Nigerian Journal of Technology (NIJOTECH)
Vol. 34 No. 3, July 2015, pp. 631 – 635

University of Nigeria, Nsukka, ISSN: 0331-8443
www.nijotech.com
http://dx.doi.org/10.4314/njt.v34i3.29

PREDICTION OF INCEPTION LENGTH OF FLOW OVER DIFFERENT STEPPED CHUTE GEOMETRY

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ABSTRACT

This research was performed to develop an inception model to be used over three different chute geometries which was not done by earlier researchers. The inception parameters (roughness Froude number and sine of the chute angles) were determined from the inception data of Munta and Otun. These parameters were analysed using a regression model to form the inception length equation in this study. The results showed that the inception length to the roughness height increases with increase in both roughness Froude number and slope of the chute angle. The results also indicated that for every unit discharge, inclined stepped chute type has the least length of inception compared to the plain and the end-sill chute types; indicating that the point of inception has shifted optimally upstream of the chute in the inclined stepped chute. The developed inception model has insignificant error range values of 0.044-0.89% over the various step chutes under consideration. Inclined step chute is more suitable to be used to safely transmit flood flow downstream of a dam.

Keywords*: stepped chute, skimming flow, inception length, prediction, parameters*

1. INTRODUCTION

The search for effective spillway designs has been ongoing since the very beginning of the building of dams [1]. Stepped spillways have been used for over 2,500 years [2]. The recent technological advance of Roller Compacted Concrete (RCC) dams has increased the interest in stepped spillways [3]. Over a short period, the use of RCC dams and the associated use of stepped spillways for the gravity dams, have gained widespread acceptance; partly due to the intrinsic low-cost and speed of construction [4]. The RCC technique is also adopted increasingly for the rehabilitation of earth and concrete dams. Steps have been added with the RCC technique to dam embankments to allow safe passage of overtopping floods. Thus, the capacity of the spillways can be increased to accommodate extreme hydrological events such as the Probable Maximum Flood (PMF) at little cost [5].

A stepped spillway consists of an open channel with a series of steps that are built into the face (chute) of the spillway. The rough or stepped face of the spillway can dissipate a significant portion of the energy of the flow over its surface. The dissipation of kinetic energy reduces the scour in the natural channel below the structure and hence reduces the cost of the stilling basin. It also eliminates the problem of cavitations on the spillway [1].

For a given slope, the general behavior of the flow over a stepped chute is characterized by three different flow regimes, depending on the discharge. Nappe flow, for low discharges; the flow drops from step to step. The free falling nappe hits directly one step to be deflected to the next one downstream. An air cavity is trapped between the vertical face and the nappe, and if it is not aerated pressure inside this cavity can drop below the atmospheric value [6]. Transition flow, associated with intermediate discharges, the passage from nappe flow to skimming flow is gradual and continuous through a transition regime [7]. Skimming flow is for large discharges. The flow skims as a coherent stream over a pseudo-bottom formed by the outer edge of the steps. Beneath it recirculation cells are trapped inside the step, rotating in a rounded triangular vortex [8].The skimming flow over the stepped chute is categorized into two regions separated by a point called inception; which is identified when the turbulent boundary layer from the floor, at entrance of the stepped chute, intersects the water surface. The boundary layer

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(length of inception) or the non-aerated region has been a valuable parameter to engineers as it is the zone that is prone to cavitation due to high velocity of flow.
Bauer [9] determined the inception length, which is the only available practical method used. Munta and Otun [10] modified Bauer's length to determine the optimal length of inception and length ratio with the former.
The following relations have been used for defining the inception point, distance from just below the crest along the stepped chute.
Chanson [2] presented an equation for determining length of inception of flow over plain step chute of angles

$$27^0 < \theta < 52^0 \; as \; \frac{L}{K} = 9.719(sin\theta)^{0.076} F_*^{0.713} \quad (1)$$

