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รายงานวิจัยฉบับสมบูรณ์

โครงการ: การศึกษาจากการทดลองของสภาพการไหลในรางขั้นบันได
แบบความชันย้อนกลับ

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Abstract

This research report presents new experimental data on water flow on stepped chutes with upward inclined steps. The slopes of the chutes are 30°, 45°, and 60° while the upward angles of the inclined steps are 10°, 20°, and 30°, respectively. Classifications of flow patterns by empirical correlations are presented. Based on dimensional analysis, the important parameters are analyzed and the relevant dimensionless parameters are formed. The energy loss and outlet velocity are strongly influenced by the Drop number and the slope of the stepped chutes. As the Drop number increases the energy loss ratio decreases. At identical Drop number the energy loss ratio on the milder slope is greater than on the steeper. The adverse slope of the inclined steps increases the energy loss ratio and decreases the outlet velocity by less than 10 %. To estimate kinetic energy ratio, an empirical correlation is proposed.

บทคัดย่อ

รายงานวิจัยฉบับนี้ได้นำเสนอข้อมูลของผลการทดลองใหม่ของการไหล บนรางขั้นบัน-ไดที่มีความลาดชันแบบย้อนกลับ ความลาดเอียงของรางคือ 30°, 45°, และ 60° ขณะที่มุมลาดเอียงของขั้นบันไดคือ 10°, 20°, และ 30° ตามลำดับ การแบ่งประเภทของการไหลด้วยสมการแบบ empirical correlations ได้ถูกนำเสนอ ตัวแปรที่สำคัญได้ถูกวิเคราะห์ด้วยวิธีมิติทำให้เกิดเทอมไร้มิติที่เกี่ยวข้องกับลักษณะการไหล การสูญเสียพลังงานและความเร็วการไหลที่ท้ายรางถูกกำหนดอย่างมาถจาก Drop number และความลาดเอียงของรางขั้นบันได เมื่อ Drop number เพิ่มขึ้น สัดส่วนการสูญเสียลดลง ที่ค่า Drop number หนึ่งๆ พบว่าสัดส่วนการสูญเสียพลังงานบนรางลาดเอียงน้อยจะมากกว่าที่พบบนรางลาดเอียงที่มากกว่า ความลาดเอียงย้อนกลับของขั้นบันไดทำให้สัดส่วนการสูญเสียพลังงานเพิ่ม และลดความเร็วท้ายรางลง 10% เพื่อการประมาณสัดส่วนพลังงานจลน์ สหสัมพันธ์ได้ถูกนำเสนอ

Executive Summary

Stepped chutes are useful in civil engineering applications such as drainage systems in mountainous areas and emergency spillways over downstream faces of embankment dams. Over the last two decades, stepped chutes have regained popularity due to the evolution of roller compacted concrete (RCC) dams. Besides the ease of construction and maintenance, one of the advantages over the plain-bed chute is enhanced energy dissipation. As a result the flow leaves the stepped chute at a lower velocity and a smaller energy dissipator is required.

The objective of this study is to conduct experiments on stepped chutes with inclined steps. The results include the prediction of the onset of skimming flow, the evaluation of the energy dissipation and outlet velocity in dimensionless form. These results are compared with other researches relating to stepped chutes with horizontal steps.

In the experiments, water was pumped from a laboratory sump to a V-notched weir tank from which water entered the stepped chute through an approach channel. At the bottom of the stepped chute, a horizontal outlet carried the water back to the sump. The discharge, which varied from 4 to 68 l/s (0.01 to 0.17 m^2/s), was measured by the V-notch. The stepped chutes made of plexiglass had a width of 0.40 m and consisted of 20 steps. The slopes of the stepped chutes from the horizontal, α, were 30°, 45°, and 60°. The total drop heights of the stepped chutes, H_T, were 1.50, 2.12, and 2.60 m, respectively. The dimensions of the step can be defined as h/l, wherein h is the step height and l is its horizontal step length. To investigate the effect of step inclination, three upward angles of inclined steps (θ) were tested, i.e. 10°, 20°, and 30°.

The flow regimes on stepped chutes with inclined steps can be classified as those found in horizontal stepped chutes (Chanson 2002). For small discharge, free-falling nappe was found at the brink of the inclined step while hydraulic jump was observed on the inclined step face. For intermediate discharge, the succession of free-jet was disappeared. The free surface of the flow was wavy with spray. For large discharge, the free surface of the flow was smooth and air entrainment was small.

Comparison between flow on horizontal steps and inclined steps shows that the upward angle of the inclined step has no effect on the upper limit of nappe flow, but gives a small increment of the lower limit of skimming flow. When the angle of the inclined steps increases, the lower limit of skimming flow slightly increases. This is caused by the relative increase of the elevation of the outer step edge. This results in

an increase of the space of the pool height and the air pocket under the falling jet of nappe flow. Therefore, more discharge is needed to establish the onset of skimming flow. This result is opposed to the data of Essery and Horner (1978) for inclined steps due to a different assumption of the onset of skimming flow.

By empirical correlation, the maximum discharge for nappe flow regime and the minimum discharge required for the onset of the skimming flow regime are as follows:

$$\frac{d_c}{h} = 0.927 - 0.005\,\theta - 0.388\left(\frac{h}{l}\right) \tag{1}$$

$$\frac{d_c}{h} = \left(0.844 + 0.003\,\theta\right)\left(\frac{h}{l}\right)^{-0.153+0.004\theta} \tag{2}$$

where θ is the angle of upward inclined step $(0.1 \le h/l \le 1.73)$.

The energy loss ratio E_L/H_T decreases as the drop number increases. According to the criteria for nappe flow and skimming flow regimes on stepped chutes, the variations of E_L/H_T with q^2/gH_T^3 in different flow regimes are distinctively different. It should be noted that the range of transition flow on stepped chutes of 60° is large. This is because the flowing water splashes and streamlines are not parallel due to the water impact along the outer edge of the steps.

In the nappe flow regime where the drop number is very low, E_L/H_T decreases rapidly as q^2/gH_T^3 increases and the angle of the inclined step has a little effect upon E_L/H_T, especially for chutes with milder slopes. The angle of inclined step increases the energy dissipation by less than 3 % as most of the flow energy is dissipated due to jet breakup and jet mixing on the step and the formation of hydraulic jump on the step.

In the skimming flow regime, E_L/H_T gradually decreases toward a constant value as q^2/gH_T^3 increases. It can be observed that a higher angle θ increases E_L/H_T. An inclined step increases the energy dissipation by about 6 % of H_T (depending on θ). As the upward angle of the inclined steps increases, the energy loss increases due to the obstruction of the steps to the flow direction producing more spray and the recirculation vortices being trapped on the chute steps. Larger flow circulations are found and they are more stable than those in the smaller angles of inclined steps. More energy is therefore dissipated on this kind of structure.

The effect of the chute slope, α, for the same q^2/gH_T^3, the milder chute slope gives a greater energy loss ratio. At the highest q^2/gH_T^3, the value of E_L/H_T for $\theta = 0°$ (horizontal step) to $\theta = 30°$ (30 degree angle of inclined step) for $\alpha = 30^{\circ}$ varies from 0.71 to 0.74, while for $\alpha = 45^{\circ}$ and 60° this ratio varies from 0.68 to 0.74 and from 0.67 to 0.73, respectively.

Another approach to estimate the energy loss on chutes is the comparison between the ratio of energy loss to the total head (E_L/E_O) and the ratio of the critical flow depth to the step height (d_c/h) (Christodoulou 1993). It is found that the energy ratio decreases when the discharge increases which is in the same trend when the drop number is applied.

The flow velocity V_T at the end of the chute can be expressed in dimensionless form. It was found that the velocity ratio $\left(V_T / \sqrt{gH_T}\right)$ increases with increasing drop number for every chute slope and angle of inclined step. The observed data can be represented by the following logarithmic correlation

$$\frac{V_T}{\sqrt{gH_T}} = 0.131 \ln\left(\frac{q^2}{gH_T^3}\right) + 0.036 - 0.0009\,\theta \qquad (3)$$

As compared with the horizontal steps, the $\left(V_T / \sqrt{gH_T}\right)$ ratio is smaller because of higher energy loss on the stepped chutes with inclined steps. The kinetic energy ratio increases almost linearly with q^2/gH_T^3 and agrees reasonably well with the variation of E_L/H_T with q^2/gH_T^3. As the energy loss decreases when q^2/gH_T^3 increases, the remaining kinetic energy at the chute outlet increases. In the nappe flow regime, the kinetic energy at the outlet for all cases is small and almost the same because most of the flow energy is dissipated along the stepped chutes. In the skimming flow regime, the kinetic energy at the chute outlet with inclined steps is less than for the horizontal stepped chutes because more flow energy is dissipated.

เนื้อหางานวิจัย

Introduction

Stepped chutes are useful in civil engineering applications such as drainage systems in mountainous areas and emergency spillways over downstream faces of embankment dams. Over the last two decades, stepped chutes have regained popularity due to the evolution of roller compacted concrete (RCC) dams. Besides the ease of construction and maintenance, one of the advantages over the plain-bed chute is enhanced energy dissipation. As a result the flow leaves the stepped chute at a lower velocity and a smaller energy dissipator is required.

The step geometry can be classified as horizontal, pooled, inclined, or of gabion-type. A number of experimental studies on the flow behavior of horizontal stepped chutes have been conducted (Chanson 2002). Hydraulic design guidance of horizontal stepped spillways was developed by Boes and Hager (2003b). Other stepped-like structures, such as drop structures, were investigated by Moore (1943), Rand (1955), Rajaratnam and Chamani (1995), and Chanson and Toombes (1998).

Although a number of researches have been conducted on the hydraulics of drops and horizontal stepped chutes, the hydraulics of inclined steps have received less attention. A few research works on flow over stepped chutes with inclined steps were carried out by Essery and Horner (1978). They provided simple relationships for the energy number (specific energy-to-step length ratio) and flow number (critical depth-to-step length ratio) for step inclinations between 5° and 20° and compared with the results of horizontal steps. However, the loss of hydraulic energy over a stepped chute with inclined steps and the outlet velocity downstream were not reported.

Concerning with the scale effect, Boes and Hager (2003a) investigated the aeration characteristics of skimming flows on stepped spillways. The minimum Reynolds and Weber numbers of around 10^{5} and 100, respectively, were presented to minimize scale effects in physical modeling of two-phase air-water flows on stepped spillways. Moreover, they found that, different from clear water, highly turbulent two-phase air-water flow in open channel could not be modeled without scale effect resulting from the variation of viscosity and surface tension. Pegram et al. (1999) conducted two sets of modeled stepped spillways on the 1:10 and 1:20 scale models. Based on the results of the sequent depth of the hydraulic jump at the toe of the spillways, they reported that models with scales of 1:20 and larger could represent the prototype behavior of stepped spillways.

The objective of this study is therefore to conduct experiments on stepped chutes with inclined steps. The results include the prediction of the onset of skimming flow, the evaluation of the energy dissipation and outlet velocity in dimensionless form. These results are compared with other researches relating to stepped chutes with horizontal steps.

Experimental apparatus and procedure

A definition sketch of the experimental arrangement is shown in Fig. 1. Water was pumped from a laboratory sump to a V-notched weir tank from which water entered the stepped chute through an approach channel. At the bottom of the stepped chute, a horizontal outlet carried the water back to the sump. The discharge, which varied from 4 to 68 l/s (0.01 to 0.17 m^2/s), was measured by the V-notch.

