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EFFECT OF OFFTAKE CHANNEL BASE ANGLE OF STEPPED SPILLWAY ON SCOUR HOLE*

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Abstract– Scour holes formed downstream from a stepped spillway may affect the safety and stability of a structure. The development of such scour hole can cause failure of the structure by undermining the riverbed, thus it is important to develop criteria that result in understanding how such a scour hole can develop. The literature contains many studies dealing with energy dissipation, aeration and oxygen transfer in stepped spillways. However, their downstream scour hole depth and geometry is not well documented. In this study, a physical model is employed to study the impact of offtake channel base angle of stepped spillways on the scour hole. The area of the longitudinal profile of the scour hole is used to evaluate the amount of scour at downstream from the stepped spillways. Experimental results showed that the takeoff angle of 30^{o} is the optimum angle which gives minimum longitudinal area and maximum depth of the scour hole.

Keywords– Stepped spillway, offtake channel base angle, scour hole geometry, scour depth

1. INTRODUCTION

Roller compacted concrete (RCC) stepped spillways have increased in popularity as a method of rehabilitating aging watershed dams. Urban sprawl, topographic features, and property owner rights have placed limitations on the ability to alter the dimensions of the existing dam or auxiliary spillway. An advantage of installing a RCC stepped spillway is that it can be placed over the top of the existing dam; thus, engineers are allowed to disregard other design alternatives due to limitations caused by the increased development in the vicinity of the dam. Energy is dissipated by friction through the chute channel. The stepped spillway is a more economical alternative to other conventional spillways.

Scour occurs naturally due to erosive effects of flowing water including the morphological changes of rivers and also due to the construction of all types of structures in water ways. Excessive scouring can progressively undermine the foundations of hydraulic structures and cause failure. The scour downstream of hydraulic structures constitutes an important field of research due to its frequent occurrence in engineering applications. [1]

At the downstream of cascades, the flow is generally supercritical and is followed by a hydraulic jump in the energy dissipator with baffle blocks, and it is possible that dentate sills flow is subcritical at the end of this section. The form of the scour depends on many factors (for example, the submergence, the tailwater depth, and the degree of dissipation of the jet energy).

Many researchers have studied scour downstream of hydraulic structures such as grade-control structures, pipe outlets, and stilling basins. Typical examples were investigated by Blaisdell and Anderson [2] and Rice and Kadavy [3]. Gijs et al., [4] studied local scour downstream of hydraulic structures.

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Farhoudi and Smith [5] studied the scour profiles downstream of a spillway. They found a similarity relationship for the temporal variation of the scour profiles. A detailed review of the foregoing works and further studies was given by Simons and Senturk [6]. The scour process was experimentally studied by [7-12], among others. A number of empirical and semi-empirical relationships were developed for predicting the scour resulting from two-dimensional jets. Breusers and Raudkivi [1] provided an interesting and useful synthesis of much of the work done on scour below various types of hydraulic structure. Ghobadian and Bajestan [13] investigated the sediment patterns at river confluence [14]. Talebbeydokhti and Aghbolaghi [15] investigated the scour depth of bridge piers. In one work Emiroglu and Tuna [16] conducted an experimental study to determine the maximum scour depth at downstream of the stepped chutes and developed the equations.

In literature, there are many studies about energy dissipation, aeration and oxygen transfer in the stepped spillways. However, their downstream scour depth and geometry is not well documented. In the present study, the effect of chute angle, on scour hole geometry and maximum scour depth at the downstream of the stepped-chutes (or cascades) was investigated experimentally.

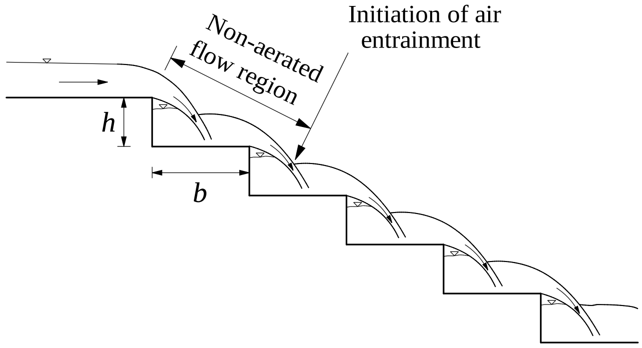
2. STEPPED-CHANNEL CHUTES

The mechanisms by which air is entrained and transferred into water because of a stepped-channel chute are several and complex. Three basic air entrainment mechanisms are described in stepped-channel chutes. These are skimming flow regime, transition flow regime and nape flow regime. A description of these mechanisms is given below.