Boes [11] also developed inception model of flow for plain step chute with angles $27^0 < \theta < 52^0$ as

$$\frac{L}{K} = 9.72(Cos\theta)^{1.29} F_*^{0.86} \quad (2)$$

Boes and Hager [12] also used Equation (3) for prediction the inception length of flow over plain step chute with angles $26 < \theta < 55^0$

$$\frac{L}{K} = \frac{5.90\,(Cos)^{0.2} F_*^{0.80}}{(sin\theta)} \quad (3)$$

Where L_i is the distance from the start of growth of boundary layer to the inception point of air entrainment, $K_s = S_n \cos\theta$, S_n is the step height, $F_* = q/\sqrt{g\, sin\theta K^3}$ is the roughness Froude number and $26 < \theta < 55^0$, which is the range for the inception equations, where and θ is the chute angle. Equations (1, 2 and 3) were all for plain stepped chute geometry; inception equation that involves different stepped cute geometries is lacking. The aim of this research was to develop an empirical equation, from the inception data generated by Munta and Otun [10], used for the prediction of inception length of flow over any of the three stepped chute geometry (plain, end-sill and inclined chute).

2. MATERIALS AND METHODS

2.1 Physical models

The physical models were fabricated and installed at the Hydraulics Laboratory of the Department of Water Resources and Environmental Engineering, Ahmadu Bello University Zaria-Nigeria. Six models designated as Stepped Chute Models (SCM) of different chute geometry were selected from the ones produced by Munta and Otun [10] for the purpose of optimization of the inception parameters and can be viewed in Figure 1 and Table 1.

2.2 Inception length

The inception length used in this study was determined by Munta and Otun [10], as can be viewed on Table 2.

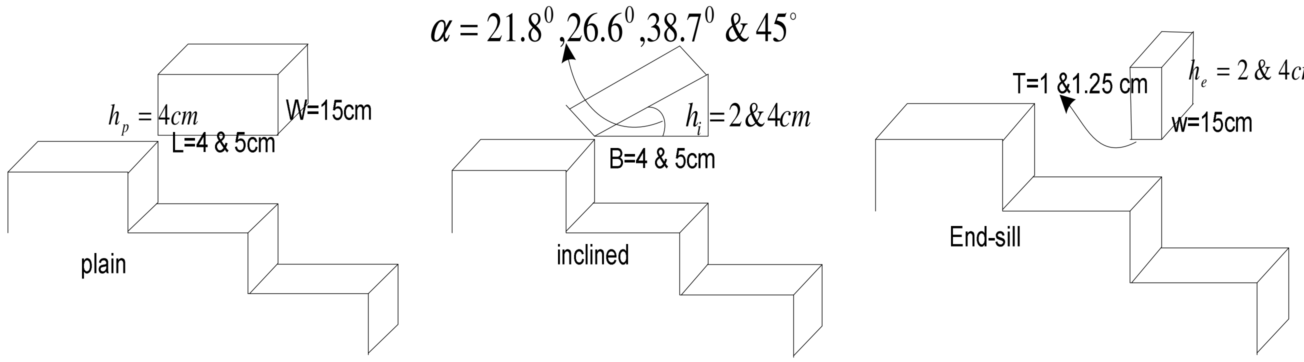

Figure 1: Details of the stepped chute models [10])

Table 1: Different stepped chute model used [10]

Chute configuration	Model No.	Model height (cm)	S_h (cm)	K_s(cm)	θ(deg)	L(cm)
Plain	SCM-1	104	4	3.12	38.7	166.3
	SCM-2	104	4	2.83	45	147
End-sill	SCM-3	104	8	5.47	38.7	166.3
	SCM-4	104	8	4.80	45	147
Inclined	SCM-5	104	8	6.24	38.7	166.7
	SCM-6	104	8	5.66	45	147

Table 2: Inception length used [10]

