depth (y_t). Another non-dimensional important parameter that governs the hydraulic jump phenomenon is supercritical Froude number Fr_1. Figure 6 shows the discharge Q on X-axis and post jump depth (y_2) and tailwater depth (y_t) on Y-axis to form two curves - 'jump height curve' (JHC) and 'tail water rating curve' (TWRC) respectively.

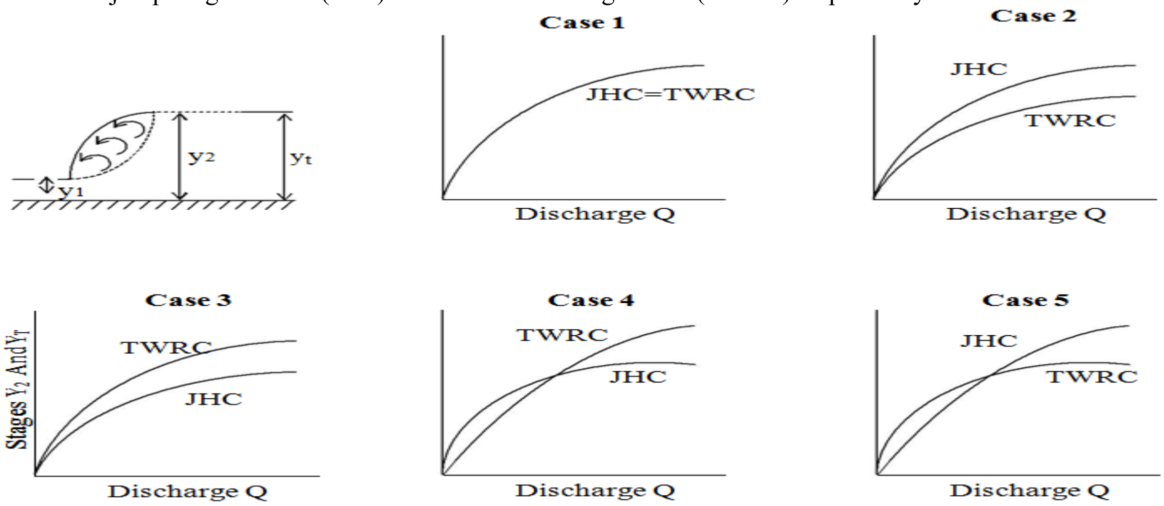

Fig. 7 Classification of tailwater conditions for the design of energy dissipator [17]

Mass and energy balance equation for the open channel

Concerning the schematic diagram shown in Figure 8 the mass flows at points 1, 3, and 4 can be expressed as m_1, m_3, and m_4, respectively. And if the velocities at these points are known, the momentum at these points can be expressed as:

$$M_1 = m_1 u_1 \quad (1)$$

$$M_3 = m_3 u_3 \quad (2)$$

$$M_4 = m_4 u_4 \quad (3)$$

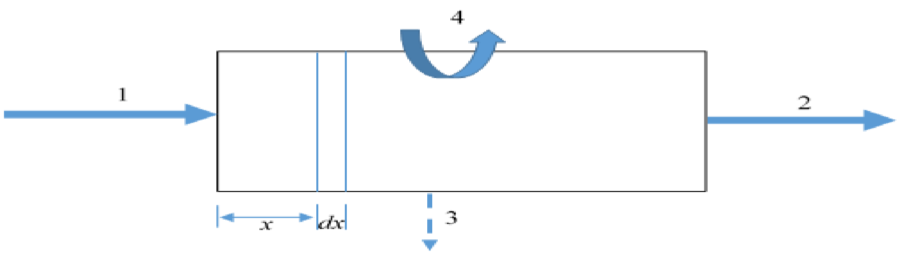

Fig. 8 Schematic diagram of the mass and energy balance in the channel

Considering a strip of the thickness of the channel at a distance x from the left-hand side, the momentum at exit (i.e. at point 2), can be expressed as:

$$M_2 = m_1 u_1 + \frac{d}{dx}(m_1 u_1)dx \quad (4)$$

The rate of change of momentum, following the schematic diagram, can be expressed as:

$$M_{change} = M_2 + M_3 + M_4 - M_1 \quad (5)$$

Substituting values and subtracting,

$$M_{change} = m_1 u_1 + \frac{d}{dx}(m_1 u_1)dx + m_3 u_3 + m_4 u_4 - m_1 u_1 \quad (6)$$