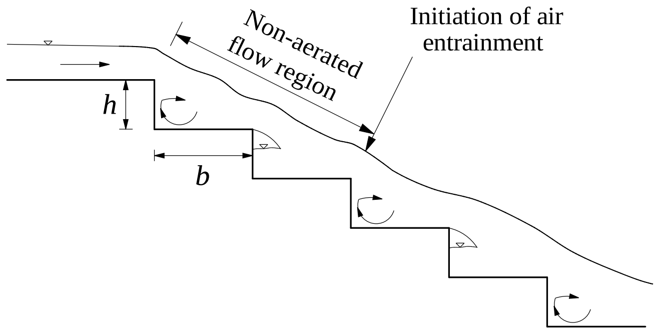
For large discharges, the water flows down a stepped-channel chute as a coherent stream “skimming” over the steps. The external edges of the steps form a pseudo-bottom over which the flow skims. Beneath the pseudo-bottom, re-circulating vortices develop and recirculation is maintained through the transmission of shear stress from the main stream (Fig. 1a). Small-scale vorticity is also generated at the corner of the steps. The aerated flow region follows a region where the free-surface is smooth and glassy. Next to the boundary, however, turbulence is generated and the boundary layer grows until the outer edge of the boundary layer reaches the surface. When the outer edge of the boundary layer reaches the free surface, the turbulence can initiate natural free surface aeration. The location of the start of air entrainment is called the point of inception. Downstream of the inception point of free-surface aeration, the flow becomes rapidly aerated and the free-surface appears white. Air and water are fully mixed forming a homogeneous two-phase flow [17].

Ohtsu and Yasuda [18] were probably the first to introduce the concept of a “transition flow” regime, although they did not elaborate on its flow properties. For a given stepped-channel chute geometry, a range of flow rates gives an intermediary flow regime between nape flows at low discharges and skimming flows at large flow rates. In the transition flow regime, air bubble entrainment takes place along the jet upper nape and in the spray region downstream of the stagnation point. Since the flow is highly turbulent, air and water are continuously mixed (Fig. 1b). The air entrainment process in transition flow is not yet fully understood [17]. The transition flows have very different characteristics from both nape and skimming flows. Dominant features include intense droplet ejection and spray.

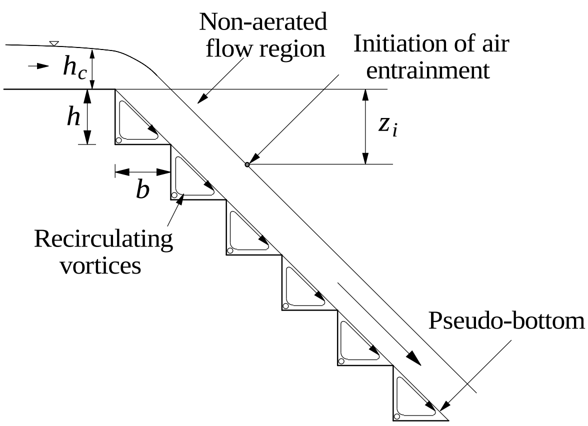
For a given flat step geometry, low flows behave as a series of free-falling jets with nape impact onto the downstream step: i.e. nape flow regime. At the upstream end of each step, the flow is characterized by a free-falling nape, an air cavity and a pool of recirculating fluid (Fig. 1c). In a nape flow, air is entrained at the jet interfaces and by a plunging jet mechanism at the intersection of the lower nape with the recirculating pool, while de-aeration is often observed downstream. In the free-falling nape, interfacial aeration takes place at both the upper and lower napes. At the lower nape, the developing shear layer is characterized by a high level of turbulence and significant interfacial air entrainment is observed [17].



(a) Nappe flow regime



(b) Transition flow regime



(c) Skimming flow regime

Fig. 1. Air Entrainment Mechanisms above Stepped-Channel Chute

Three different flow regimes, namely the nape, the transition and the skimming flow regimes occur in stepped spillways, depending on step height, and chute angle and unit discharge. As shown in Fig. 2, a tendency towards the nape flow regime was observed with increasing step height and decreasing chute angle [19]. For small steps or larger discharges, the water generally flows over the stepped chute in skimming flow regime. The transition from nape to skimming flow can be expressed as the ratio of critical flow depth h_c and step height h [20]. Skimming flow begins with ratios larger than

$$\frac{h_c}{h} = 0.91 - 0.14\tan\alpha \quad (1)$$

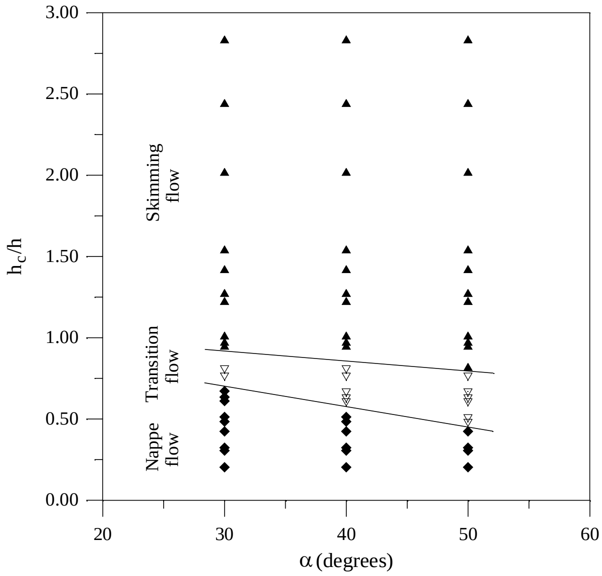


Fig. 2. Classification of flow conditions in stepped spillways [18]

