Experimental Study on the Limits of Flow Regimes for Different Configurations of Stepped Spillway

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Abstract

Flow over a stepped spillway can be divided mainly into three flow regimes that are nappe, transition and skimming depending upon the discharge and the dimensions of the stepped spillway. The determination of the flow regime is a very important aspect in the design of stepped spillway due to the different properties for each flow regime. Experimental work on flow regime limits for stepped spillways has been conducted using twelve stepped spillway models. The models were manufactured with three downstream slope angles: 25, 35 and 45°, and four numbers of steps: 5, 10, 15 and 20. Five configurations of steps were tested, which are conventional Flat, pooled, porous end sills, pooled with gabions and porous end sills with gabions. The results revealed that the end sills highly affect flow regime type; this effect is primarily for the lower limits of skimming flow. Using end sills increases the range of transition flow regime (by increasing the lower limit of skimming flow) as well as increases the instabilities that occur in this flow regime. Gabions reduce the effects of end sills on the lower limit of skimming flow regime to near the limit of flat steps. New empirical equations were suggested based upon the experimental results.

Keywords: Flow Regimes, Gabions Steps, Nappe Flow Regime, Pooled Steps, Skimming Flow Regime, Stepped Spillway, Transition Flow Regime.

1. Introduction

The stepped spillway is a spillway whose face is provided with a series of steps from near the crest to the toe, they have gained popularity with modern construction techniques including roller compacted concrete (RCC) and gabions (Chanson 2001, Felder and Chanson 2013, Guenther et al. 2013) In the last two decades, there has been an increasing interest in the stepped spillways in various laboratories around the world (Khatsuria 2005). The stepped spillway design is not limited to flat uniform steps, some prototype stepped chutes were designed with pooled steps (e.g. Sorpe dam, Germany), alternate sills (e.g. Neil Turner stepped weir, Australia) and weir structures designed with gabion steps, etc. (Chanson and Gonzalez 2004, Felder and Chanson 2013), the alternative stepped designs are poorly understood (Felder and Chanson 2013). In recent years, the flows on pooled stepped spillways were researched in a few studies (Felder et al. 2012). Also, the hydraulics of gabions stepped spillway has received less attention due to the complexity to evaluate the flow patterns and flow resistance (Chinnaarasri et al. 2008). The advantages of gabions are: low cost, ease of installation, flexibility, and ease of maintenance (USACE 1986). With proper construction practice, spillways having a stepped downstream face built of gabions can withstand floods of up to 3 m^2/s without damage (Peyras et al. 1992). Stone size and shape have little influence on the energy loss and flow velocity as compared to the increasing effect of the weir slope (Chinnaarasri et al. 2008).

Many relationships have been developed to predict the limits of flow regimes for conventional flat stepped spillway. The flow should be distinctly either in the nappe flow or the skimming flow regime for the design discharge and the safety check flood (Boes and Hager 2003). Due to the high instabilities and the impact load caused by the transition flow regime, researchers suggested a safety factor of 10-20% or even more to be added to the lower limit of skimming flow regime or subtracted from the upper limit of nappe flow regime determined by empirical equations (e.g. Boes 2012). Modern stepped spillways are designed for the skimming flow regime (Chanson 2001). The conservative design with the mentioned safety factor is suggested to avoid transition flow regime while it cannot be avoided if the chute is designed for skimming flow for un-gated spillways (Boes and Hager 2003).

This study aims to contribute in the developing of a design guide for the limits of flow regimes on stepped spillways for five configurations of steps, which are: conventional Flat, pooled, porous end sills, pooled with gabions and porous end sills with gabions. Another objective is the introducing of configurations that may reduce the transition flow instabilities and the hydraulic loads on the concrete face of the RCC stepped spillways.

2. Experimental Work

Twelve stepped spillway models were made from wood and coated with varnish to avoid wood swelling of water and to increase its smoothness. The models have vertical upstream face with three downstream slope angles (25, 35 and 45°). For each slope, four models were designed as ogee stepped spillway with 5, 10, 15 and 20 steps. All models have 0.3 m width and 0.3 m height (from the base to the upper point in the crest).

The tests were carried out in a recirculating flume located at the fluid laboratory of Engineering College, Babylon University, Iraq (Photo 1). The flume is 10 m length and 0.3 m width. It has transparent side walls with height of 45 cm. The flume has a pump with a discharge capacity of 30 l/s, a flow meter is installed on its pipeline for measuring the discharge of the passing flow. Two movable carriages with point gauges were mounted on brass rail at the top of flume sides, which have an accuracy of 0.1 mm.