	SCM-1					SCM-2				
Plain	q E-3(m^2/s)	26.1	31.5	35.6	43.4	q E-3(m^2/s)	26.1	31.5	35.6	43.4
	L_e(cm)	51.1	58.5	63.8	73.8	L_e(cm)	49.3	56.4	61.7	71.2
	SCM-3					SCM-4				
End-sill	q E-3(m^2/s)	26.1	31.5	35.6	43.4	q E-3(m^2/s)	26.1	31.5	35.6	43.4
	L_e(cm)	48.2	55.4	60.8	70.1	L_e(cm)	46.9	53.8	58.7	67.9
	SCM-5					SCM-6				
Inclined	q E-3(m^2/s)	26.1	31.5	35.6	43.4	q E-3(m^2/s)	26.1	31.5	35.6	43.4
	L_e(cm)	47.6	54.9	60.1	69.3	L_e(cm)	46.2	53.0	57.8	67.0

2.3 Development of the inception length equation

The length of inception L_e used in this study is depended upon acceleration due to gravity g, step roughness height, K_s discharge per unit width q, and slope of the stepped chute, $\sin\theta$.

$$L_e = f(g, q, K_s sin\ \theta) \quad (4)$$

$$or \quad f_1(L_e = g, q, K_s, sin\ \theta) = 0 \quad (5)$$

Equation (5) may be re-written as:

$$f_1(\pi_1, \pi_2, \pi_3) = 0 \quad (6)$$

gK_s in equation (5) are considered as repeating variables hence,

$$\left.\begin{aligned} \pi_1 &= g^{\alpha} K_s^{\beta} L_e \\ \pi_2 &= g^{\alpha} K_s^{\beta} q \\ \pi_3 &= g^{\alpha} K_s^{\beta} \sin\theta \end{aligned}\right] \quad (7)$$

α and β in Equation (7) are determined by the principle of dimensional homogeneity.

Substituting the values of π_1, π_2 and π_3 in Equation (6); the functional relationship becomes:

$$f_1\left(\frac{L_e}{L_s}, g^{-\frac{1}{2}} K_s^{-\frac{3}{2}} q, sin\theta\right) = 0 \quad (8)$$

$$or\ \frac{L_e}{L_s} f_2\left(\frac{q}{\sqrt{gK^3}}, sin\theta\right) \quad (9)$$

where, f_2 is a "function of"; Equation (9) may be rewritten as

$$\frac{L_e}{L_s} = \alpha_1 (sin\theta)^{\alpha 2} F_e^{\alpha 3} \quad (10)$$

Taking the logarithm of the terms in Equation (10), we have

$$Log\left(\frac{F_e}{K_s}\right) = Log\ (\alpha_1) + \alpha_2\ Log(Sin\theta) + a_3\ Log\ (F_e) \quad (11)$$

where $F_e = q/\sqrt{gK_s^3}$ = roughness Froude number, a_1, a_2 and a_3 are determined through a regression model.

3. RESULTS AND DISCUSSION

3.1 Inception model

The inception parameters (roughness Froude number and sine of the chute angles) were determined, as can be viewed in Figures 2a to 2d; which were analysed using a regression model (summary Table 3) to obtain the values of the unknown in Equation (10). a_1= antilog K, where K is a constant in Table 3, a_2 = -0.355, a_3 = 0.728 and R^2 is the reliability of the model used.

Results in Figures 2a to 2d, showed that L_e/K_s increases as both F_e and sinθ increase; which agreed with the statement made by Baylar et al [13] that for all experiments, the ratio of the non-aerated length to stepped height increases as the roughness Froude number increases but decreases as the chute angle increases. Also, this is attributed to the fact that Froude number and the slope are the functions of velocity; hence increase in flow velocity increases the chances of a spillway to be prone to cavitation. For both chute angles, L_e/K_s for plain step chute are higher than that of the end-sill and least in inclined chute.