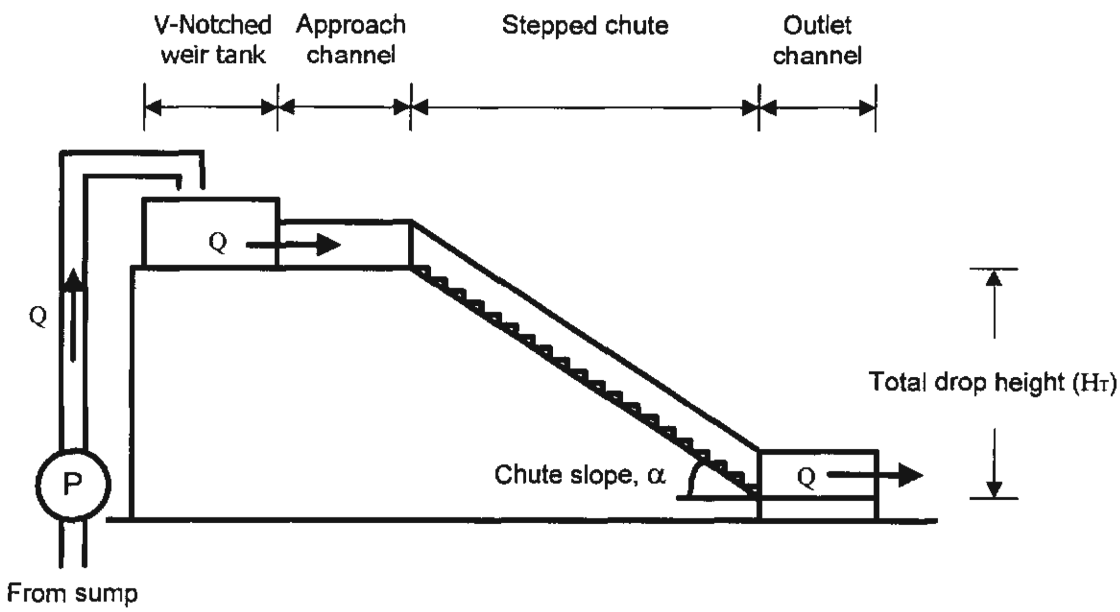

Fig. 1 Schematic diagram of experimental set-up

The stepped chutes made of plexiglass had a width of 0.40 m and consisted of 20 steps. The slopes of the stepped chutes from the horizontal, α, were 30°, 45°, and 60°. These angles are classified as steep channel slopes (Chanson 1994). The total drop heights of the stepped chutes, H_T, were 1.50, 2.12, and 2.60 m, respectively. The dimensions of the step can be defined as h/l, wherein h is the step height and l is its horizontal step length. To investigate the effect of step inclination, three upward angles of inclined steps (θ) were tested, i.e. 10°, 20°, and 30°. The method of construction and construction cost of the inclined steps were not found significantly different as compared to the horizontal steps. Figure 2 shows the dimensions of the inclined steps.

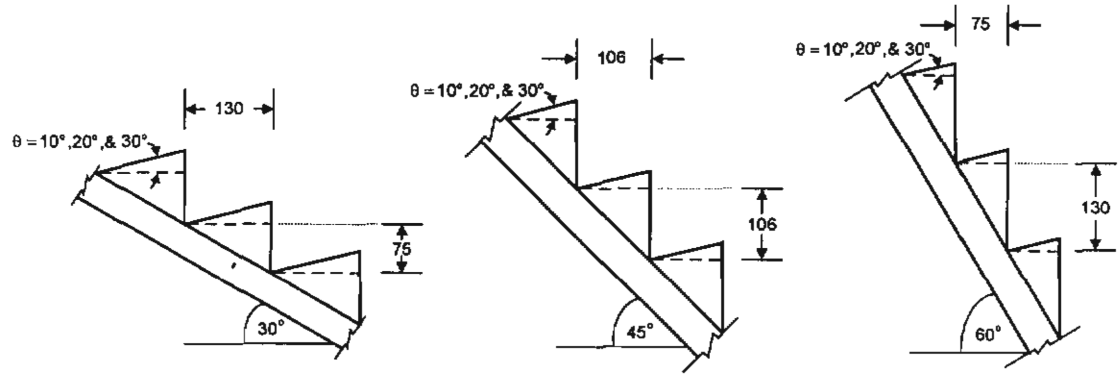

Fig. 2 Dimension of inclined steps in millimeters

The depth and velocity in the outlet channel were measured at a location where air entrainment was significantly diminished. It was about 3-4 times the step length away from the lowest step face. The depths across the chute width were measured by a vernier-depth gage. The velocities were measured by two methods, first by a pitot tube and second by dividing discharge by the measured flow area. The values obtained were within 10%. In calculating the energy dissipation the velocity obtained from the first method was used. Details of the experiments are summarized in Tables 1 - 3.

In the present study, which the flow depth and flow velocity were measured at a location where air entrainment was significantly diminished, the results can also represent the prototype behavior of stepped chutes with a limit of scale model. By Froude similitude, therefore, the presented results are limited for the height or length of the prototype spillways not greater than 20 times the modeled tests and the prototype discharges per unit width are in the range of 0.9 to 15.1 m^2/s.

Classifications of stepped chute flow with inclined steps

Based on literature reviews, the flow regime on a horizontal stepped chute can be divided into three flow regimes: nappe flow, transition flow, and skimming flow. In nappe flow, the steps act as a series of overfalls with the water plunging from one step to another. Nappe flow is found for low discharges and large step lengths. In contrast, skimming flow results for large discharges and small step lengths. Water flows as a coherent stream without air pockets under the jets on the pseudo-bottom formed by the outer step edges.

Table 1. Details of experimental set A (chute slope = 30°, H_T = 1.50 m, h = 0.075 m).

Inclined step angle, θ (degree)	Run no.	q ($m^3/s/m$)	V_T (m/s)	Observed flow type	$\frac{d_c}{h}$	Energy loss (m)
0	1	0.010	0.63	NA	0.29	1.49
	3	0.031	1.78	NA	0.61	1.39
	5	0.052	2.43	TRA	0.89	1.27
	7	0.071	2.79	SK	1.07	1.20
	9	0.090	2.95	SK	1.25	1.17
	11	0.111	3.13	SK	1.44	1.13
	13	0.128	3.24	SK	1.58	1.11
	15	0.147	3.35	SK	1.74	1.08
	17	0.170	3.43	SK	1.91	1.06
10	1	0.010	0.77	NA	0.29	1.48
	3	0.030	1.57	NA/TRA	0.60	1.42
	5	0.049	2.21	TRA	0.83	1.32
	7	0.069	2.60	SK	1.05	1.25
	9	0.089	2.78	SK	1.24	1.22
	11	0.109	2.95	SK	1.42	1.19
	13	0.129	3.14	SK	1.59	1.14
	15	0.149	3.28	SK	1.75	1.11
	17	0.170	3.35	SK	1.91	1.10
20	1	0.010	0.89	NA	0.29	1.49
	3	0.030	1.71	NA/TRA	0.60	1.41
	5	0.050	2.17	TRA	0.84	1.34
	7	0.070	2.51	SK	1.06	1.28
	9	0.090	2.77	SK	1.25	1.23
	11	0.109	2.92	SK	1.42	1.20
	13	0.128	3.12	SK	1.58	1.15
	15	0.147	3.28	SK	1.73	1.12
	17	0.166	3.37	SK	1.88	1.10
30	1	0.010	0.64	NA	0.29	1.49
	3	0.030	1.59	NA/TRA	0.60	1.42
	5	0.050	2.03	TRA	0.85	1.36
	7	0.070	2.34	SK	1.06	1.32
	9	0.090	2.63	SK	1.25	1.25
	11	0.111	2.83	SK	1.44	1.22
	13	0.129	3.02	SK	1.59	1.17
	15	0.152	3.20	SK	1.77	1.13
	17	0.167	3.32	SK	1.89	1.11

(NA = nappe flow regime; TRA = transition; and SK = skimming flow regime)

Table 2. Details of experimental set B (chute slope = 45°, H_T = 2.12 m, h = 0.106 m).

Inclined step angle, θ (degree)	Run no.	q ($m^3/s/m$)	V_T (m/s)	Observed flow type	$\frac{d_c}{h}$	Energy loss (m)
0	1	0.010	1.00	NA	0.20	2.09
	3	0.029	2.19	NA	0.42	1.93
	5	0.050	2.75	TRA	0.60	1.81
	7	0.071	3.30	TRA	0.76	1.66
	9	0.091	3.43	SK	0.89	1.63
	11	0.111	3.62	SK	1.02	1.58
	13	0.128	3.80	SK	1.12	1.52
	15	0.146	3.90	SK	1.22	1.49
	17	0.170	4.05	SK	1.35	1.45
10	1	0.010	1.11	NA	0.20	2.07
	3	0.030	2.08	TRA	0.43	1.94
	5	0.050	2.71	TRA	0.60	1.81
	7	0.070	3.13	TRA	0.75	1.71
	9	0.089	3.31	TRA/SK	0.88	1.67
	11	0.110	3.47	SK	1.01	1.63
	13	0.129	3.69	SK	1.13	1.56
	15	0.151	3.85	SK	1.25	1.52
	17	0.162	3.91	SK	1.31	1.51
20	1	0.010	1.11	NA	0.20	2.08
	3	0.030	1.98	TRA	0.43	1.97
	5	0.050	2.68	TRA	0.60	1.81
	7	0.070	3.05	TRA	0.75	1.74
	9	0.090	3.26	TRA/SK	0.89	1.69
	11	0.110	3.41	SK	1.01	1.65
	13	0.130	3.60	SK	1.13	1.59
	15	0.152	3.70	SK	1.26	1.57
	17	0.169	3.84	SK	1.35	1.53
30	1	0.010	1.05	NA	0.20	2.09
	3	0.030	1.98	TRA	0.43	1.98
	5	0.050	2.70	TRA	0.60	1.82
	7	0.070	3.00	TRA	0.75	1.77
	9	0.090	3.16	TRA/SK	0.89	1.73
	11	0.110	3.36	SK	1.01	1.68
	13	0.130	3.52	SK	1.13	1.64
	15	0.148	3.66	SK	1.23	1.61
	17	0.164	3.78	SK	1.32	1.58

(NA = nappe flow regime; TRA = transition; and SK = skimming flow regime)

Table 3. Details of experimental set C (chute slope = 60°, H_T = 2.60 m, h = 0.130 m).