Photo 1: The used flume (Civil Engineering Department, Engineering College, Babylon University, Iraq).

The experiments were conducted for fifteen discharges runs ranging from 0.9 to 9.3 l/s (Table 1). This range was satisfying the need of this study.

The used end sills are of height equals to half step height i.e.: $h_e = 0.5$ h; h_e is the end sill height and h is the step height. Four thicknesses of end sills are used, that are: 0.5, 1, 3 and 5 mm for the models having number of steps of 5, 10, 15 and 20 steps respectively.

The gabion dimensions are $\left(h_e \times (l\text{-t}) \times 0.3\text{ m}\right)$, where h_e: is the end sill height, l: is the step length, and t: is the end sill thickness. During testing runs, the gabions were placed into the steps and removed alternately. Wire mesh of rhombus shape with side length of 0.68 cm and diagonals of 0.65 and 1.2 cm has been used. The wire mesh boxes were filled with gravel of size 0.95-1.27 cm and porosity of 41%. These types of wire mesh and gravel were selected taking into account that the filled material should be larger than 1.5 times the wire mesh opening and the porosity values between 38 and 42 are preferable as suggested by previous studies (such as Stephenson (1979) and Kells (1993) cited in Salmasi et al. 2012).

Table 1: Discharges used in the 15 runs.

Run No.	Q (l/s)	q (l/s.m)	Run No.	Q (l/s)	q (l/s.m)
1	0.90	3.00	9	5.70	19.00
2	1.50	5.00	10	6.30	21.00
3	2.10	7.00	11	6.90	23.00
4	2.70	9.00	12	7.50	25.00
5	3.30	11.00	13	8.10	27.00
6	2.90	13.00	14	8.70	29.00
7	4.50	15.00	15	9.30	31.00
8	5.10	17.00			

3. Observations

Many observations are taken by using digital video-camera Nikon™ D3100 (Frame advance rate: 3 fps, Shutter Speed: 1/4,000 to 30 s) in addition to the visual observations, these observations can be summarized as follows:

3.1. Pooled stepped models (non-porous end sills) have larger ranges of transition flow regimes rather than all the tested configurations. It seems that the end sills affect primarily the lower limit of the skimming flow regime.

Photo 2: Flow regimes on flat and pooled stepped models (θ= 45 °, 5 steps, run no. 9).

3.2. Gabions reduce the effects of end sills on the lower limit of skimming flow regime to near the limit of flat steps

Photo 3: Flow regime and instabilities on pooled steps with and without gabions (θ=25°, 5 steps, run no. 9).

3.3. For porous end sills, there is an additional type of flow, which is the flow through pores (Photo 4). This type of flow was included with the typical flow regimes. It can be identified visually for low discharges in nappe flow regime with a same behaviour.

Photo 4: Flow through pores.

4. Data Analysis

4.1 Upper Limit of Nappe Flow Regime

The equations selected for comparing with the present study data are presented in Table 2 (NA refers to the nappe flow regime and SK is the abbreviation of skimming flow regime).

Table 2: The studied relationships of flow regimes limits.

Researcher	Equation	Case
Yasuda and Ohtsu (1999)	$\frac{h}{y_c}=1.4(1.4-\tan\theta)^{-0.26}$	NA-Flat steps
Chanson (2001a)	$\frac{y_c}{h}=0.89-0.4\left(\frac{h}{l}\right)$	NA-All cases
Chinnarasri (2002):	$\frac{y_c}{h}=0.98(0.55)^{h/l}$	NA-Flat steps
Chanson and Toombes (2004)	$\frac{y_c}{h}=0.9174-0.381\frac{h}{l}$	NA-Flat steps
Chinnarasri and Wongwises (2004)	$\frac{y_c}{h}=0.927-0.005\alpha-0.388\left(\frac{h}{l}\right)$	NA-All cases
Yasuda and Ohtsu (1999)	$\frac{h}{y_c}=\frac{7}{6}\left(\frac{h}{l}\right)^{\frac{1}{6}}$	SK-Flat steps
Chanson (2001a)	$\frac{y_c}{h}=1.2-0.325\left(\frac{h}{l}\right)$	SK-All cases
Boes and Hager (2003)	$\frac{y_c}{h}=0.91-0.14\frac{h}{l}$	SK-Flat steps
Chanson and Toombes (2004)	$\frac{y_c}{h}=\frac{0.9821}{\left(\frac{h}{l}+0.388\right)^{0.384}}$	SK-Flat steps
Chinnarasri and Wongwises (2004)	$\frac{y_c}{h}=(0.844+0.003\alpha)\left(\frac{h}{l}\right)^{-0.153+0.004\alpha}$	SK-All cases
Chinnarasri et al. (2008)	$\frac{y_c}{h}=0.61\left(\frac{h}{l}\right)^{-0.26}$	SK-Gabion steps