This results in:

$$M_{change} = \frac{d}{dx}(m_1 u_1)dx + m_3 u_3 + m_4 u_4 \qquad 7$$

$$M_{change} = (m_1 u_1 - m_2 u_2)L + m_3 u_3 + m_4 u_4 \qquad 8$$

The rate of change must equal the external force in this control volume.
Since the water is stagnant, the external force can be derived for the pressure head causing flow at point 1.
Thus, $F = P_1 A_1 = P_1 \frac{m_1}{\rho_1 u_1}$ 9

Equating 5 and 6:

$$P_1 = \rho_1 u_1[(m_1 u_1 - m_2 u_2)L + m_3 u_3 + m_4 u_4]/\, m_1 \qquad 10$$

Since the velocity at which the fluid evaporates at point 4 is negligible, the velocity is substituting as:

$$P_1 = \rho_1 u_1 \left[(m_1 u_1 - m_2 u_2)L + m_3 u_3 + m_4 * \frac{m_4}{\rho_4 A_4}\right]/\, m_1 \qquad 11$$

And since the fluid is homogenous, the expression above is generally written as:

$$P_1 = \rho u_1 \left[(m_1 u_1 - m_2 u_2)L + m_3 u_3 + m_4 * \frac{m_4}{\rho A_s}\right]/\, m_1 \qquad 12$$

Where the exposed surface area of the water is denoted byA_s.

Specific energy and critical depth

In open-channel flows, one of the important parameters is the “specific energy” and is defined as,

$$E = y + \frac{V^2}{2g} \qquad 13$$

Where y is the water depth and V is the flow velocity. It is also called an *energy grade line* (EGL). For a given stream rate, there are two potential states for the same specific energy as shown in Figure 9.

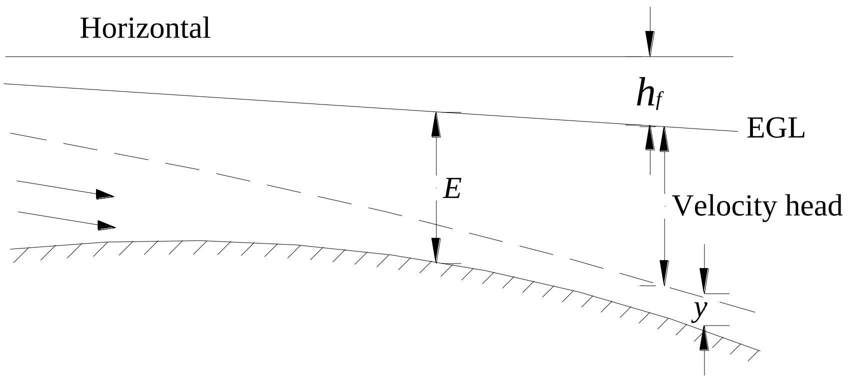

Fig. 9 Sketch for the specific energy

RESULTS AND DISCUSSION

Hydraulic jump parameters measurement

Table -1 Dissipated energy characteristics of weir and flume experiments

Test run no.	ΔE_{weir} (mm)	ΔE_{flume} (mm)	$\frac{\Delta E_{weir}}{\Delta E_{flume}}$	$F_{r,weir}$	$F_{r,flume}$	$\frac{F_{r,weir}}{F_{r,flume}}$	ΔE_{weir} Change Compared with ΔE_{flume}(%)
1	72.00	-1.00	-72.00	7.69	0.47	16.56	+101.38
2	160.00	-2.00	-80.00	10.72	0.50	21.44	+101.25
3	78.00	-3.00	-26.00	7.07	0.62	11.40	+103.85
4	370.0	-5.00	-74.00	16.32	0.52	31.38	+101.35
5	300.0	-6.00	-50.00	14.75	0.75	19.66	+102.00
Mean Value			60.40			20.09	+101.97
Standard Deviation			22.33			7.37	+1.09
Coefficient of Variation			0.37			0.37	+0.011