For stepped spillways, the step height is often governed by the dam construction procedure. The maximum unit discharge is either determined by the spillway width due to limited site conditions, or by hydraulic constraints. The maximum unit discharge on the stepped chute should not exceed $30m^3$/s.m because the energy dissipation capacity may decrease. In selecting the step height of a stepped spillway, the designer usually chooses from a certain range of values determined by the dam construction procedure. For RCC dams, for example, the step height is usually one to four times the thickness of a compacted lift of typically 0.3 m, i.e., between 0.3 m and 1.2 m. Hydraulic considerations are cavitation potential and energy dissipation [20]. A stepped chute design significantly increases the rate of energy dissipation taking place along the spillway face, and eliminates or reduces greatly the need for a large energy dissipater at the toe of the chute [21]. If there is a significant drop in the land surface, increased slope of a canal in soil may lead to undesirable erosion. Stepped chutes dissipate a larger portion of the hydraulic energy than the corresponding conventional chutes or spillways. Some investigators have studied various mechanisms attached to the steps or adverse slopes on the steps to force a hydraulic jump on the steps and increase energy dissipation [22].

In a recent experimental work Tuna and Emiroglu[23] explained that step geometry, downstream water levels and the sill types of the stilling basin are very important parameters for the geometry of the scour hole.

3. MATERIALS AND METHODS

The experiments were conducted using an experimental apparatus in the Hydraulic Laboratory at the Engineering Faculty of Firat University, Elazig, Turkey. The experimental work was performed in a stepped cannel-chute with a re-circulating flow system. A schematic diagram of the experimental set-up is given in Fig. 3, showing a prismatic rectangular chute channel, 0.30 m wide and 0.50 m deep, in which the steps were installed. The sidewalls were made of transparent methacrylate in order to monitor the flow regime. Models of stepped spillway with three offtake angles (30^o, 40^o, 50^o) were tested to find the angle resulting in a minimum scour hole. Also, recorded were maximum scour depths. Water was pumped from the storage tank to the stilling tank, from which water entered the chute through an approach channel, with its bed 2.75 m above the laboratory floor. Experiments were conducted using a glass sided flume with a layer of sand on its bed in order to help simulate actual conditions. The flume is 2.50 m in length, 0.30 m in width and 0.50 m in height. It is equipped with a shutoff valve, which was used to control the water flow rate. In this study, models of spillways were prepared from steel. Longitudinal slope of the flume is kept constant during the experiments. Experiments were done with different flow rates in order to test the effect of flow on scour depth. Each model is tested using four different flow rates which are categorized as minimum, medium, high and maximum flow rates. The measured values of the minimum, medium, high and maximum flow rates were $17.24x10^{-3}$ m^2/s, $34.48x10^{-3}$ m^2/s, $51.72x10^{-3}$ m^2/s and $68.96x10^{-3}$ m^2/s respectively. Step height h was determined as 0.05, 0.10, and 0.15 m.

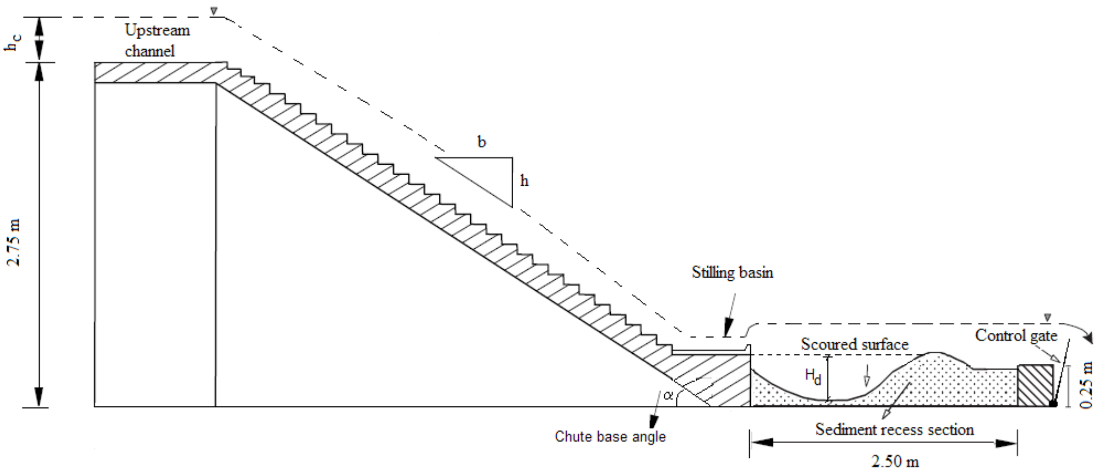


Fig. 3. Laboratory stepped spillway apparatus (not scale)

The stilling basin, a cross section of which is shown in Fig. 4, was placed at the end of the stepped chute Stilling basin sill height was taken as, 0.0 (without sill), 0.02 and, 0.04 m.

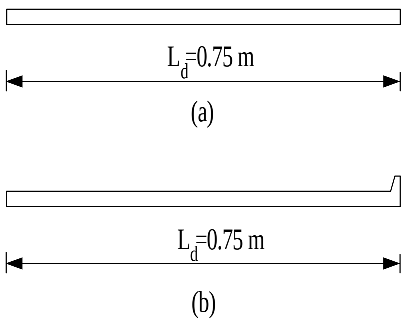


Fig. 4. Stilling basin sill types

As seen in Fig. 3, a relief structure (control gate) was placed at the end of the downstream channel in order to adjust tailwater level (control gate height, z=0.25, z=0.30 and z=0.35 m). As a result, tailwater depth changed in range between 0.026-0.17 m.