Inclined step angle, θ (degree)	Run no.	q ($m^3/s/m$)	V_T (m/s)	Observed flow type	$\frac{d_c}{h}$	Energy loss (m)
0	1	0.011	1.21	NA/TRA	0.18	2.55
	3	0.030	2.37	TRA	0.35	2.37
	5	0.051	3.16	TRA	0.49	2.17
	7	0.070	3.54	TRA	0.61	2.06
	9	0.090	3.83	TRA	0.72	1.97
	11	0.108	4.11	SK	0.81	1.87
	13	0.130	4.22	SK	0.92	1.83
	15	0.147	4.39	SK	1.00	1.77
	17	0.170	4.49	SK	1.10	1.74
10	1	0.010	1.12	NA/TRA	0.17	2.56
	3	0.030	1.89	TRA	0.35	2.46
	5	0.050	2.66	TRA	0.49	2.31
	7	0.070	3.32	TRA	0.61	2.12
	9	0.089	3.65	TRA	0.72	2.01
	11	0.109	3.91	TRA	0.82	1.92
	13	0.128	4.00	SK	0.91	1.90
	15	0.148	4.14	SK	1.01	1.84
	17	0.170	4.24	SK	1.10	1.84
20	1	0.011	1.10	NA/TRA	0.18	2.55
	3	0.031	1.73	TRA	0.35	2.49
	5	0.050	2.30	TRA	0.49	2.39
	7	0.070	3.30	TRA	0.61	2.12
	9	0.089	3.60	TRA	0.72	2.03
	11	0.111	3.88	TRA	0.83	1.93
	13	0.128	3.96	SK	0.91	1.91
	15	0.149	4.09	SK	1.01	1.86
	17	0.170	4.13	SK	1.10	1.85
30	1	0.010	1.05	NA/TRA	0.17	2.57
	3	0.030	1.81	TRA	0.35	2.49
	5	0.050	2.59	TRA	0.49	2.33
	7	0.070	3.09	TRA	0.61	2.20
	9	0.089	3.40	TRA	0.72	2.11
	11	0.112	3.68	TRA	0.83	2.02
	13	0.129	3.84	SK	0.92	1.97
	15	0.149	3.99	SK	1.01	1.92
	17	0.170	4.03	SK	1.10	1.90

(NA = nappe flow regime; TRA = transition; and SK = skimming flow regime)

The transition flow is characterized by a pool of recirculating water with or without a small air pocket. This does not present the appearance of skimming flows or the succession of free jets. Due to the changes of streamline direction in the transition flow, this implies a different pressure distribution and induces vibration of the chute (Chanson 2002).

For engineering purposes, skimming flow is more relevant than nappe flow. Researches on skimming flow on horizontal stepped chutes were made by Rajaratnam (1990), Chanson (1994), Chamani and Rajaratnam (1999), and Chinnarasri (2002).

In this study, the flow regimes on stepped chutes with inclined steps can be classified as those found in horizontal stepped chutes (Chanson 2002). Examples of flow regimes observed from 30° chute slope and 20° upward inclined step are shown in Fig. 3. For small discharge, free-falling nappe was found at the brink of the inclined step while hydraulic jump was observed on the inclined step face (Fig. 3(a)). For intermediate discharge, the succession of free-jet was disappeared. The free surface of the flow was wavy with spray (Fig. 3(b)). For large discharge, the free surface of the flow was smooth and air entrainment was small (Fig. 3(c)).

In 1990, Rajaratnam re-analyzed Essery and Horner's data and proposed the onset of skimming flow on horizontal stepped chutes using d_c/h and h/l. For the range of h/l from 0.4 to 0.9, at the onset of skimming flow, d_c/h was approximately equal to 0.8. Chanson (1994) suggested the critical value for the occurrence of skimming flow as the straight line

$$\frac{d_c}{h} = 1.057 - 0.465\frac{h}{l} \tag{1}$$

Chinnarasri (2002) compared his experimental results on horizontal stepped chutes with those of Essery and Horner (1978), Beitz and Lawless (1992), and Yasuda and Ohtsu (1999), and defined for h/l from 0.1 to 1.4 the onset of skimming flow as

$$\frac{d_c}{h} \geq 0.80\left(\frac{h}{l}\right)^{-0.22} \tag{2}$$

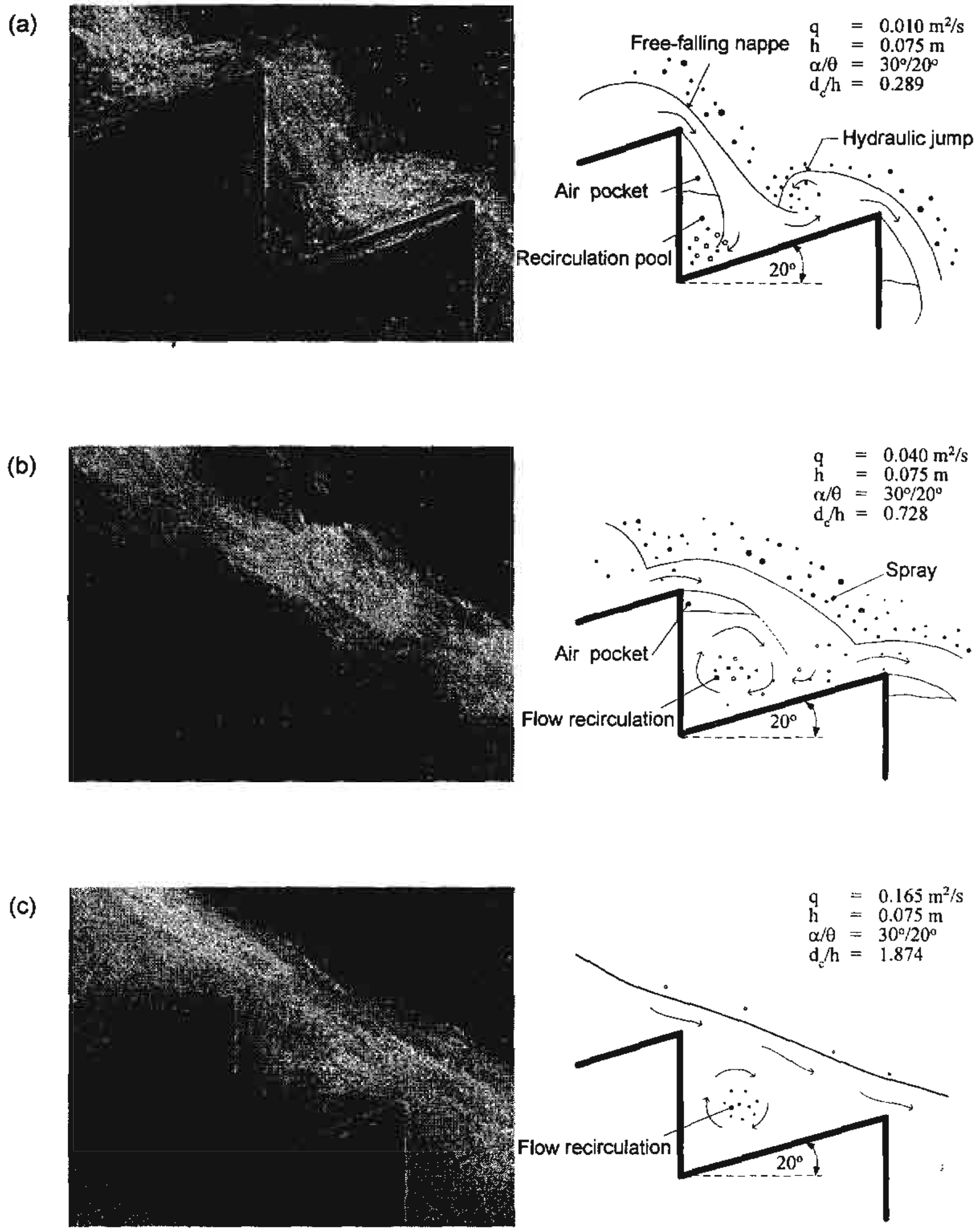

Fig. 3 Flow regimes on a 30° chute with upward inclined steps
(a) Nappe flow; (b) Transition flow; and (c) Skimming flow

Effect of step angle

To investigate the onset of skimming flow on stepped chutes, the experimental data obtained in this study were compared with other experiments on horizontal steps. The re'ation between d_c/h and h/l are shown in Fig. 4 and lines for the lower limit of skimming flow and upper limit for nappe flow can be drawn. In this study, the lower limit of skimming flow is defined by the disappearance of the air cavity beneath the free falling nappes and the water flowing as a quasi-homogeneous stream (Chanson 1996). The upper limit of nappe flow is defined by no succession of free jets on the chute. In Fig. 4, the transition flow regime between nappe flow and skimming flow is clearly separated. For large step lengths, e.g. α = 30° (l/h = 1.73), the flowing water proceeds in a series of plunges from one step to another. For smaller step lengths, e.g. α = 60° (l/h = 0.577), the water falls over the outer edge of the downstream steps with a pool of recirculating water was observed.

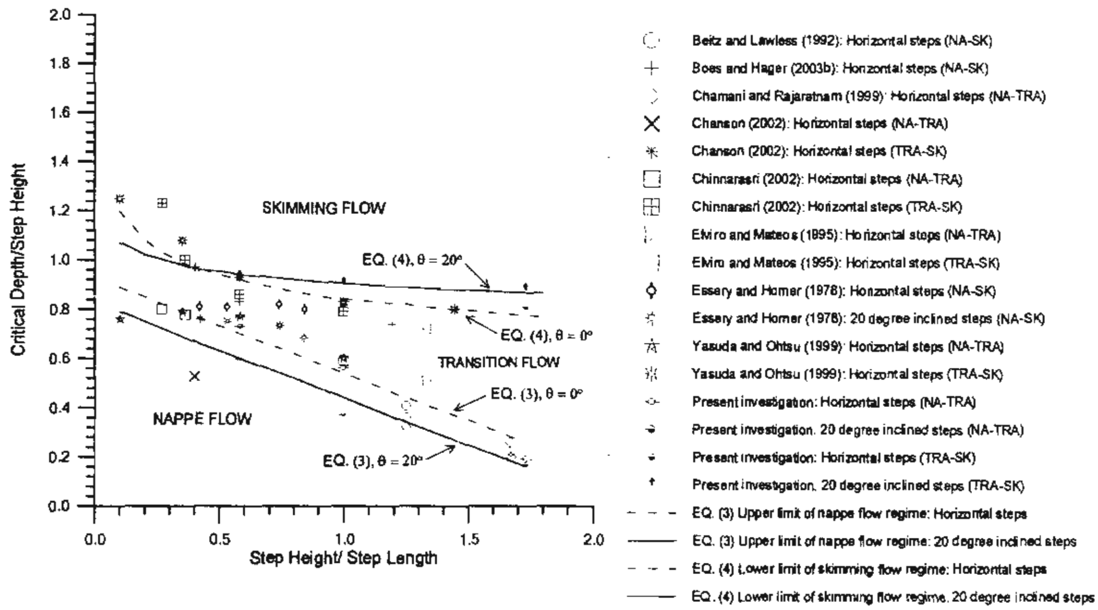

Fig. 4 Comparison of experimental data with empirical correlation for flow classifications on chutes with upward inclined steps

Comparison between flow on horizontal steps and inclined steps shows that the upward angle of the inclined step has no effect on the upper limit of nappe flow, but gives a small increment of the lower limit of skimming flow. When the angle of the inclined steps increases, the lower limit of skimming flow slightly increases. This is caused by the relative increase of the elevation of the outer step edge. This results in an increase of the space of the pool height and the air pocket under the falling jet of nappe flow. Therefore, more discharge is needed to establish the onset of skimming flow. This result is opposed to the data of Essery and Horner (1978) for inclined steps due to a different assumption of the onset of skimming flow.

By empirical correlation, the maximum discharge for nappe flow regime is $(0.1 \le h/l \le 1.73)$

$$\frac{d_c}{h} = 0.927 - 0.005\,\theta - 0.388\left(\frac{h}{l}\right) \tag{3}$$

where θ is the angle of upward inclined step.