Table -2 Flow depths and energy head loss due to overflow

Flow test no.	y_o	y_c	y_c, calculated	y_c, Theory	$\frac{y_o}{y_c}$	F_{r1}	F_{rc}
1.	0.014	0.009	0.009	0.009	1.50	0.032	1.00
2.	0.018	0.012	0.012	0.012	1.50	0.048	1.00
3.	0.021	0.014	0.014	0.014	1.50	0.057	1.00
4.	0.029	0.019	0.019	0.019	1.50	0.077	1.00
5.	0.029	0.019	0.019	0.019	1.50	0.077	1.00
6.	0.030	0.020	0.020	0.020	1.50	0.083	1.00
7.	0.030	0.020	0.020	0.020	1.50	0.083	1.00
8.	0.036	0.024	0.024	0.024	1.50	0.103	1.00

Table -3 Relationship between upstream weir and weir overflow

		Upstream of weir			**Weir overflow**		
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
The flow test runs no.	Zweir (m)	y_1 (mm)	V_1 (m/s)	$Q_1 \times 10^{-4}$ (m^3/s)	y_c (mm)	V_c (m/s)	$Q_c \times 10^{-4}$ (m^3/s)
1.	0.075	0.089	2.00	0.09	0.009	0.30	2.00
2.	0.075	0.093	3.20	0.012	0.012	0.35	3.20
3.	0.075	0.096	4.00	0.014	0.014	0.37	4.00
4.	0.075	0.104	6.09	0.019	0.019	0.43	6.09
5.	0.075	0.104	6.20	0.019	0.019	0.43	6.20
6.	0.075	0.105	6.53	0.020	0.020	0.44	6.53
7.	0.075	0.105	6.60	0.020	0.020	0.44	6.60
8.	0.075	0.111	9.00	0.024	0.024	0.49	9.90

As presented in Tables 1 to 3 all the results show that the upstream discharge Q_u and downstream discharge Q_d (are beyond the wake of jump) which is very closely proportional as presented in Figures 10 and 14 respectively. This shows the stream is consistent and uniform in these sections. It can be seen that as the upstream discharge increases**,** the distance between weir and jump increases as well. Also as the weir depth **(**Zweir**)** increases, the distance between weir and jump increases too. That means that the distance between weir and jump is proportional to the upstream discharge and the height of the weir which provides an equation to predict the location of the hydraulic jump in the channel with a very strong R^2 =0.9291 ($y = -0.0037 + Fr^3 + 0.0929Fr^2 - 0.3128\,Fr\ + 4.7182$)

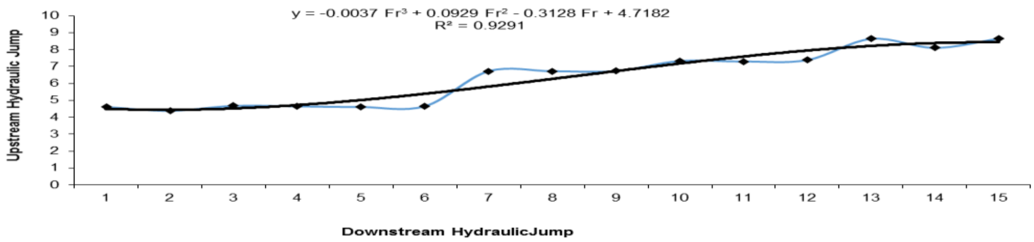

Fig. 10 Graph of upstream jump vs downstream jump

Similarly, Figures 9 and 13 compares the calculated and theoretical critical depth with the experimental estimation. The result shows that $y_{c,exp}$, $y_{c,cal}$ and $y_{c,theory}$ are very closely proportional but with $y_{c,exp}$ with about an average of 5.0 mm lesser than others, the results are shown in Figures 10 to 12 respectively. The mean, standard deviation, and variance coefficient of $\frac{y_{c,exp}}{y_{c,cal}}$ were 0.743, 0.103 and 0.138 respectively. Also, the mean, standard deviation, and variance of $\frac{y_{c,exp}}{y_{c,theory}}$ were 0.677, 0.100 and 0.148, respectively.