In the downstream pool, a material with 0.25 m thickness and two gradations of non-cohesive bed material were used. A sieve analysis was carried out to determine the grain size distribution for each material of sand, the results of which are shown in Fig. 5. From this, the median grain size (d_{50}) and coefficient of uniformity ($C_u = (d_{85} - d_{16})/d_{50}$) were obtained. Mass density of the bed material (ρ_s) was obtained using a vacuum air removal technique. Porosity (n) was determined by first evaluating the dry unit weight (γ_d), and then calculating the void ratio ($e = G_s\gamma_w / \gamma_d - 1$), where G_s is specific gravity (sometimes abbreviated s.g.) that indicates how much heavier than water a given substance is. The porosity was then calculated from $n = e/(1+e)$. Table 1 shows a summary of the test conditions.

Table 1. Characteristics of the bed material

Sediment type	d_{50} (mm)	Coeff. of uniformity C_u	Specific gravity (s.g.) G_s	Porosity *n (%)*	Geometric standard deviation σ_g
M1	3.17	0.55	2.65	37	1.30
M2	9.94	0.73	2.65	37	1.39

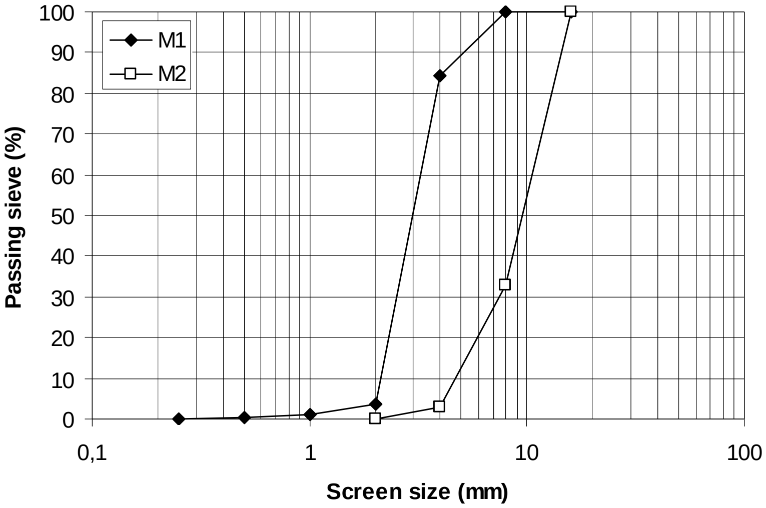


Fig. 5. Sediment size curve (M1, M2)

Water level and scour depth measurements were taken with precision electronic limnimeter, ± 0.01 mm sensitive. Discharges were measured with an electromagnetic flowmeter. Flow (water jet) velocities were measured with an acoustic velocity meter.

After the scour depth reached the equilibrium state, the profile of the scour hole was recorded. A total of 216 experiments were conducted. After each experiment, in order to determine the scour hole geometry, measurements were conducted in directions of *X*, *Y*, and *Z* and a cross-section of the area where the maximum scour depth occurred was produced from the obtained data.

4. RESULT AND DISCUSSION

The stepped spillway is cheaper than other conventional types of spillways and it is effective in dissipating water energy. Scouring hole at downstream is the main problem encountered when using spillways. So for safety and stability of the structure, special attention must be given to monitoring scour holes formed at downstream. Offtake channel base angle may affect the scour hole and it is necessary to recommend the optimum angle that causes minimum scour hole at downstream of the stepped spillway. Experiments were conducted to determine the maximum scour depth and scour geometry on the downstream of the stepped spillways. In this study, it is observed that the area of the longitudinal profile and maximum depth of scour hole changed with offtake channel base angle and the flow rate. Experiments were carried out for different tail water depths. Tailwater depths were changed between 0.06 m and 0.17 m.

Three different flow regimes, namely the nape, the transition and the skimming flow regimes, occur in stepped spillways, depending on step height, and chute angle and unit discharge. A tendency towards the nape flow regime was observed with increasing step height and decreasing chute angle. Moreover, the results showed a tendency towards the transition flow regime as chute angle increased. A decrease was observed in nape flow regime as chute angle increased. The results indicate that for all chute angles, a tendency towards the nape flow regime occurs with increasing step height. In addition, a tendency towards the skimming flow regime was observed as chute angle increased.

Figure 6 shows the depth of scour hole for different offtake channel base angle and flow rates. The results demonstrate that the maximum scour depth increases with the increase in both the chute angle and the unit discharge. For α =30°, 40° and α =50°, H_{dmax}/h values were obtained as 0.00 to 1.22, 0.00 to 1.47 and 0.10 to 1.92, respectively.