Likewise the minimum discharge required for the onset of the skimming flow regime is, as shown in Fig. 4, $(0.1 \le h/l \le 1.73)$

$$\frac{d_c}{h} = \left(0.844 + 0.003\,\theta\right)\left(\frac{h}{l}\right)^{-0.153+0.004\theta} \tag{4}$$

Energy dissipation of flow on stepped chutes with inclined steps

In skimming flow, most energy is dissipated to maintain stable horizontal vortices beneath the pseudo-bottom formed by the external edges of the steps. Generally, the energy loss of flow on an inclined stepped chute E_L depends on the total discharge per unit width of spillway *q*, the chute drop height H_T, the step height *h*, the step length *l*, the slope of the spillway α or $\tan^{-1}(h/l)$, the slope of the step inclination θ, and the gravitation acceleration *g*. These variables are shown in Fig. 5 and can be expressed functionally as

$$E_L = f_1\,[q, H_T, h, l, \theta, g] \tag{5}$$

Using the Buckingham Pi theorem, the variables in eq. [5] can be expressed in non-dimensional form as:

$$\frac{E_L}{H_T} = f_2\ [\frac{q^2}{gH_T^3}, \frac{h}{l}, \theta] \tag{6}$$

where the dimensionless term $\frac{q^2}{gH_T^3}$ is the "Drop number", the ratio $\frac{h}{l}$ is referred to as the chute slope α, and θ is the angle of the upward inclined step.

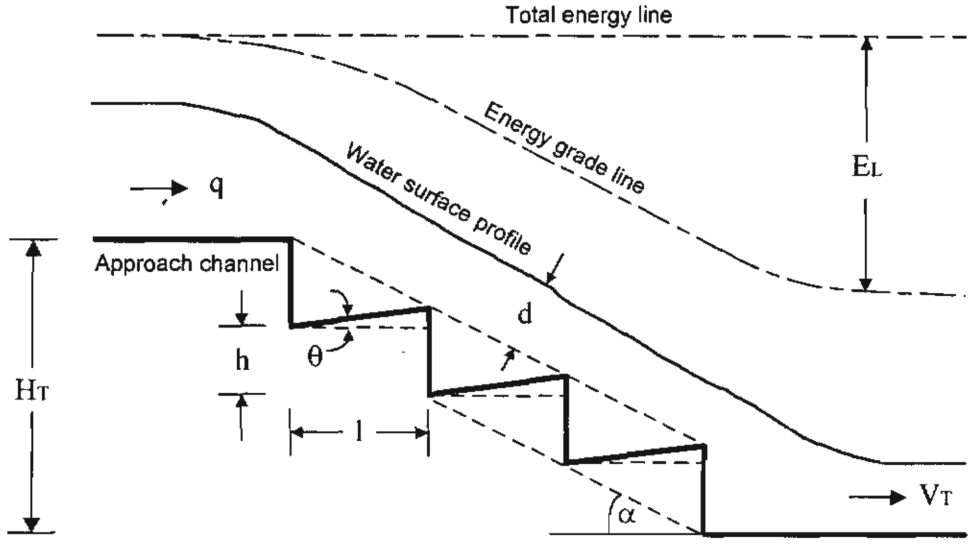

Fig. 5 Variables in dimensional analysis

The relationships between the energy loss ratio on stepped chutes and the drop number are shown in Fig. 6 for 30° chute slopes.

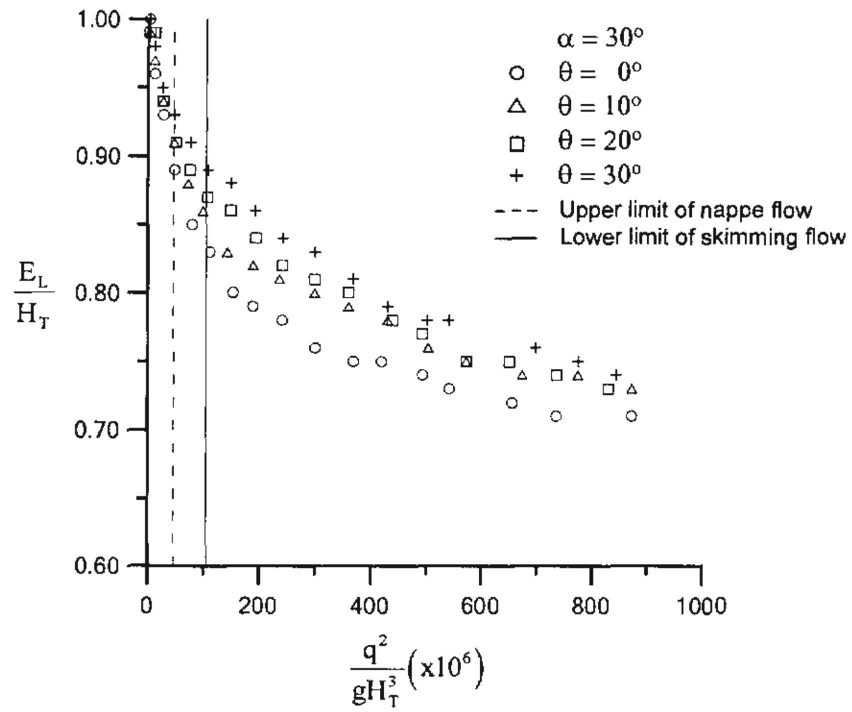

Fig. 6 Energy dissipation and drop number of 30° stepped chutes

It can be seen that the energy loss ratio E_L/H_T decreases as the drop number increases. According to the criteria for nappe flow and skimming flow regimes on stepped chutes as proposed in eqs. [3] and [4] with $\theta = 0°$, the variations of E_L/H_T with q^2/gH_T^3 in different flow regimes are distinctively different. It should be noted that the range of transition flow on stepped chutes of 60° is large. This is because the flowing water splashes and streamlines are not parallel due to the water impact along the outer edge of the steps.

In the nappe flow regime where the drop number is very low, E_L/H_T decreases rapidly as q^2/gH_T^3 increases and the angle of the inclined step has a little effect upon E_L/H_T, especially for chutes with milder slopes. The angle of inclined step increases the energy dissipation by less than 3 % as most of the flow energy is dissipated due to jet breakup and jet mixing on the step and the formation of hydraulic jump on the step.

In the skimming flow regime, E_L/H_T gradually decreases toward a constant value as q^2/gH_T^3 increases. It can be observed that a higher angle θ increases E_L/H_T. An inclined step increases the energy dissipation by about 6 % of H_T (depending on θ). As the upward angle of the inclined steps increases, the energy loss increases due to the obstruction of the steps to the flow direction producing more spray and the recirculation vortices being trapped on the chute steps. Larger flow circulations are found and they are more stable than those in the smaller angles of inclined steps. More energy is therefore dissipated on this kind of structure.

The effect of the chute slope, α, for the same q^2/gH_T^3, the milder chute slope gives a greater energy loss ratio. At the highest q^2/gH_T^3, the value of E_L/H_T for $\theta = 0°$ (horizontal step) to $\theta = 30°$ (30 degree angle of inclined step) for $\alpha = 30°$ varies from 0.71 to 0.74, while for $\alpha = 45°$ and 60° this ratio varies from 0.68 to 0.74 and from 0.67 to 0.73, respectively.

Another approach to estimate the energy loss on chutes is the comparison between the ratio of energy loss to the total head (E_L/E_O) and the ratio of the critical flow depth to the step height (d_c/h) (Christodoulou 1993). In this study, the relation of these parameters with d_c/h in the range of 1 to 2 are shown in Fig. 7. It is found that the energy ratio decreases when the discharge increases which is in the same trend when the drop number is applied.

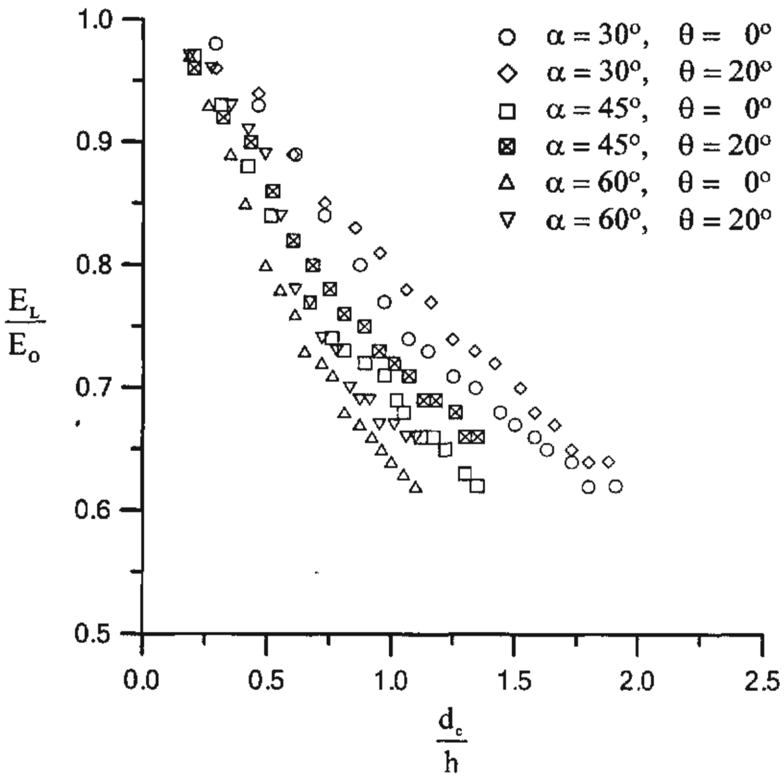

Fig. 7 Energy dissipation and ratio of critical flow depth to step height

Flow velocity at outlet

The flow velocity V_T at the end of the chute can be expressed as

$$\frac{V_T}{\sqrt{gH_T}} = f_3 \ [\frac{q^2}{gH_T^3}, \ \frac{h}{l}, \ \theta] \tag{7}$$

As shown in Fig. 8, the velocity ratio $\left(V_T / \sqrt{gH_T}\right)$ increases with increasing drop number for every chute slope and angle of inclined step. These data can be represented by the following logarithmic correlation

$$\frac{V_T}{\sqrt{gH_T}} = 0.131 \ln\left(\frac{q^2}{gH_T^3}\right) + 0.036 - 0.0009\,\theta \tag{8}$$

As compared with the horizontal steps, the $\left(V_T / \sqrt{gH_T}\right)$ ratio is smaller because of higher energy loss on the stepped chutes with inclined steps. The regions of nappe and skimming flow regimes are presented based on the drop number in Fig. 6. The kinetic energy ratio increases almost linearly with q^2/gH_T^3 and agrees reasonably well with the variation of E_L/H_T with q^2/gH_T^3. As the energy loss decreases when q^2/gH_T^3 increases, the remaining kinetic energy at the chute outlet increases.

In the nappe flow regime, the kinetic energy at the outlet for all cases is small and almost the same because most of the flow energy is dissipated along the stepped chutes. In the skimming flow regime, the kinetic energy at the chute outlet with inclined steps is less than for the horizontal stepped chutes because more flow energy is dissipated.