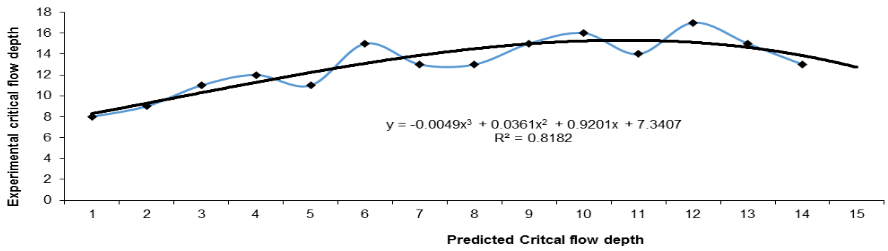

Fig. 11 Experimental and predicted critical flow depth

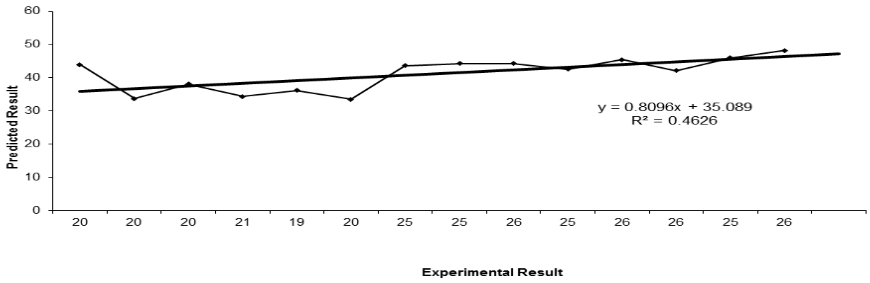

Fig. 12 Predicted result against the experimental result

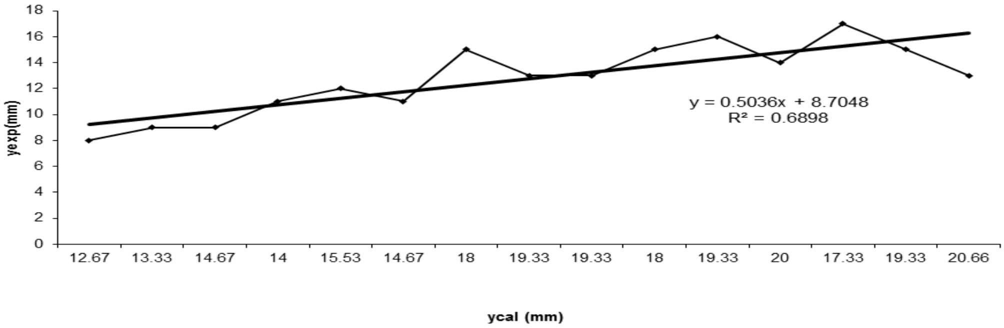

Fig. 13 Yc experimental against Yc Calculated

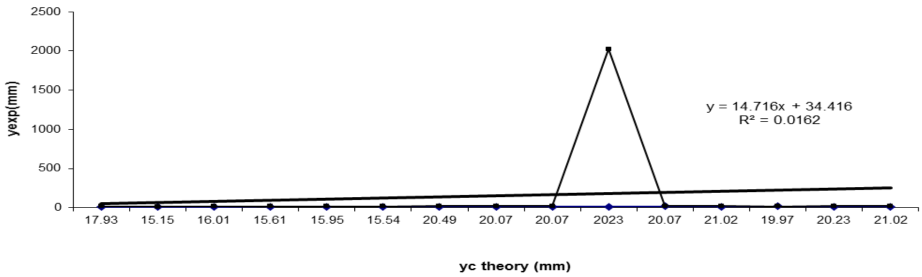

Fig. 14 Yc experimental against Yc theory

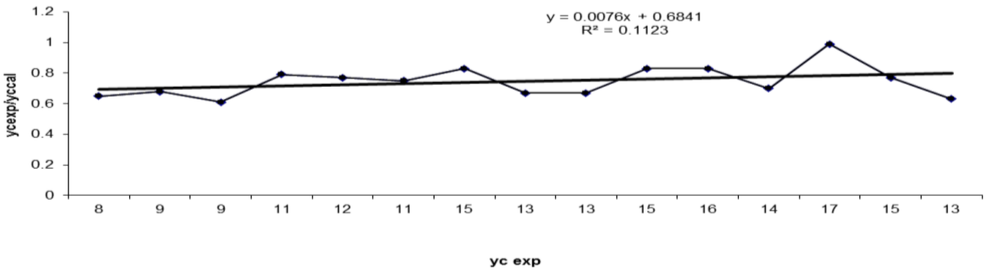

Fig.15 Yc experimental against Yc calculated

The effect of length of jump against the depth of flow

Nevertheless, Figures 14 to 15 compares the Froude numbers obtained, at the upstream of the weir, the Froude numbers range from 0.09 to 0.23 ($0.09 < F_{r1} < 0.23$), showing that the flows are subcritical. At the pre-hydraulic jump section, the Froude numbers