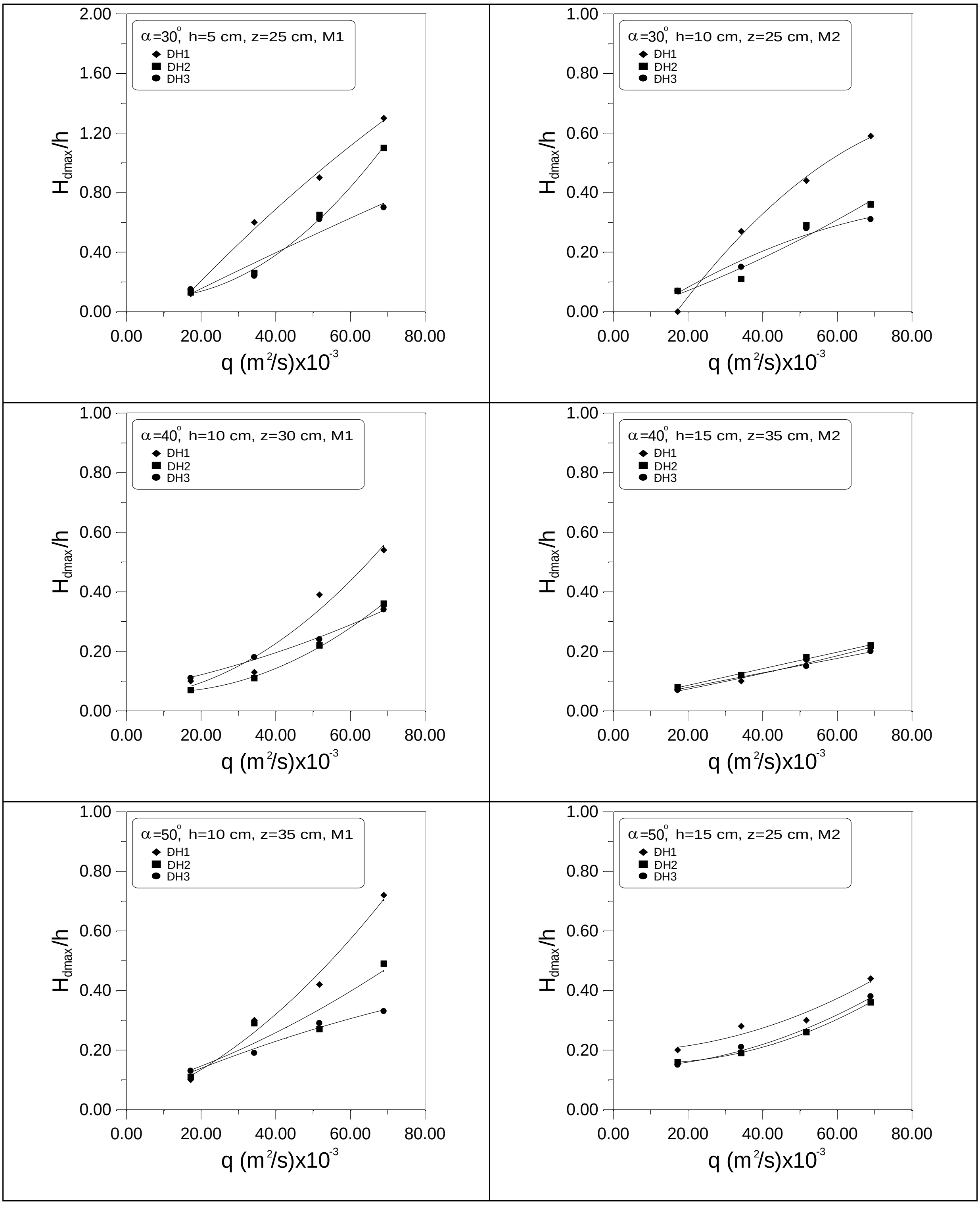


Fig. 6. Relationship of offtake channel base angle with the maximum scour depth

Figure 7 shows that for all experiments with stepped-channel chutes, the H_d values decrease with increasing tailwater level. The reason for this is that the energy of the jet that formed the scour was dissipated by diving into the water bag that was formed when the tailwater level increased. Previous research has shown that the dynamics of local scour is dependent on the tailwater depth.