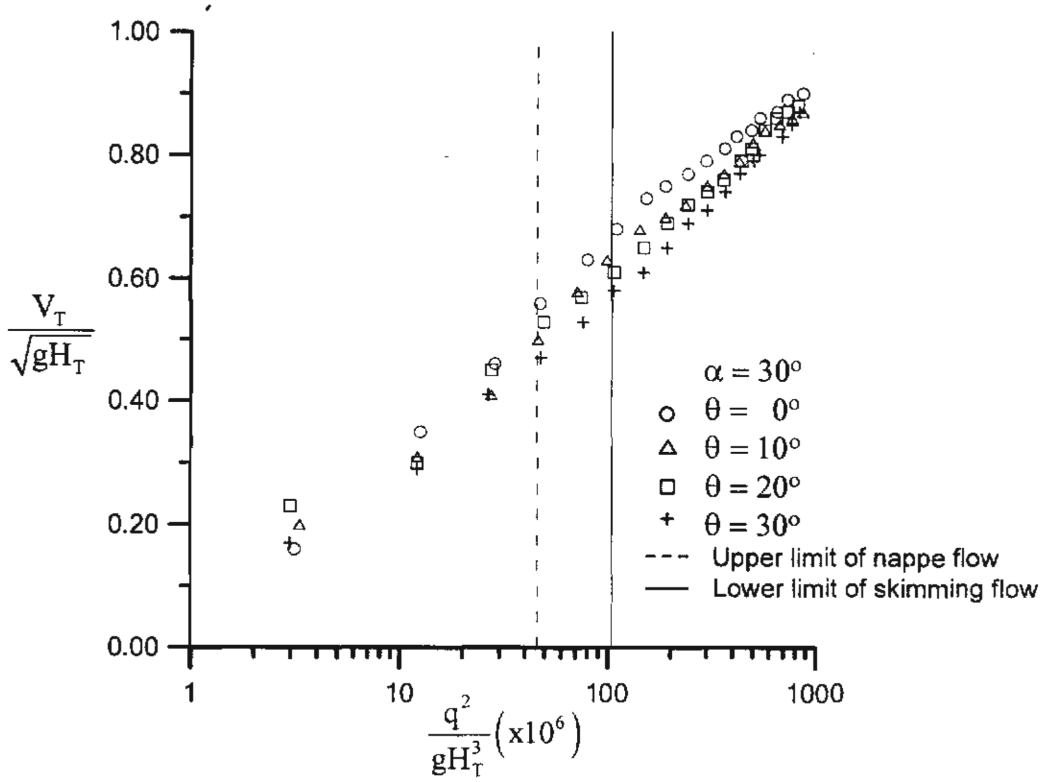

Fig. 8 Flow velocity at outlet and drop number of 30° stepped chutes

Conclusions

Flow regimes on chutes with upward inclined steps were considered and classified as nappe flow, transition flow, and skimming flow regimes. The onset of skimming flow is characterized by the relation of critical depth/step height (d_c/h) and step height/step length (h/l). The onset of skimming flow on stepped chutes with inclined steps is predicted by empirical correlations, which are good for $(0.1 \leq h/l \leq 1.73)$.

Under identical flow conditions and step geometries, an upward inclined step causes more energy loss than horizontal steps, especially in the skimming flow regime, i.e. about 6% of H_T (depending on θ). As the upward angle of the inclined steps increases, the energy loss increases due to the obstruction of the steps to the flow direction producing more spray. Stepped chutes with upward inclined steps at milder slopes yield an energy loss ratio E_L/H_T greater than steeper. In the nappe flow regime, the energy loss decreases rapidly when the drop number increases. However, this decreasing rate become less and approaches a constant value when the flow is in the skimming flow regime.

The velocity ratio $\left(V_T / \sqrt{gH_T}\right)$ increases with increasing drop number for every chute slope and angle of inclined step. To estimate kinetic energy ratio, an empirical equation is proposed in [8].

As the method of construction and construction cost of the inclined steps were not found significantly different compared to the horizontal steps, the inclined step is an alternative for energy dissipater along spillway face.

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Output ที่ได้จากโครงการ

จากการศึกษา การทดลองของสภาพการไหลในรางขั้นบันไดแบบความชันย้อนกลับ ทำให้มีการสร้างชุดอุปกรณ์ประกอบการทดลอง ได้แก่ รางขั้นบันไดแบบความชันย้อนกลับ หอถังนำน้ำเข้าราง ทางระบายน้ำออกจากราง ทางระบายใต้ดินเพื่อการหมุนเวียน ระบบสูบน้ำและท่อ และเครื่องมือวัดต่างๆที่จำเป็น เพื่อใช้ในการวิจัยและเป็น Output ที่ได้จากโครงการทางตรง บทความที่ได้จากการวิจัยทางตรง ได้ตอบรับการตีพิมพ์แล้ว 1 เรื่อง ดังนี้ (สำเนาจดหมายตอบรับแสดงดังภาคผนวก ก)

1. *Chinnarasri, C.* and Wongwises, S. (2004), Flow regimes and energy loss on chutes with upward inclined steps, Canadian Journal of Civil Engineering (accepted for publication).

นอกจากนี้ ยังมีบทความหนึ่งเรื่องที่อยู่ในระหว่างการจัดทำ โดยใช้ชื่อเรื่องว่า Flow patterns and energy loss on various stepped structures ซึ่งเป็นการเขียนร่วมกันระหว่าง *Chinnarasri, C.* and Wongwises, S. และคาดว่าจะส่งไปลงที่ Journal of Irrigation and Drainage Engineering

นอกจากนั้นงบประมาณที่ได้จากทุนวิจัยยังได้นำไปสร้างรางทดรองรูปแบบอื่นอีก ได้แก่ รางขั้นบันไดแบบพื้นราบ รางขั้นบันไดแบบมีธรณีที่ปลายขั้น และรางขั้นบันไดแบบกล่อง Gabions ทำให้ได้ผลการทดลองของลักษณะการไหลผ่านรางขั้นบันไดในลักษณะต่างๆกัน เพื่อใช้ในการวิจัยของนักศึกษาระดับปริญญาโทของผู้รับทุนวิจัย ผลงานที่ได้เป็น Output ที่ได้จากโครงการทางอ้อม

ผลการศึกษาเหล่านี้ ได้นำมาเขียนเป็นบทความและได้รับการตีพิมพ์ (กล่าวขอบคุณสำนักงานคณะกรรมการการอุดมศึกษาและสำนักงานกองทุนสนับสนุนการวิจัย ในกิตติกรรมประกาศ) ดังต่อไปนี้ (รายละเอียดของบทความแสดงดังภาคผนวก ข)

1. *Chinnarasri, C.* and Donjadee, S., Characteristics of flows over gabion stepped spillways, submitted for possible accept for publication in Journal of Hydraulic Research.
2. *Chinnarasri, C.*, Israngkura, U. and Donjadee, S. (2004), Pressure on step and flow depth on gabion stepped chutes, Research and Development Journal of the Engineering Institute of Thailand, Vol. 15(2), pp. 1-7 (in Thai).
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5. *Chinnarasri, C.*, Israngkura, U., and Chaturabul, T. (2003), Fnergy Dissipation on Stepped Spillways with End Sill, The 4th Regional Symposium on Infrastructure Development in Civil Engineering (RSID4), Bangkok, Thailand, April 3-5, pp. B6-9-B6-16.

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ภาคผนวก ก

จดหมายจากบรรณาธิการ Canadian Journal of Civil Engineering ตอบรับการตีพิมพ์ บทความเรื่อง Flow regimes and energy loss on chutes with upward inclined steps

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27 May 2004

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Dear Dr. Chinnarasri:

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ภาคผนวก ฃ1

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7/7/47

Characteristics of flows over gabion stepped spillways

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ABSTRACT

Gabions are useful for building small retaining structures and have increased the interest in stepped spillways. However, less attention has received for these kinds of structures. This paper presents the new results of the experimental studies on the hydraulics of skimming flow on gabion stepped spillways. The slopes of the gabion spillways are of 30°, 45°, and 60° with total drop heights 1.50, 2.12, and 2.60 m, respectively. Based on dimensional analysis, the important parameters are analyzed and the relevant dimensionless parameters are formed. These data are analyzed and compared with other investigator's results to evaluate the onset of skimming flows on gabion stepped spillways. The energy loss ratios in the gabion stepped spillways are greater than those in the corresponding horizontal stepped spillways by 10% approximately for all spillway slopes. As a result, the velocity at the outlet is less. The pressure acting on the step face for the gabion stepped spillways is less than the pressure for the horizontal steeped spillways. The averaged pressure difference is about 27% owning to the absorption of energy from filled stones. The friction factor of gabion stepped spillways is found higher than that of the horizontal stepped spillways about 3.6 times.

Keywords: Skimming flow, gabions, stepped spillways, laboratory.

1 Introduction

Stepped spillway is a hydraulic structure, which its floor is built up of a series of steps. Besides the ease of construction and maintenance, one of its advantages over the plain-bed spillway is that more of the flow energy can be dissipated through it. As a result the flow leaves the stepped spillway at a lower velocity and a smaller size of energy dissipator can be used.

Recently, new construction materials e.g. gabions and design techniques have increased the interest in stepped chutes and spillways. Generally, gabions are used for building small retaining structures such as small gabion weirs, channel linings, and supporting parts of small earth dams. Gabions are hexagonal mesh boxes filled with small sizes of stones. Their advantages as construction materials are: 1) their stability, 2) low cost, 3) flexibility, and 4) porosity. The porosity of gabions is an important characteristic preventing the building up of uplift pressures (Chanson, 2002).

Although a lot of research has been conducted on hydraulics of flow over stepped chutes and spillways, the hydraulics of flow over gabions has received less attention. Few research works on energy dissipation over gabion stepped structures was made by Stephenson (1979&1988) and Peyras et al. (1992) and simple relationships of energy loss and spillway drop number were provided. However, no comparison of characteristics of flow between horizontal stepped spillways and gabion stepped spillways was reported.

To understand the characteristics of flow over gabion stepped spillway, therefore, the objective of the study is to conduct a new experimental test in order to investigate the rate of energy dissipation and to compare the energy loss between the horizontal stepped spillways and gabion stepped spillways. The effect of filled stones on the energy loss ratio is presented. In addition, the time-averaged pressure on the step face and the flow resistance under equilibrium condition are proposed and discussed.

2 Experimental apparatus and procedure

An outline of the experimental arrangement is shown in Figure 1. Water was pumped from a laboratory sump to the V-notched weir tank from which water entered the stepped spillway through an approach channel. At the bottom of the stepped channel, a horizontal outlet carried the water back to the sump. The discharge was measured by the V-notched weir tank. The discharge was varied from 4 – 68 l/s (0.01 to 0.17 m^2/s).

The stepped spillways are made of plexiglass having widths of 0.40 m and consist of 20 steps. The slope of the stepped channel, α, are 30°, 45°, and 60°. The total drop heights of the stepped channel, H_T, are 1.5, 2.12, and 2.60 m, respectively. The dimensions of the step can be defined as h/l, wherein h is the step height and l is its horizontal length. Each step, gabion boxes filled with stones are placed on the step face. The volume of the gabion boxes are (h) x (l) x (spillway width).

To investigate the effect of filled stones three types of stones are used, i.e. i) crushed stone of 25-35 mm diameter, ii) rounded stone of 25-35 mm diameter, and iii) crushed stone of 50-70 mm diameter. The average void ratios of gabions are 0.27, 0.30, and 0.39, respectively. Figure 2 shows gabion dimension.

The measurements of depth and velocities in the spillway outlet were measured at about 3-4 times of the step length away from the lowest step face where turbulence and air entrainment effect became significantly diminished. The depths across the chute width were measured by a vernier-depth gauge. The velocities were measured by two methods, first by a pitot tube and second by dividing the measured flow area. The values obtained were within 10% differences. In calculating the energy loss the velocity obtained from the first method was used.