range from 1.93 to 3.34 ($1.93 < F_{r2} < 3.34$), showing that the flows there are supercritical and the jumps vary from weak to oscillating. The Froude numbers obtained from the post-hydraulic jump section range from 0.38 to 0.56 ($0.38 < F_{r3} < 0.56$), also showing that the flows are subcritical. This proves that hydraulic jump occurs in an open channel when a flowing liquid transits from unstable, supercritical, or rapid flow to stable, subcritical, or tranquil one.

The flow over the broad crested weir and the localized occurrence of the position of the hydraulic jump in the channel is depicted in Figures 13 to 21 respectively.

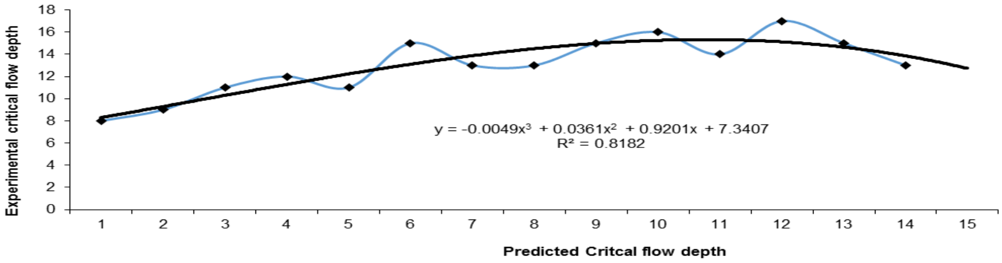

Fig. 16 Graph of Experimental critical flow depth against predicted critical flow depth