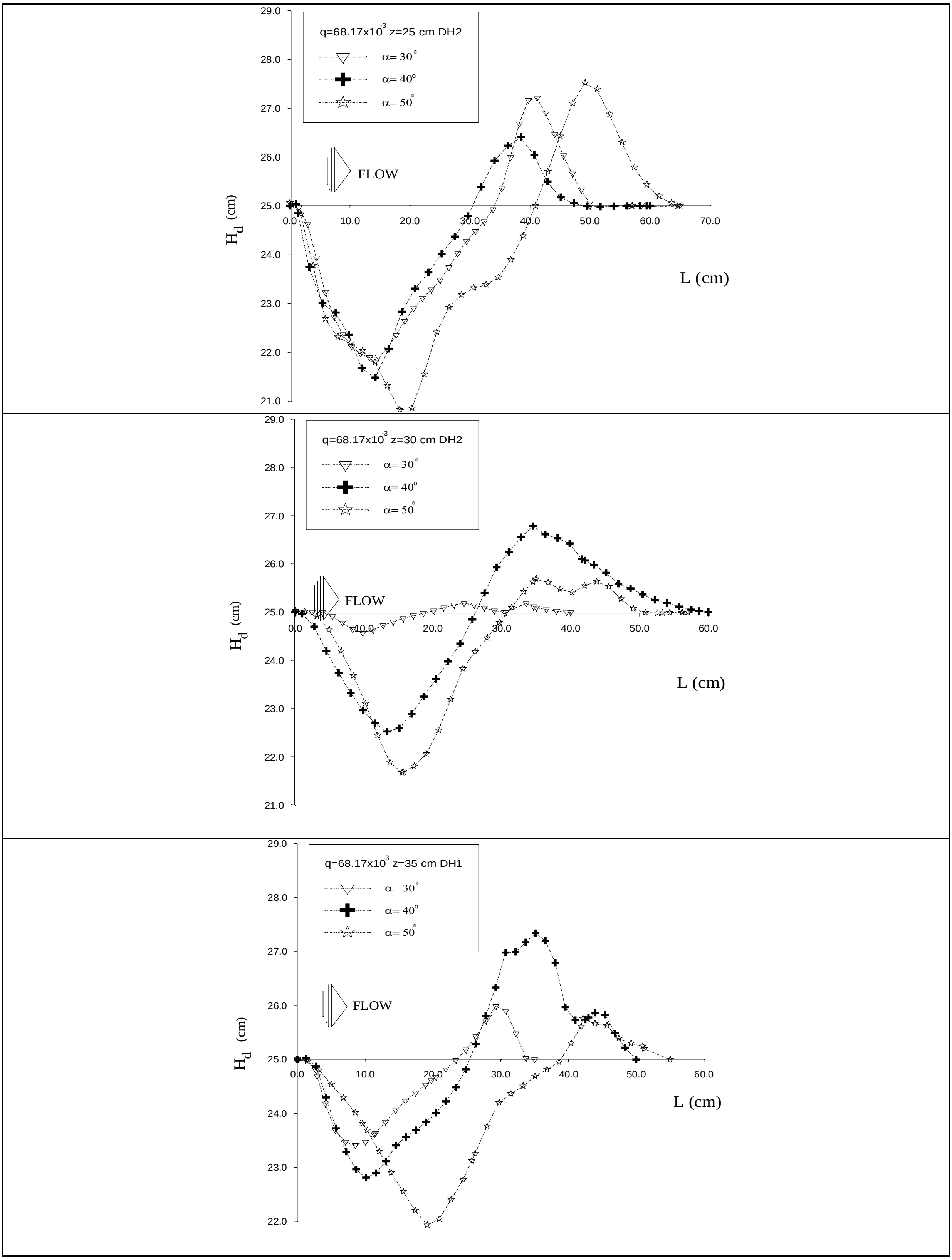
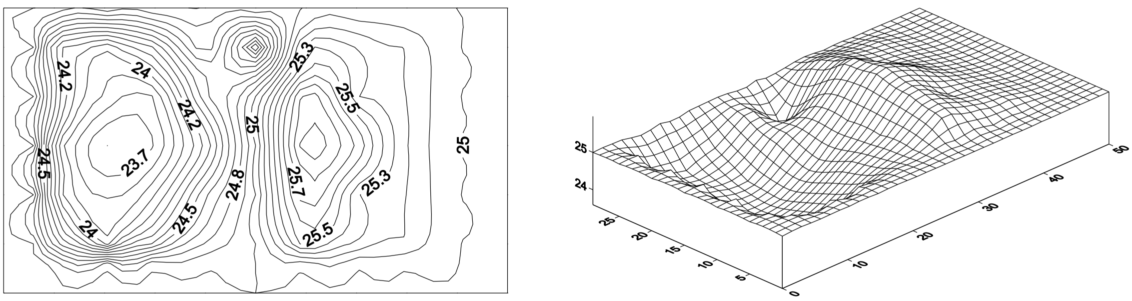
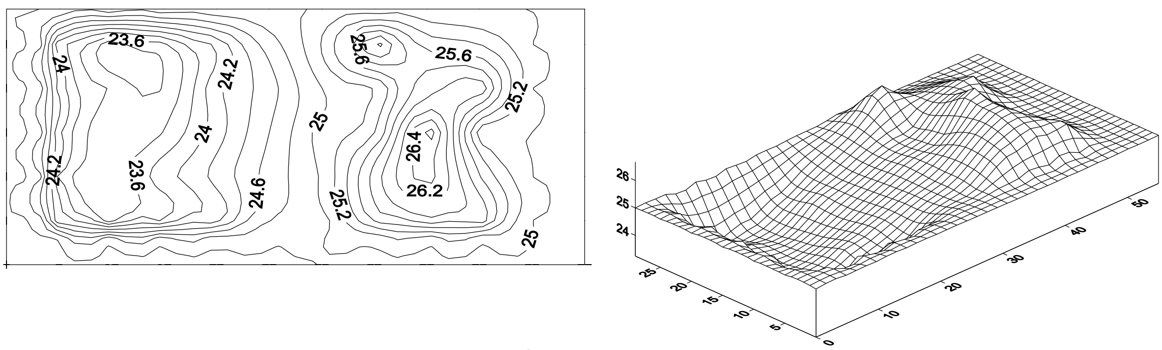


Fig. 7. Cross-section from maximum scour depth area with different chute base angle