The pressure on step face was measured by U-tube manometers tapping at the holes on the face of the odd number steps. Five locations of pressure taps were provided on the step face. When the flow through the spillways reached steady condition, the pressure at each point on the step face was observed and was recorded for a certain period. Four sets of experimental conditions were investigated, i.e. set A: horizontal stepped spillways, set B: gabion stepped spillways with stone I, set C: gabion stepped spillways with stone II, and set D: gabion stepped spillways with stone III. Primary details of experiments were summarized in Tables 1 - 4.

3. Results and discussion

In the present study, which the flow depth and flow velocity were measured at a location where air entrainment was significantly diminished, the results can also represent the prototype behavior of stepped chutes with a limit of scale model. As mentioned by Pegram et al. (1999) who conducted two sets of modeled stepped spillways on the 1:10 and 1:20 scale models. Based on the results of the sequent depth of the hydraulic jump at the toe of the spillways, they reported that models with scales of 1:20 and larger could represent the prototype behavior of stepped spillways.

By Froude similitude, therefore, the presented results are limited for the height or length of the prototype spillways not greater than 20 times the modeled tests and the prototype discharges per unit width are in the range of 0.9 to 15.1 m^2/s.

3.1 Onset of skimming flow

When water flows over a gabion structure, the flowing water can be divided into two parts, i.e. base flow through the void between the filled stones and overflow on the gabion structure. The amount of base flow depends on the dimensions of gabions, the porosity, and the type of flow regime. Typically the step height equals the height of the gabion. The stone size of the rockfill is equal to at least 1 to 1.5 times the mesh size but should not be larger than 2/3 of the minimum dimension of the gabion. With these dimensions, the flow pattern may be either nappe flow at low flow rates or skimming flow at larger flow rates. Due to the occurrence of the base flow, the dimension of the air cavity beneath the free-falling nappes of the flow on gabion stepped spillways is smaller than that of the flow on horizontal stepped spillways. As the air cavity beneath the free-falling nappes disappears, the skimming flow begins. Flow regimes observed in the study are shown in Figure 3.

The study of onset of skimming flow was initiated by Essery and Horner (1978) who proposed the occurrence of skimming flow as the function of d_c/l and h/l, wherein d_c is the critical depth of flow, h is the step height and l is its horizontal length. Rajaratnam (1990) re-analyzed Essery and Horner's data and proposed the onset of skimming flow on horizontal stepped spillways as a new function of d_c/h and h/l. For the range of h/l from 0.4 to 0.9, at the onset of skimming flow d_c/h was approximately equal to 0.8. Chanson (1994) suggested a critical value for occurrence of skimming flow as

$$\frac{d_c}{h} = 1.057 - 0.465\frac{h}{l} \tag{1}$$

Chamani and Rajaratnam (1999) developed an equation to predict the onset of skimming flow on horizontal steps. Their equation is based on the assumption that skimming flow begins when the jet leaving a step has a slope equal to that of the stepped chutes when it impinges on the pool behind the jet on the next step. The main difference with Chanson's assumptions is that the air pockets under the jet still exist. Their equation for the onset of skimming flow is

$$\frac{h}{l} = \sqrt{0.89\left[\left(\frac{d_c}{h}\right)^{-1} - \left(\frac{d_c}{h}\right)^{-0.34} + 1.5\right] - 1} \tag{2}$$

While Chinnarasri (2002) compared his experimental results on horizontal stepped spillways with the data of other researchers and found that for the range of h/l from 0.1 to 1.4, the onset of skimming flow occurred when

$$\frac{d_c}{h} \geq 0.80\left(\frac{h}{l}\right)^{-0.22} \quad (3)$$

To investigate the onset of skimming flow on gabion stepped spillways the experimental data obtained in the study are compared with the experimental results on gabion stepped spillways conducted by Stephenson (1988) and Peyras et al. (1992). Summary of characteristics of experimental studies are shown in Table 5. The relation between d_c/h and h/l are shown in Figure 4. With a limited experimental data, a transition line between nappe flow and skimming flow can be drawn and the equation of onset of skimming flow can be expressed as

$$\frac{d_c}{h} \geq 0.61\left(\frac{h}{l}\right)^{-0.26} \quad (4)$$

3.2 Energy dissipation

In a skimming flow regime, the steps act as a large roughness channel. Most of the energy is dissipated to maintain stable horizontal vortices beneath the pseudo-bottom formed by the external edges of the steps. Generally, the energy loss through a stepped spillway E_L depends on the total discharge per unit width of spillway q, the spillway drop height H_T, the step or gabion height h, the step length l, the stone diameter D, the slope of the spillway α, and the gravitation acceleration g. These variables are shown in Figure 5 and can be expressed functionally as

$$E_L = f_1\left[q,\ H_T,\ h,\ l,\ D,\ g\right] \quad (5)$$

Using Buckingham Pi theorem, the variables in Eq. (5) can be expressed in non-dimensional form as

$$\frac{E_L}{H_T} = f_2\left[\frac{q^2}{gH_T^3},\ \frac{H_T}{h},\ \frac{D}{h}\right] \quad (6)$$

The dimensionless term $q^2/\left(gH_T^3\right)$ is named as "spillway drop number", the ratio H_T/h is actually the number of steps in the spillway and the ratio D/h is the relative stone height. To include the effect of spillway slope the term $q^2/\left(gH_T^3\right)$ is multiplied by the dimensionless term Δ, whereas Δ is the spillway slope (i.e. $\Delta = \tan\alpha = h/l$). It becomes a new dimensionless term named as "modified spillway drop number, $D_m = q^2\Delta^2/\left(gH_T^3\right)$".

The relationships between measured energy loss on gabion stepped spillways and modified spillway drop number are shown in Figure 6. The correlations between E_L/H_T and D_m for horizontal stepped spillways and gabion stepped spillways can be expressed as

For horizontal stepped spillways: $\frac{E_L}{H_T} = 0.39 D_m^{-0.07}$ (7)

For gabion stepped spillways: $\frac{E_L}{H_T} = 0.50 D_m^{-0.05}$ (8)

It is found that the flow energy is more dissipated in the gabion stepped spillways than in the horizontal stepped spillways. As the water flows over the gabion stepped spillways, the water is divided into two parts, i.e. flow over gabion boxes and flow through the gabion boxes (base flow). In the base flow, the water can flow through the void between filled stones, which results in reduction of the impact of the mass of the water on the face of the spillway steps. Small unstable vortices behind stones are observed, while more energy is required due to the interference of wake and step face.

Generally, the energy loss ratios in the gabion stepped spillways are greater than those in the corresponding horizontal stepped spillways by 10% approximately for all spillway slopes. For low flow, the nape flow regime is observed while at high flow the skimming flow occurs. The energy loss ratio varies inversely with the modified spillway drop number (D_m). The energy loss ratio decreases sharply at small value of the modified spillway drop number. The skimming flow pattern is observed as the modified spillway drop number increases further, the rate of decrease of energy loss ratio is reduced and shows the trend to approach a constant value.

In skimming flow regime, it is found that the flow energy is more dissipated in the spillway of milder slope than the steeper one at the same drop number. For spillway of milder slope, the step length (l) is longer than the step height (h) therefore the recirculating vortices can not fill the entire cavity between the step edges and the wake from one edge interferes with the next step. For steep slope, a stable recirculation in the cavities between adjacent steps is observed. The energy loss is due to the circulation of these vortices.

To study the effect of the size of filled stone it is found that the flow energy can be more dissipated by the bigger stone size than by the smaller one, within the range of this study. The crushed stone could dissipate more energy than the rounded one. The gabion filled with bigger stones has higher void ratio than the one filled with smaller stones. As some energy of flow is dissipated in the void in the gabion, therefore the higher void ratio produces higher rate of energy dissipation. However, the effect of stone size and shape seems to have little influence on the energy loss as compared with increasing effect of spillway slope.

Similar to the energy dissipation, the flow velocity at the spillway outlet V_T can be expressed in dimensionless form as

$$\frac{V_T}{\sqrt{gH_T}} = f_3\left[D_m, \frac{H_T}{h}, \frac{D}{h}\right] \tag{9}$$

The velocity ratio $\left(V_T/\sqrt{gH_T}\right)$ increases directly with increasing spillway drop number for every slopes and every gabion type as shown in Figure 7. As compared with the horizontal stepped spillways, this ratio is smaller, which is the result of higher energy loss on the gabion. The correlations between $\left(V_T/\sqrt{gH_T}\right)$ and D_m for horizontal stepped spillways and gabion stepped spillways can be expressed as

For horizontal stepped spillways: $$\frac{V_T}{\sqrt{gH_T}} = 0.12\ \ln\left(D_m\right) + 1.90 \tag{10}$$

For gabion stepped spillways: $$\frac{V_T}{\sqrt{gH_T}} = 0.12\ \ln\left(D_m\right) + 1.78 \tag{11}$$

3.3 Pressure on the step face

In the uniform flow condition, the pressure on the step face should be influenced by the impact force of the flowing water on the step face and the recirculating fluid trapped between the step lips. Neglecting the effects of flow aeration, skin roughness, and the viscosity of the fluid, dimensional analysis yields

$$\frac{P}{\gamma H_i} = f_4\left(\frac{q^2}{gH_i^3}, \alpha, \frac{x}{l}\right) \tag{12}$$

where P is the pressure at a point on a step, γ is the specific weight of fluid, g is the acceleration due to gravity, H_i is the drop height measured from the spillway approach to the step being considered, h is the step height, l is the step length, α is the slope of the spillway, and x is the distance from the upstream end of the step to the point being considered. Term $P/(\gamma H_i)$ represents relative pressure on the step face and term $q^2/\left(gH_i^3\right)$ represents step drop number.

Consider the maximum pressure at any distance, x, on a step face, the term $P/(\gamma H_i)$ becomes the relative maximum pressure on the step face. Hence Eq. (12) becomes:

$$\frac{P}{\gamma H_i} = m\left(\frac{q^2}{gH_i^3}\right)^n \tag{13}$$

The relation of the maximum pressure on step face and step drop number of both horizontal stepped spillways and gabion stepped spillways is good as shown in Figure 8. The spillway slope is given in legend. The coefficients m and n for the case of horizontal stepped spillways are 1.36 and 0.31 while the coefficients m and n for the case of gabion stepped spillways are 0.85 and 0.29. The pressure acting on the step face for the gabion stepped spillways is less than the pressure for the horizontal stepped spillways. The averaged pressure difference is about 27%. It is due to the fact that the filled stones in the gabions absorb the fluid force acting on the step face by the seepage of fluid to the lower void of the mesh boxes.

As the void ratio of gabion boxes is correspondence to the size of filled stone, therefore the impact of flowing water hitting the step face is higher for the case of bigger size of filled stone. However, the magnitude of pressure is not much different.