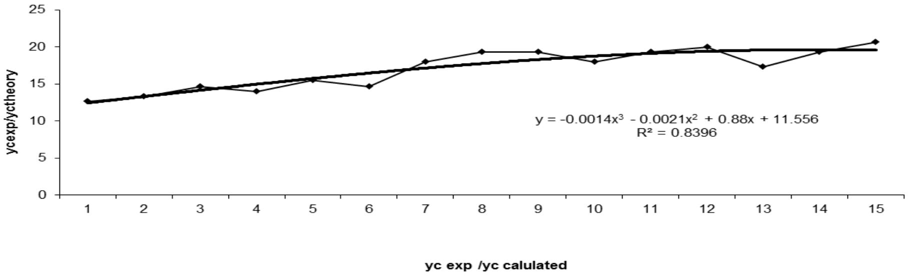

Fig.17 Yc experimental against yc calculated

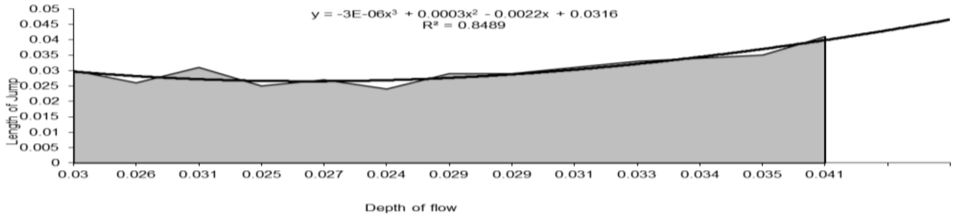

Fig. 18 Length of jump against the depth of flow

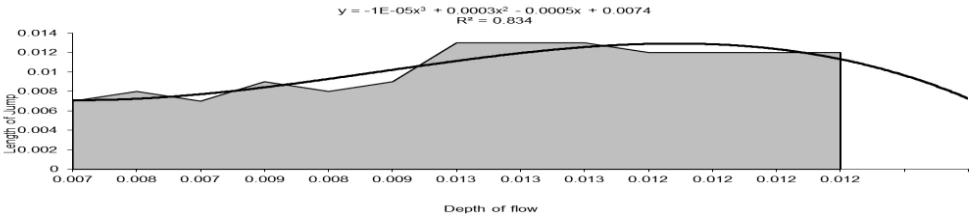

Fig. 19 Length of jump against the depth of flow

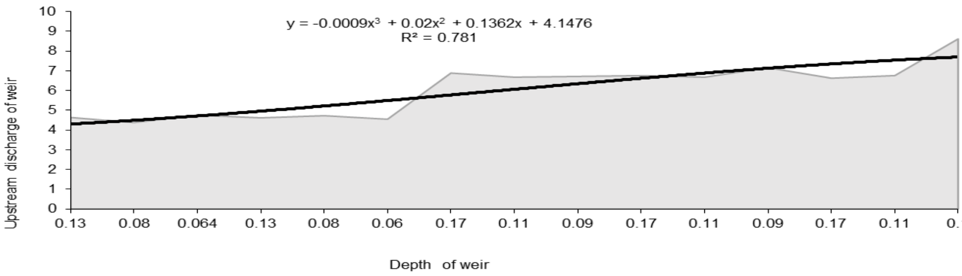

Fig. 20 Upstream of discharge against the depth of weir

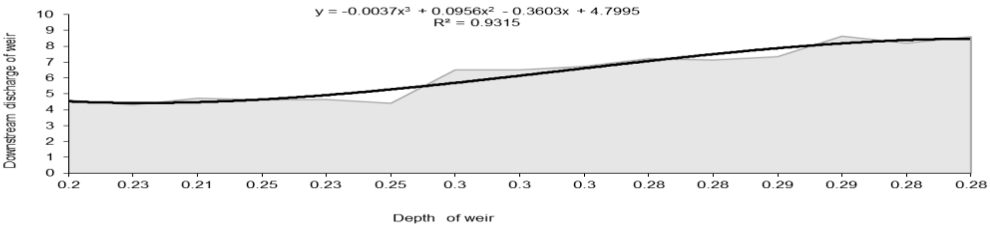

Fig. 21 Downstream discharge against the depth of weir

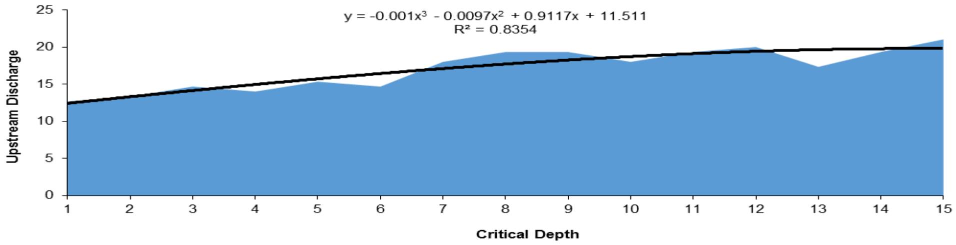

Fig. 22 Upstream of discharge against critical depth

Similarly, the results in Figures 21 and 27 explain the degree of energy head loss due to the hydraulic jump, hence the location is the function of the difference in the height and depth of the flow in the channel. For the weir configuration, the Froude numbers to the jump were within the range of 1.90 to 4.10 ($1.90 < F_{r1} < 4.10$), therefore the flows are supercritical. The downstream and upstream flow Froude numbers range from 0.63 to 0.89 ($0.63 < F_{r2} < 40.89$) and 0.09 to 0.23 ($0.09 < F_{r3} < 0.23$), showing that the flows are subcritical. The energy lost due to the jump as the flow transits itself from supercritical to subcritical flow ranges from 3.20 mm to 41.50 mm (i.e., 3.20 mm $<\Delta E_{,exp}<$ 41.50 mm). $\Delta E_{, theory}$ ranges from -12.91 mm to 17.50 mm (-12.91 mm $<\Delta E_{, theory} <$ 17.50 mm), showing some energy gain instead the graphs are presented in Figures 22 to 29.