4.1.1. Suggested Relationships

The following relationships are suggested for the upper limit of nappe flow regime on stepped spillways with downstream slope angle 25° ≤ θ ≤ 45°. The relationships obtained using Microsoft Excel and Statistica (version 12) software programs. All symbols are defined in appendix 1.

Table 3: Suggested empirical equations for the upper limit of nappe flow regime.

Suggested Equations	R^2 or R	Case
$\frac{y_c}{h} = 0.5478 \left(\frac{h}{l}\right)^{-0.3575}$	R^2= 0.8025	Flat
$\frac{y_c}{h} = 1.0674 - 0.2120\ \alpha + 5.1234\ \frac{h}{l}$	R= 0.8422	Pooled
$\frac{y_c}{h} = 1.3754 - 0.4768\ \alpha + 11.9452\ \frac{h}{l}$	R= 0.8829	Porous end sills
$\frac{y_c}{h} = 0.7580 - 0.1939\ \frac{h}{l}$	R= 0.7741	Pooled with gabions
$\frac{y_c}{h} = \frac{h/l}{2.2308 \frac{h}{l} - 0.3506}$	R^2= 0.7071	Porous end sills with gabions

4.1.2. A Comparison with Previous Relationships

The scatter diagrams of the current study data and the data obtained from the relationships in Table 2 are shown in the following figures:

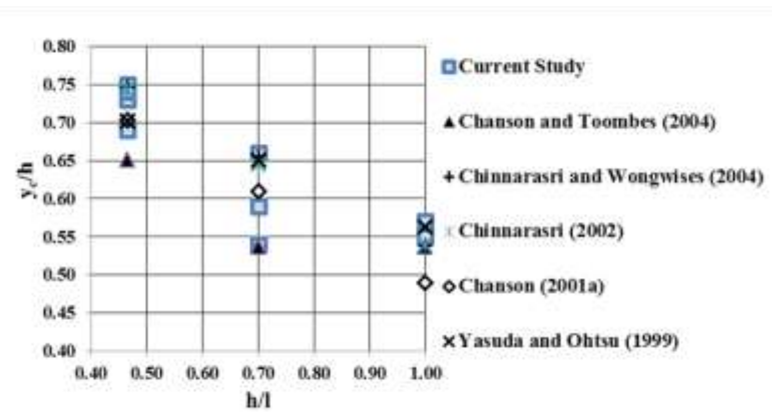

Figure 1: Nappe flow regime upper limit-flat steps.

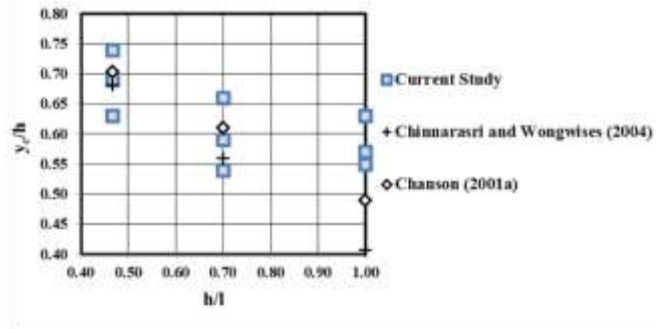

Figure 2: Nappe flow regime upper limit-pooled steps.

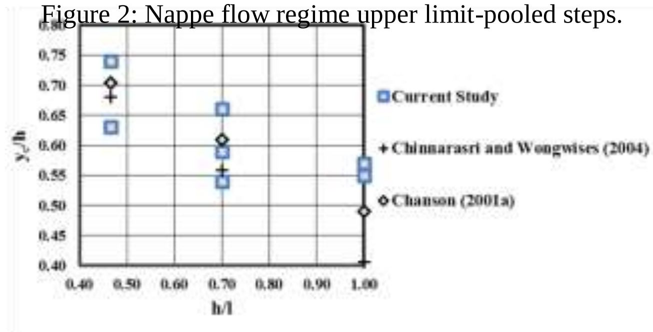

Figure 3: Nappe flow regime upper limit-pooled with gabions.