3.4 Flow resistance of skimming flows under equilibrium condition

For the large roughness elements, there are two types of hydraulic resistance, i.e. skin resistance and form resistance of the steps. In a stepped spillway, the skin roughness is less compared to the form roughness of the steps. With gabion meshes, the rough surface of filled stones and mesh boxes increase the flow resistance. In order to investigate the flow resistance of skimming flows under uniform flow condition, the average shear stress that exists between the skimming stream and the trapped recirculating fluid underneath can be expressed as

$$\tau = d_o \gamma \sin\alpha = \zeta \rho \frac{V_o^2}{8} \qquad (14)$$

where τ is the average shear stress, d_o is the normal flow depth, γ is the specific weight of the fluid, α is the slope of the step = $\tan^{-1}(h/l)$, ζ is the Darcy-Weisbach friction factor, ρ is the density of the fluid, V_o is the constant mean flow velocity. Rearranging, Eq.(14) becomes,

$$\zeta = \frac{8g \sin\alpha \, d_o^3}{q^2} \qquad (15)$$

where g is the acceleration due to gravity and q is the discharge per unit width of the spillway. Considering the concerning variables to the resistance to flow and by neglecting the effects of flow aeration, the correlation of friction factor and importance parameters can be expressed in dimensionless form as

$$\zeta = f_5\left[\frac{K_f}{d_o}, \frac{K_s}{d_o}, \Delta, R_e\right] \qquad (16)$$

where K_f is the form roughness, K_s is the skin roughness, and R_e is the Reynolds number. The dimensionless term K_f/d_o is the relative roughness of the step dimension, K_s/d_o is the relative skin roughness. and Δ is the spillway slope (i.e. $\Delta = \tan\alpha = h/l$). It is found that at high Reynolds number the friction factor is independent of the Reynolds number and the spillway acts as a wholly rough channel. Therefore, Eq. (16) becomes

$$\zeta = f_6\left[\frac{K_f}{d_o}, \Delta\right] \tag{17}$$

The relation of friction factor and relative roughness of the spillway floor, K_f/d_o, where $K_f = h\ cos\alpha$, may be expressed in general form as:

$$\frac{1}{\sqrt{\zeta}} = a + b\ log\left(\frac{d_o}{K_f}\right) \tag{18}$$

The relation between friction factor and relative roughness is plotted as shown in Figure 9. The friction factors are quite scattered but show trend to increase when relative roughness (K_f/d_o) and spillway slope increase. The Reynolds number $R_e = V_o d_o/\upsilon$, with υ being the kinematic viscosity of the fluid, was in the range of 6.2×10^4 to 1.5×10^5. For the range of the experiments in this study, the average friction factors of the horizontal stepped spillways, ζ, for $\alpha = 30^\circ$, 45°, and 60° are 0.63, 0.52, and 0.33, respectively. While the average friction factors of the gabion stepped spillways, ζ, for $\alpha = 30^\circ$, 45°, and 60° are 2.07, 1.73, and 1.51, respectively For the case of gabion stepped spillways, the friction factor is found higher than that of the horizontal stepped spillways about 3.6 times.

Chinnarasri (2002) combined his experimental results of skimming flow over horizontal stepped spillways and others researcher results and suggested that the coefficients a and b in Eq. (18) are 2.00 and 1.19, for the range of spillway slope from 15° to 59° and valid for $0.1 \leq K/d_o \leq 2.1$ (the dash line in Figure 9). The experimental results of the present study on horizontal stepped spillways are found somewhat higher than Chinnarasri (2002) results. Based on the present experimental data, the correlations between friction factor and K_f/d_o for gabion stepped spillways can be expressed as:

$$\frac{1}{\sqrt{\zeta}} = 7.50 + 1.85 log\left(\frac{d_o}{K_f}\right) \tag{19}$$

4 Conclusions

Flow regimes on gabion stepped spillways are observed and can be classified as nappe flow and skimming flow regimes. The onset of skimming flow is characterized by the relation of critical depth/step height (d_c/h) and step height/step length (h/l). The nature of step face influences the energy dissipation process. Generally, the energy loss ratios in the gabion stepped spillways are greater than those in the corresponding horizontal stepped spillways by 10%. As a result, the velocity at the outlet is less. The size and shape of filled stone have small effects on the energy dissipation, within the range of investigation. The other parameters, i.e. spillway slope and spillway drop number have been found to effect the energy dissipation in the same manner as found in the horizontal stepped spillways.

The relationship among the maximum time-averaged pressure on step face and the step drop number is proposed. The pressure acting on the step face for the gabion stepped spillways is less than the pressure for the horizontal stepped spillways. The averaged pressure difference is about 27%. It is due to the fact that the filled stones in the gabions absorb the fluid force acting on the step face by the seepage of fluid to the lower void of the mesh boxes.

The average friction factors of the gabion stepped spillways, ζ, for $\alpha = 30^\circ$, 45°, and 60° are 2.07, 1.73, and 1.51, respectively. For the case of gabion stepped spillways, the friction factor is found higher than that of the horizontal stepped spillways about 3.6 times.

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Lists of symbols

D stone diameter

D_m modified spillway drop number

d_c critical depth of flow

d_o normal flow depth

E_L flow energy loss

g gravitation acceleration

H_i drop height measured from the spillway approach to the step being considered

H_T total drop heights of the stepped channel

h step height

l horizontal length

K_f form roughness

K_s skin roughness

P pressure at a point on a step

q discharge per unit width of spillway

R_e Reynolds number

V_o constant mean flow velocity

V_T flow velocity at the spillway outlet

α slope of the stepped channel

γ specific weight of fluid

x distance from the upstream end of the step to the point being considered

τ average shear stress

ζ Darcy-Weisbach friction factor

ρ density of the fluid

Δ spillway slope (i.e. $\Delta = \tan\alpha = h/l$)

Table 1. Primary details of experimental set A.

Experimental set	α (degree)	H_T (m)	h (m)	l (m)	Run No.	Q (l/s)	v_T (m/s)	d_0 (cm)	Maximum pressure head (cm)				Type of flow
									H_i/h 8	H_i/h 12	H_i/h 16	H_i/h 18	
A-1	30	1.50	0.075	0.130	1	4.08	0.63	*	*	*	*	*	Nappe
					3	12.29	1.78	*	*	*	*	*	Nappe
					5	20.66	2.43	*	*	*	*	*	Transition
					7	28.49	2.79	4.51	12.60	13.53	13.30	15.00	Skimming
					9	35.85	2.95	5.47	14.60	14.90	15.00	15.60	Skimming
					11	44.21	3.13	5.79	14.95	16.50	16.00	16.90	Skimming
					13	51.16	3.24	6.28	15.70	17.30	17.00	17.90	Skimming
					15	58.99	3.35	6.82	18.85	19.15	18.35	19.15	Skimming
					17	68.04	3.43	7.16	22.10	20.90	21.75	21.20	Skimming
A-2	45	2.12	0.106	0.106	1	4.19	1.00	*	*	*	*	*	Nappe
					3	11.67	2.19	*	*	*	*	*	Nappe
					5	19.82	2.75	*	*	*	*	*	Transition
					7	28.49	3.30	*	*	*	*	*	Transition
					9	36.24	3.43	4.45	17.60	15.50	15.90	15.05	Skimming
					11	44.21	3.62	4.76	18.90	16.90	16.90	16.95	Skimming
					13	51.16	3.80	5.25	19.90	18.50	18.20	17.55	Skimming
					15	58.46	3.90	5.88	20.75	20.20	20.20	19.60	Skimming
					17	68.04	4.05	6.39	22.50	22.10	21.30	20.50	Skimming
A-3	60	2.60	0.130	0.075	1	4.41	1.21	*	*	*	*	*	Nappe
					3	11.88	2.37	*	*	*	*	*	Transition
					5	20.38	3.16	*	*	*	*	*	Transition
					7	27.81	3.54	*	*	*	*	*	Transition
					9	36.04	3.83	*	*	*	*	*	Transition
					11	43.33	4.11	4.01	**	19.10	18.40	19.50	Skimming
					13	52.14	4.22	4.22	**	21.90	20.30	21.50	Skimming
					15	58.72	4.39	4.69	**	23.10	21.50	22.00	Skimming
					17	68.04	4.49	5.16	**	24.30	22.60	23.10	Skimming

* The flow is not in skimming flow regimes.

** The flow in skimming flow regimes but not uniform flow.

Table 2. Primary details of experimental set B.

Experimental set	α (degree)	H_T (m)	h (m)	l (m)	Run No.	Q (l/s)	v_T (m/s)	d_u (cm)	Maximum pressure head (cm) H_i/h 8	H_i/h 12	H_i/h 16	H_i/h 18	Type of flow
B-1	30	1.50	0.075	0.130	1	4.08	0.54	*	*	*	*	*	Nappe
					3	12.29	1.37	*	*	*	*	*	Nappe
					5	20.66	2.05	*	*	*	*	*	Transition
					7	28.49	2.45	7.21	12.30	10.30	9.50	10.50	Skimming
					9	35.85	2.62	7.85	13.10	10.80	9.80	10.80	Skimming
					11	44.21	2.82	8.62	14.30	11.20	10.50	11.10	Skimming
					13	51.16	2.99	9.37	14.80	11.60	11.20	11.40	Skimming
					15	58.99	3.12	9.87	15.50	11.90	11.60	12.10	Skimming
					17	68.04	3.19	10.19	16.10	12.10	12.10	12.80	Skimming
B-2	45	2.12	0.106	0.106	1	4.24	0.66	*	*	*	*	*	Nappe
					3	11.47	1.55	*	*	*	*	*	Nappe
					5	19.54	2.35	*	*	*	*	*	Transition
					7	29.71	2.86	*	*	*	*	*	Transition
					9	36.84	3.13	6.82	13.70	12.70	13.20	12.60	Skimming
					11	43.77	3.25	7.53	14.40	13.30	13.70	13.60	Skimming
					13	50.92	3.44	8.14	15.30	13.60	14.20	14.10	Skimming
					15	60.04	3.54	8.56	15.90	15.10	15.70	15.40	Skimming
					17	68.04	3.61	8.97	16.50	15.40	16.20	15.90	Skimming
B-3	60	2.60	0.130	0.075	1	3.97	0.77	*	*	*	*	*	Nappe
					3	12.29	2.00	*	*	*	*	*	Transition
					5	20.10	2.75	*	*	*	*	*	Transition
					7	28.15	3.10	*	*	*	*	*	Transition
					9	36.04	3.38	*	*	*	*	*	Transition
					11	44.65	3.58	6.88	**	12.30	11.90	11.70	Skimming
					13	52.14	3.70	7.34	**	12.90	12.60	12.60	Skimming
					15	60.31	3.84	7.69	**	13.20	13.40	13.80	Skimming
					17	68.04	3.94	8.31	**	14.00	14.20	14.30	Skimming

* The flow is not in skimming flow regimes.

** The flow in skimming flow regimes but not uniform flow.

Table 3. Primary details of experimental set C.

Experimental set	α (degree)	H_T (m)	h (m)	l (m)	Run No.	Q (l/s)	v_T (m/s)	d_0 (cm)	Maximum pressure head (cm)				Type of flow
									H_i/h 8	H_i/h 12	H_i/h 16	H_i/h 18	
C-1	30	1.50	0.075	0.130	1	4.08	0.56	*	*	*	*	*	Nappe
					3	12.29	1.49	*	*	*	*	*	Nappe
					5	20.95	2.15	*	*	*	*	*	Transition
					7	28.49	2.50	7.15	14.10	10.50	11.00	10.00	Skimming
					9	36.24	2.69	7.76	14.90	11.60	11.50	10.70	Skimming
					11	45.10	2.89	8.37	15.90	12.50	11.70	11.40	Skimming
					13	51.16	3.01	9.00	16.50	12.70	12.00	11.80	Skimming
					15	59.25	3.12	9.74	17.50	13.10	12.50	12.60	Skimming
					17	68.04	3.20	10.48	18.20	13.60	13.10	13.10	Skimming
C-2	45	2.12	0.106	0.106	1	4.08	0.64	*	*	*	*	*	Nappe
					3	12.40	1.65	*	*	*	*	*	Nappe
					5	20.38	2.43	*	*	*	*	*	Transition
					7	29.36	2.89	*	*	*	*	*	Transition
					9	35.65	3.16	6.67	13.90	12.80	13.70	12.60	Skimming
					11	43.33	3.29	7.45	15.40	13.40	14.50	13.80	Skimming
					13	51.16	3.43	8.03	16.10	14.20	14.80	15.10	Skimming
					15	59.78	3.60	8.41	16.80	15.10	15.30	16.10	Skimming
					17	68.04	3.72	8.87	18.00	16.20	15.90	17.80	Skimming
C-3	60	2.60	0.130	0.075	1	4.41	0.89	*	*	*	*	*	Nappe
					3	11.67	2.05	*	*	*	*	*	Transition
					5	20.10	2.81	*	*	*	*	*	Transition
					7	28.15	3.12	*	*	*	*	*	Transition
					9	36.24	3.41	*	*	*	*	*	Transition
					11	44.21	3.63	6.51	**	11.10	12.50	12.90	Skimming
					13	52.38	3.74	7.23	**	12.90	13.50	13.90	Skimming
					15	60.04	3.88	7.61	**	14.20	15.50	16.10	Skimming
					17	68.04	3.96	8.27	**	16.30	16.00	16.50	Skimming

* The flow is not in skimming flow regimes.