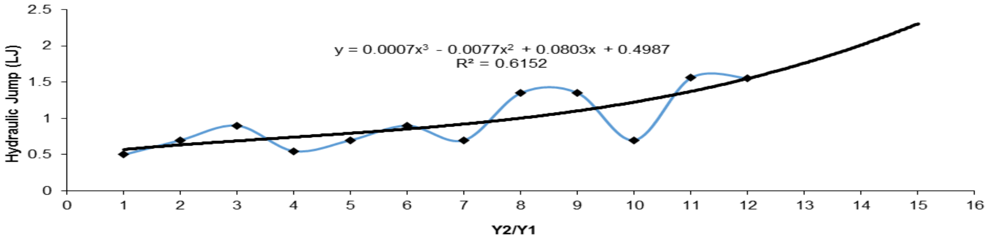

Fig. 23 Graph of the location of jump against sequent depth

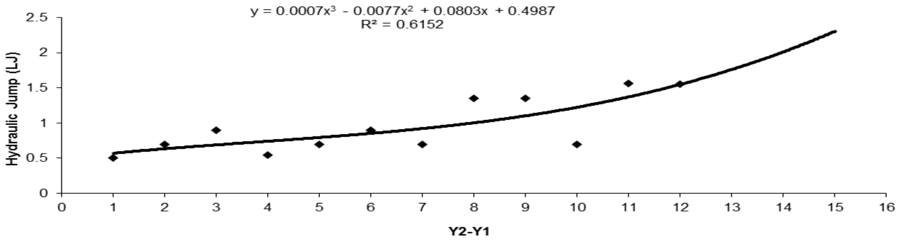

Fig. 24 Graph of the location of jump against depth

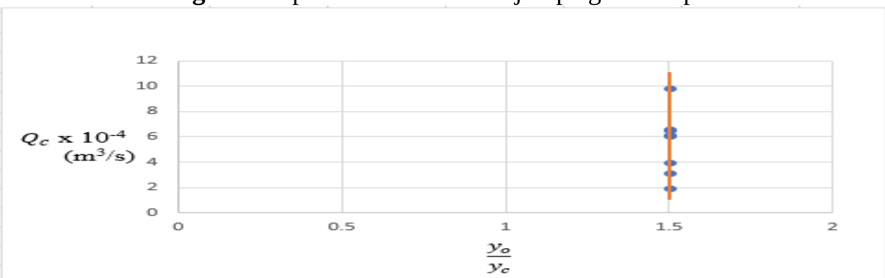

Fig. 25 Critical overflow vs. dimensionless depth

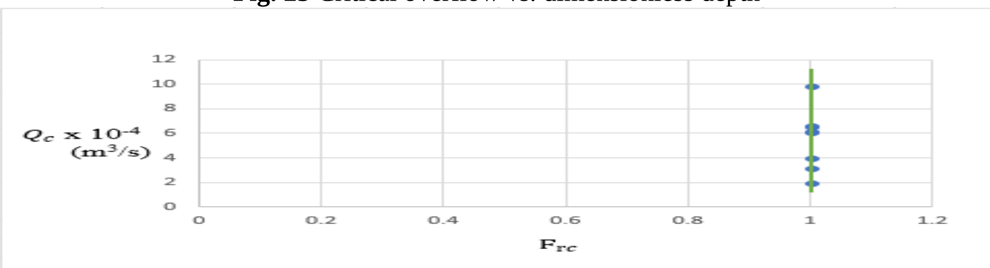

Fig. 26 Critical Overflow vs. overflow Froude number

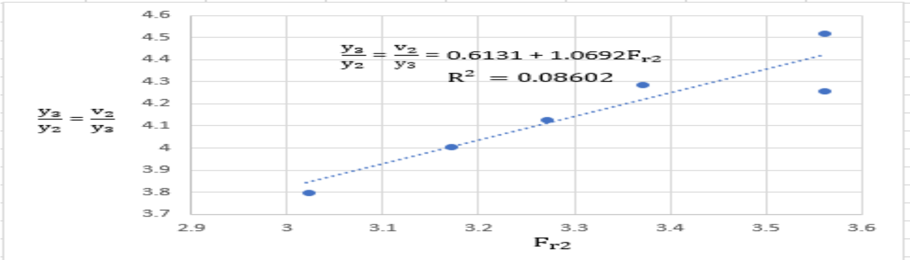

Fig. 27 Sequent Depth ratio against the inflow Froude number (Weir)