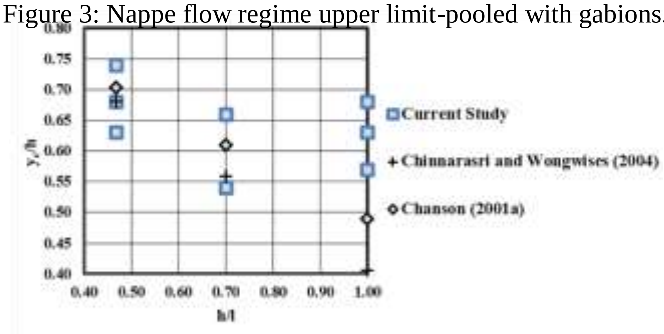

Figure 4: Nappe flow regime upper limit-porous end sills.

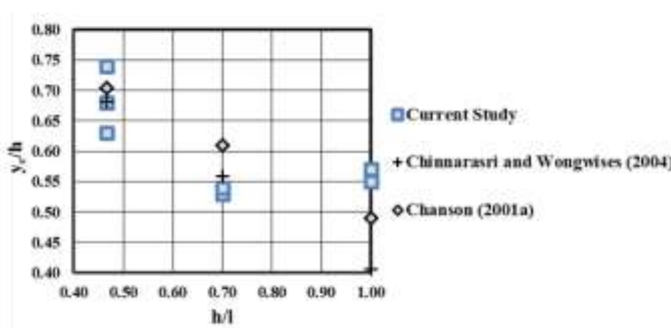

Figure 5: Nappe flow regime upper limit-porous end sills with gabions.

4.2 Lower Limit of Skimming Flow Regime

4.2.1 Suggested Relationships

The following relationships are suggested for the lower limit of skimming flow regime on stepped spillways with downstream slope angle $25° \leq \theta \leq 45°$, the relationships obtained using Microsoft Excel and Statistica (version 12) software programs.

Table 4:

Suggested Equations	R^2 or R	Case
$\frac{y_c}{h} = 1.2090 - 0.4349\frac{h}{l}$	R= 0.8340	Flat
$\frac{y_c}{h} = \frac{h/l}{5.2321\alpha - 0.2801}$	R^2= 0.7049	Pooled
-	Weak correlation between data	Pooled with gabions
-	Weak correlation between the data	Porous end sills
-	Weak correlation between the data	Porous end sills with gabions

Suggested relationships for lower limit of skimming flow.

4.2.2 A Comparison with Previous Relationships

The scatter diagrams of the current study data and the data obtained from the relationships in Table 2 are presented in the following figures:

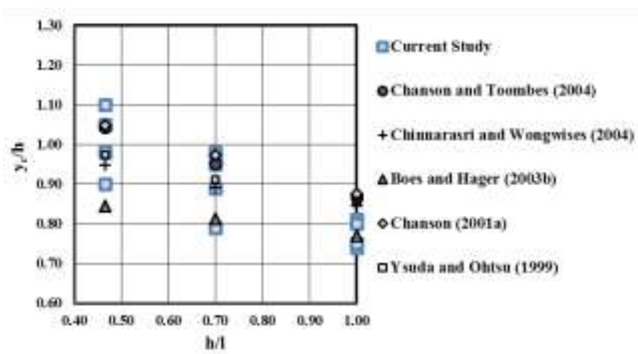

Figure 6: Skimming flow regime lower limit-flat steps.

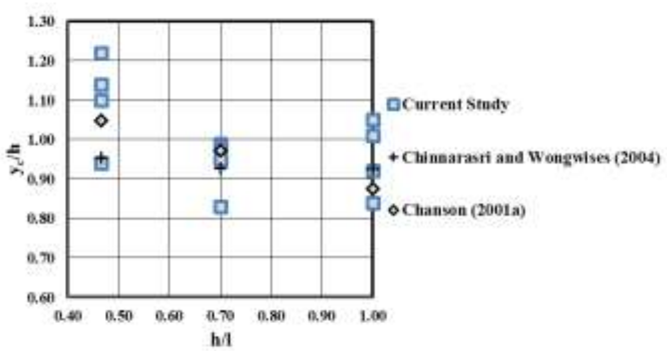

Figure 7: Skimming flow regime lower limit-pooled steps.