Table 3: Values of unknown in Eq. (10)

parameters	coefficients	R^2	error
K	1.010		
F_e	0.728	0.9963	0.0008285
Sinθ	-0.355		

3.2 Model validation

The developed inception length in this study was validated; where the experimental values were compared with the calculated values (Figures, 3a to 3c). The percentage errors were between 0.044-0.89%; which shows that there were good agreement between the experimental values and the ones calculated from the predicted equation. Furthermore, the predicted equation in this study was compared with that of [2, 11, 12], Figure 4, and there were good agreement between them also.

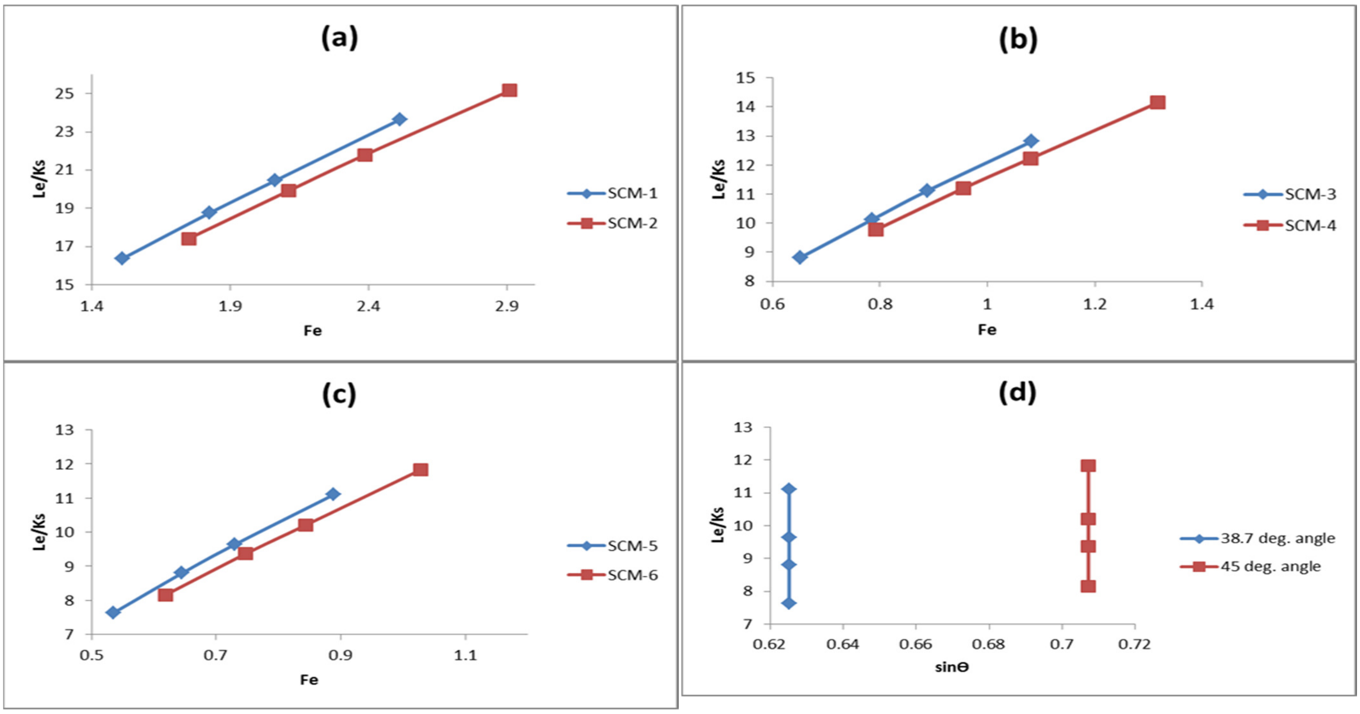

Figure 2: Length of inception to stepped roughness height as a function of roughness Froude number for (a) plain chutes; (b) end-sill (c) inclined and slope of the chute angle, (d)