Line of perfect agreement

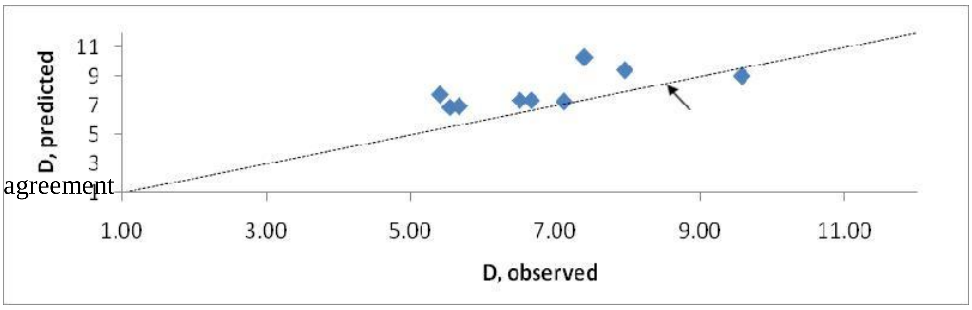

Fig. 28 Comparison between predicted D and observed with a weir drop height

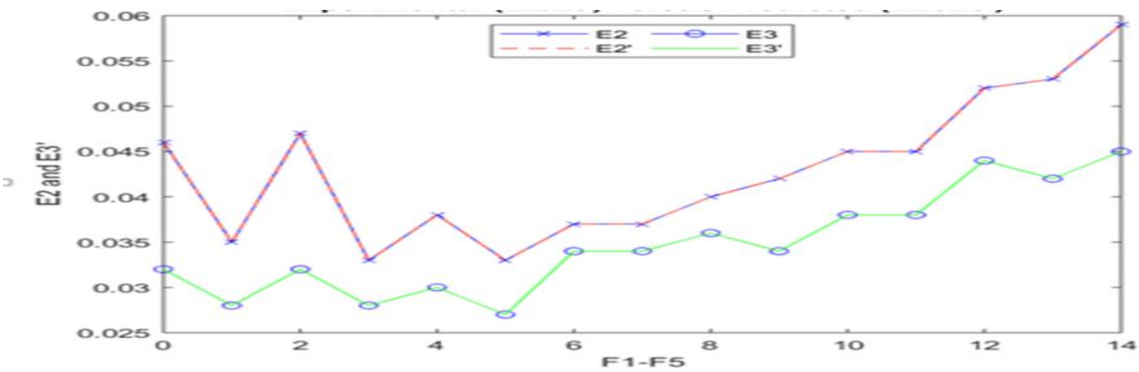

Fig. 29 Energy loss with weir height drop versus predicted energy loss

CONCLUSION

The most significant utilisation of the water driven jump is inside the dissemination of vitality beneath sluiceways, weirs, entryways, and so forth with the goal that shocking scour in the downstream channel is forestalled. The high vitality loss that happens in the water-powered jump has prompted its appropriation as a piece of the vitality dissipator framework under a pressure-driven structure. The downstream part of a water-driven structure where the vitality scattering is purposely permitted to happen with the goal that the flowing stream can securely be directed to the channel beneath is known as a stilling bowl.

A weir is a hydraulic overtopping structure which in general offers the same functions as a dam, but of smaller magnitude (height and length). Figure 1 explains the classification of dams by size. The term low-head dam is associated with weirs which besides have the function of acting as a barrier. Sea lamprey barriers are an example of low-head dams. The Froude numbers from the post-hydraulic jump section within 0.37 to 0.41 ($0.37<Fr_3<0.41$), this shows that the flows are subcritical. The relationship between sequent depth ratio y_3/y_2 and velocity ratio v_2/v_3 is approximately -5024 +1.485 Fr_2 with R^2 =0.9957 indicating that as the sequent depth ratio and velocity ratio increases the inflow Froude number Fr_2 also increases. Accordingly, in the level-bedded constricted flume, the energy loss due to hydraulic jump ranged from -0.001 to 0.001 which shows some energy gain with an increase in the rate of discharge through the flume. The upstream of the flume, the Froude numbers range from 0.038 to 0.052 ($0.038 < Fr_1 < 0.52$), showing that the flows were subcritical. Importantly, in the pre-hydraulic jump section, the Froude numbers between 1.59 t0 1.93 (1.59 $Fr_2 <$ 1.93), which shows that the flows are supercritical and the jumps obtained were weak ones.

More so, in the pre-hydraulic jump section, the Froude numbers range from 3.02 to 3.56 ($3.02 < Fr2 < 3.56$), indicating that the flows are supercritical and the jumps achieved are oscillating ones.The Froude numbers from the post-hydraulic jump section range from 0.56 to 0.68 ($0.56 < Fr_3 < 0.68$), which also shows that the flows are subcritical.

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