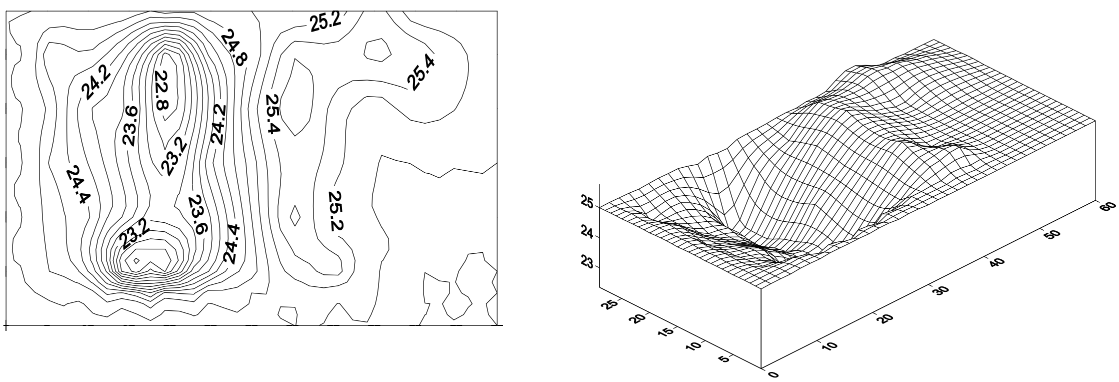
Figure 7 and 8 shows the effect of offtake channel base angle on the area of the scour hole for different flow rates. For minimum unit discharge, it is observed that the area is small for all tested angles. As a result, the impact of the offtake channel base angle on area of the profile of scour hole is obvious. It is also observed that there is a marginal difference (20%) between the areas of the longitudinal profile of scour holes which resulted from offtake channel base angles of 30^o and 50^o. This is attributed to the fact that high offtake channel base angle will have a retarding action to reduce the velocity and momentum. So, the energy of water jet for offtake channel base angles of 40^o and 50^o is higher than the energy of jets for 30^o offtake channel base angle. However, the difference between the energy of water jets (for offtake channel base angles of 40^o and 50^o) is small. This indicates that stepped spillway is more effective in dissipating water energy than the conventional spillway.



α=30^o, q=34,48 x10^{-3} m^2/s, z=25 cm, DH2, M2



α=40^o, q=34,48x10^{-3} m^2/s, z=25 cm, DH2, M1



α=50^o, q=34,48x10^{-3} m^2/s, z=25 cm

(a)Two-dimensional contour line (b)Three-dimensional representation of the scour hole

Fig. 8. Relationship of stepped-chute base angle with the scour geometry

Figure 9 shows that, the scour depth increases as the chute angle increases. This is because the energy dissipation ratio for high chute angles is less than that of small chute angles for the same total height of the chute.

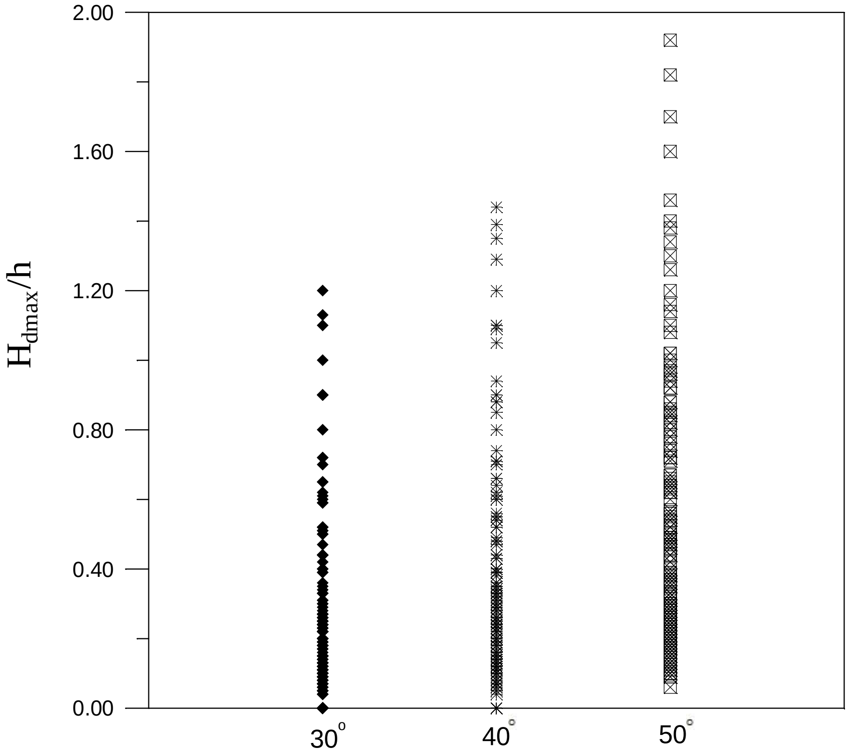


Fig. 9. Relationship of stepped-chute base angle and H_{dmax}/h

Proportional to increase in offtake channel base angle, measured velocity at the end of the stilling basin also increased. Scour depth increased with the rise of flow velocity. In the range of $0<v_o<0{,}10$ m/s, no scour was formed in any of the experimental groups. In the experimental groups with velocity v_o >2.00 m/s, the biggest depth of the scour was occurred.

Scour data were compared with equations in Table 2. After a review of the literature, no relevant work could be found on scours that occur in the downstream of stepped-channel chutes. However, there are a lot of studies related to conventional chute channels and spillways. Several studies in the literature were given in Table 2. Here d declares the scour depth is calculated by using the other investigators equations. As seen in Table 2, the values of maximum scour depth at the downstream of classical spillways are greater than those of stepped-channel chute and the results are convenient according to the literature. When conventional spillways are compared with stepped spillway, it is seen that stepped spillways dissipate about 70 to 80% of total energy and thus a small stilling basin is necessary at the downstream of the hydraulic structure for dissipating the residual energy.