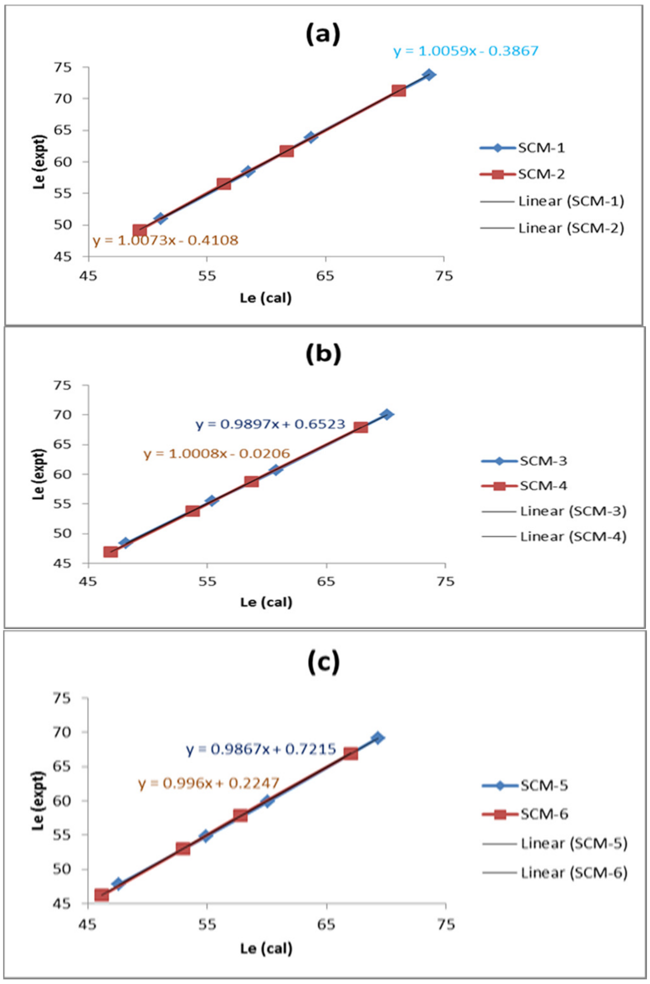

Figure 3: Comparison of measured inception length values with those from Eq. (8); (a) plain chute (b) end-sill and (c) inclined.

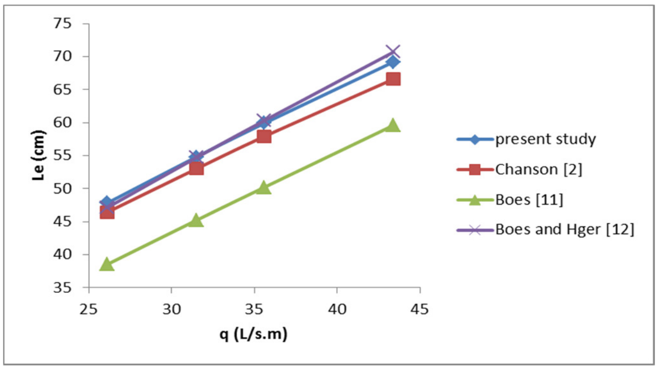

Figure 4: Comparison of Eq. (10) with those of [2, 11,12]

4. CONCLUSION

This study used some inception data generated by Munta and Otun [10] to develop an empirical equation for the length of inception of flow over different step chute geometries (plain, end sill and inclined) which has not been done by previous researchers. Only inception length equations for plain step chutes were developed earlier. Based on these findings, the following conclusions can be drawn:

1. L_e/K_s increases with increase in both F_e and $\sin\theta$
2. For both chute angles used, L_e/K_s are highest on plain step chutes and lowest on inclined types.
3. The developed inception model can adequately be employed on all the three step chute configurations because the percentage errors are between 0.044-0.89%.

4. Inclined step chutes would be preferred than the other two types, for the inception length of flow over them are shifted upstream of the chute; which could be incorporated to a downstream face of hydraulically unsafe embankment dams, as emergency spillway, to safely release a flood flow, such as Probable Maximum Flow.

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