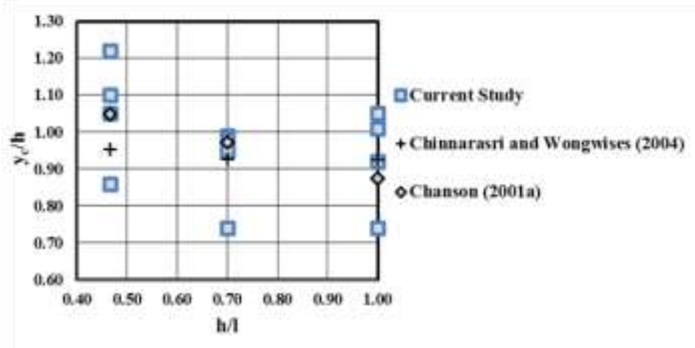

Figure 8: Skimming flow regime lower limit-pooled with gabions.

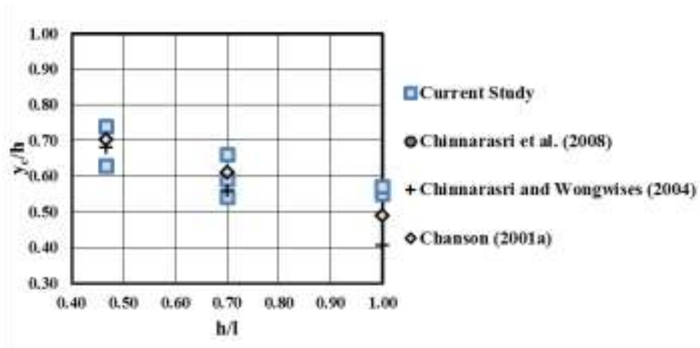

Figure 9: Skimming flow regime lower limit-porous end sills.

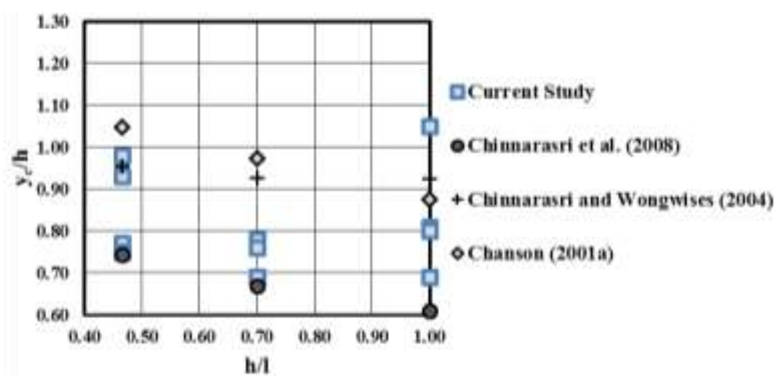

Figure 10: Skimming flow regime lower limit-porous end sills with gabions

5. Conclusions

The determination of the flow regime on stepped spillway is a very important aspect in the design of stepped spillway due to the different properties for each flow regime. Experimental work was performed using twelve stepped spillway models to study flow regime limits for stepped spillways. The models were manufactured with three downstream slope angles: 25, 35 and 45°, and four numbers of steps: 5, 10, 15 and 20. Five configurations of steps were tested, which are conventional Flat, pooled, porous end sills, pooled with gabions and porous end sills with gabions.

The results of experimental work were used to form new empirical equations for the limits of flow regimes for the configurations tested. It can be concluded that the end sills highly affect flow regime type; this effect is primarily for the lower limits of skimming flow. Using end sills increases the range of transition flow regime (by increasing the lower limit of skimming flow) as well as increases the instabilities that occur in this flow regime. Gabions reduce the effects of end sills on the lower limit of skimming flow regime to near the limit of flat steps.

6. References

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Appendix 1: Symbols

Symbol	Unit	Definition
Fr_*	[–]	Roughness Froude number = $q / \sqrt{g (\sin\theta)(h \cos\theta)^3}$
g	[m/s²]	Gravity acceleration
h	[m]	Step height
l	[m]	Step width
h_e	[m]	End sill height
Q	[m^3/s]	Discharge
q	[m^2/s]	Discharge per unit width
R^2	[–]	Coefficient of determination
y_c	[m]	Critical flow depth above spillway crest
θ	Degree	Downstream slope angle
α	[m]	$Tan^{-1}(h_e/ l)$ (it is zero for a horizontal step).