** The flow in skimming flow regimes but not uniform flow.

Table 4. Primary details of experimental set D.

Experimental set	α (degree)	H_T (m)	h (m)	l (m)	Run No.	Q (l/s)	v_T (m/s)	d_0 (cm)	Maximum pressure head (cm) H_i/h 8	H_i/h 12	H_i/h 16	H_i/h 18	Type of flow
D-1	30	1.50	0.075	0.130	1	4.19	0.49	*	*	*	*	*	Nappe
					3	12.08	1.28	*	*	*	*	*	Nappe
					5	19.96	1.93	*	*	*	*	*	Transition
					7	28.49	2.37	7.35	12.10	10.20	11.10	12.10	Skimming
					9	36.24	2.60	7.87	13.30	11.90	11.60	12.90	Skimming
					11	44.21	2.77	8.57	14.10	13.20	12.20	13.80	Skimming
					13	50.68	2.87	9.40	14.60	14.60	15.10	15.30	Skimming
					15	58.72	3.02	9.89	15.40	15.20	15.90	15.10	Skimming
					17	68.04	3.12	10.79	16.10	16.00	16.60	16.60	Skimming
D-2	45	2.12	0.106	0.106	1	4.08	0.63	*	*	*	*	*	Nappe
					3	12.40	1.71	*	*	*	*	*	Nappe
					5	20.38	2.32	*	*	*	*	*	Transition
					7	29.36	2.75	*	*	*	*	*	Transition
					9	35.65	2.95	6.76	12.30	13.60	14.40	13.60	Skimming
					11	43.33	3.15	7.43	14.50	15.20	14.70	14.70	Skimming
					13	51.16	3.35	7.93	15.50	16.00	15.40	15.90	Skimming
					15	59.78	3.47	8.38	16.20	17.60	16.70	16.50	Skimming
					17	68.04	3.58	8.93	16.70	17.90	17.40	18.20	Skimming
D-3	60	2.60	0.130	0.075	1	4.08	0.80	*	*	*	*	*	Nappe
					3	12.29	2.00	*	*	*	*	*	Transition
					5	19.27	2.75	*	*	*	*	*	Transition
					7	27.98	3.08	*	*	*	*	*	Transition
					9	36.44	3.29	*	*	*	*	*	Transition
					11	44.21	3.50	6.68	**	14.60	14.10	14.40	Skimming
					13	51.65	3.62	7.18	**	15.70	14.60	15.00	Skimming
					15	59.51	3.82	7.74	**	16.30	15.40	15.60	Skimming
					17	68.04	3.87	8.54	**	17.60	17.40	17.10	Skimming

* The flow is not in skimming flow regimes.

** The flow in skimming flow regimes but not uniform flow.

Table 5. Summary of characteristics of experimental studies.

Ref.	Flume width (m)	Slope (deg.)	Step height h (m)	Remarks
Stephenson (1988)	0.38	18.4	0.15	1. Number of steps = 4
		26.6	0.15	2. Type of transition: Nappe to Skimming flow
		45	0.15	
Peyras et al. (1992)	0.80	18.4	0.20	1. Number of steps = 3, 4, and 5
		26.6	0.20	2. Discharge = 0.04 to 0.27 m^2/s
		45	0.20	3. Type of transition: Nappe to Skimming flow
Present study	0.40	30	0.075	1. Number of steps = 20
		45	0.106	2. Type of transition: Nappe to Transition flow and
		60	0.130	Transition to Skimming flow

Figure captions:

Figure 1 Schematic diagram of experimental set-up

Figure 2 Gabion dimension in millimeters

Figure 3 Flow regimes; a) nappe flow regime and b) skimming flow regime

Figure 4 Onset of skimming flow on gabion stepped spillways

Figure 5 Variables in dimensional analysis

Figure 6 Relationship between energy dissipation on gabion stepped spillways and modified spillway drop number

Figure 7 Flow velocity at spillway outlet and modified spillway drop number

Figure 8 Relationship between maximum pressure on steps and step drop number

Figure 9 Friction factor of skimming flows under equilibrium condition

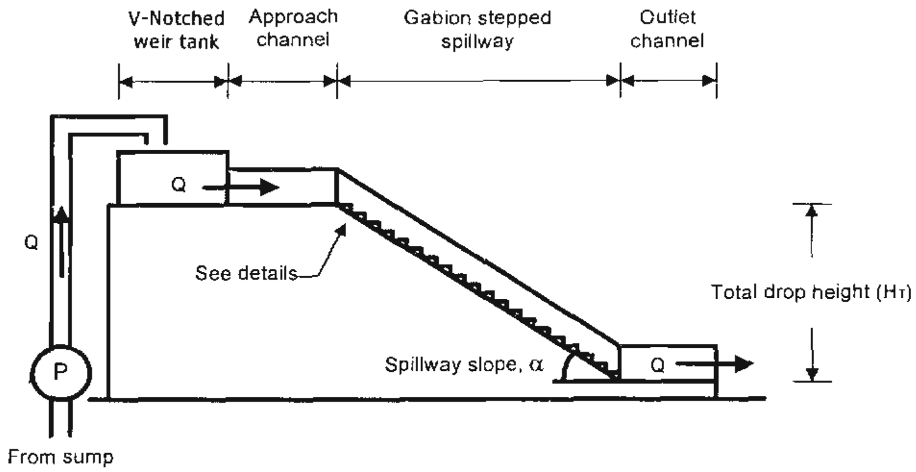

Figure 1 Schematic diagram of experimental set-up

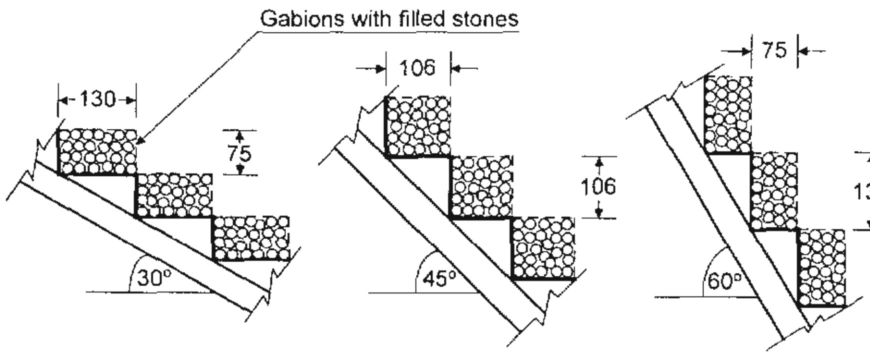

Figure 2 Gabion dimension in millimeters

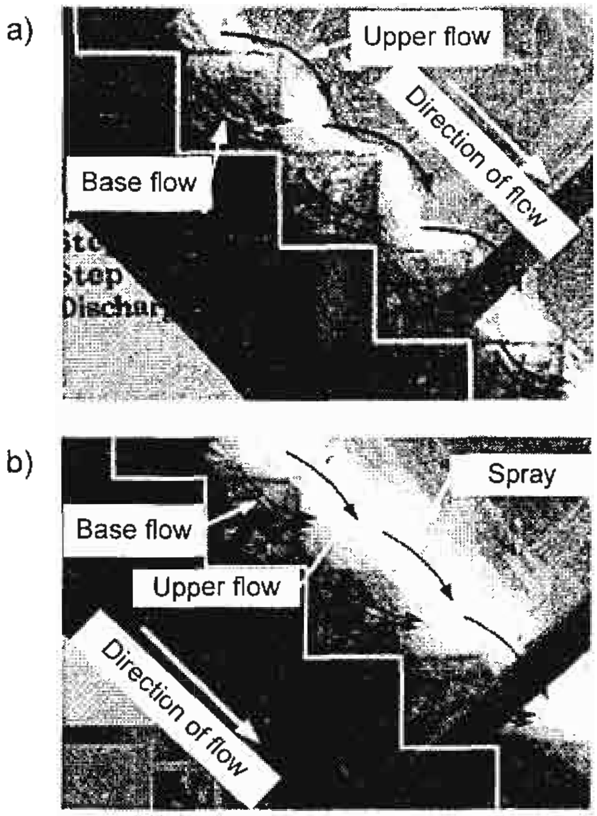

Figure 3 Flow regimes; a) nappe flow regime and b) skimming flow regime

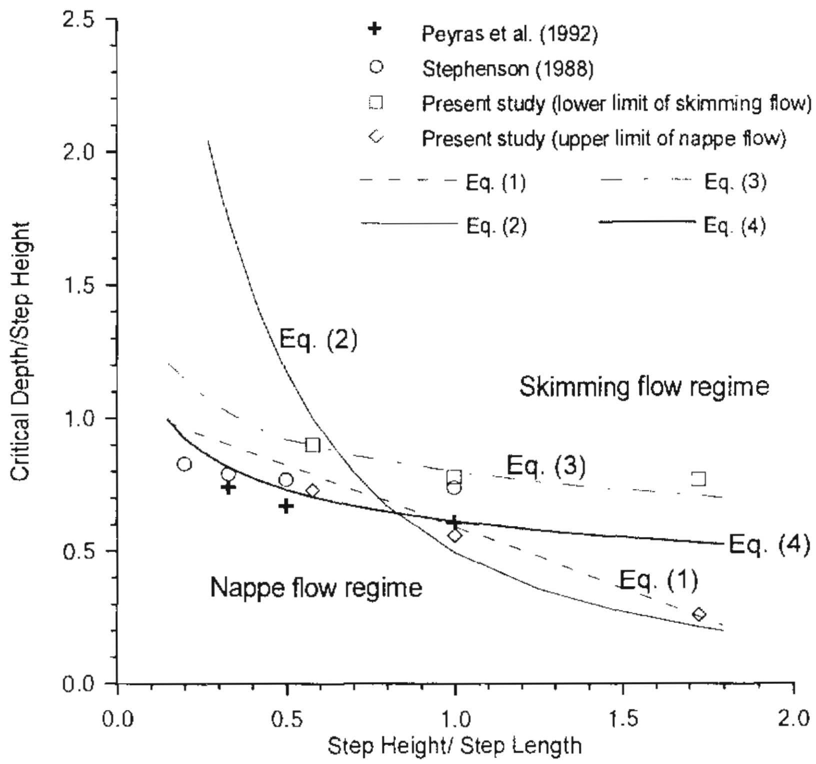

Figure 4 Onset of skimming flow on gabion stepped spillways