Table 2. Scour equations for downstream of the hydraulic structures

No (1)	Source (2)	Scour equation (3)	Description (4)	Scour depth (cm) (5)	d (6)
1	Veronese (1937)	$d_s = 1.9 H_1^{0.225} q^{0.54}$	Free falling jet. (recommended by the USBR, 1987)	27.90	2.80
2	Novak (1961)	k=0.65 and k=0.45 $d_s = k\left[6 h^{0.25} q^{0.50} \left(\frac{h}{d_m}\right)^{1/3}\right]$	Energy dissipation stilling basin	53.50	5.38
3	Kotulas (1967)	$d_s = 0.78 \frac{h^{0.35} q^{0.70}}{d_{90}^{0.40}}$	Free jet spillway (negligible jet – air mixture)	67.20	6.75
4	Mpiri (1967)	$\frac{d_s}{Z_3} = \frac{0.355 (q H_1)^{0.50}}{\left[g d_{50}^2 (Z_3 + h_2)^3\right]^{0.25}}$	Flip bucked	24.70	2.48
5	Chian (1973)	$d_s = 1.18 H_1^{0.235} q^{0.51}$	Flip bucked	36.30	3.65
6	Çataklı (1973)	For sill k=1.62; without sill k=1.42 to 1.53 $d_s = k \frac{q^{0.6} (H_1 + h_2)^{0.20}}{d_{90}}$	Stilling basin	30.60	3.08
	Wu (1973)	$\frac{d_s}{H_1} = 2.11 \left(\frac{q}{\sqrt{qH_1^3}}\right)^{0.51}$	Flip bucked	22.10	2.22
7	Martins (1975)	$d_s = 1.5 q^{0.6} H_1^{0.1}$	Free jet spillway	27.70	2.78
8	Taraimovich (1978)	$d_s = (5.5 - 6.0) h_c \tan \phi_u \quad ; \phi_u = 45^o$	Flip bucked	53.00	5.32
9	Machado (1982)	$d_s = 1.35 \frac{C_v^{0.5} H_1^{0.3145} q^{0.50}}{d_{90}^{0.0645}}$	Free jet (rock bed)	35.50	3.56
10	Mason (1984)	$d_s = 3.27 \frac{q^{0.60} H_1^{0.05} h_2^{0.15}}{q^{0.30} d^{0.10}}$	Free jet (negligible air water mixture)	28.90	2.90
12	Mason and Arumugan (1985)	$d_s = (6.42 - 3.1 h_2^{0.1}) (q^{(0.6 - 0.0033)}.$ $H_1^{(0.15 - 0.005 H)} h_2^{0.15} / g^{0.3} d^{0.1})$	Free jet scour below dams and flip bucket	38.60	3.88
14	Hoffman and Pilarczyk (1995)	γ=0.34 to 0.40 $\frac{d_s}{H_1} = \left(\frac{t}{t_1}\right)^{\gamma}$	Scour below hydraulic structures	17.00	1.71
15	Rajaratnam (1998)	$\frac{d_s}{d} = 0.5 \frac{v_o}{\sqrt{(gD \Delta\rho / \rho)}}$	Circular horizontal jets	24.90	2.50
16	Emiroglu and Tuna(2010)	$\tilde{d}_{s\max} = 0.028 + 0.02\mathbf{F}_d^{1.287} + \exp\left[\begin{array}{l} -1.43\mathbf{F}_d^{-0.207} + 0.17(\sin(\alpha))^{78.903} + 1.27\tilde{b}^{0.599} \\ -0.58\tilde{h}_t^{-0.459} + 9.67\tilde{d}^{1.233} \end{array}\right]^{2.725}$	Stepped-chute	9.95	1.00

5. SUMMARY AND CONCLUSION

The present study has been set out to test the effect of offtake channel base angle and flow rate on scour hole formed at downstream of stepped spillway. A physical model simulating the scouring at downstream of stepped spillway is employed. The results demonstrate that the maximum scour depth increases with the increase in both the chute angle and the unit discharge. Among three different offtake channel base angles for the stepped spillway, results obtained from the experiments revealed that the best offtake channel base angle is 30^o. The area of the longitudinal profile of scour hole formed at downstream of the stepped spillway was found minimum when the offtake channel base angle is 30^o. Generally, the scour pattern is not symmetrical and the maximum scour occurs either on the left or on the right from the longitudinal center line of the downstream channel. Flow rate, offtake channel base angle and downstream water level are very important parameters over the maximum scour depth and scour hole geometry.

Unlike clear water open channel flow, highly turbulent air-water flow cannot be modeled precisely, i.e. without scale effects, largely due to the relative invariance of bubble size. The experiments described in this paper cover unit discharges that are smaller than some prototype applications.

NOMENCLATURE

b	step length
d_{50}	bed material diameter which is finer by weight
h	step height
H	total height of stepped-channel chute
H_{dmax}	maximum scour depth
g	acceleration of gravity
h_c	critical flow depth
L	length of stepped-channel chute
q	water discharge per unit width
v_o	velocity of water jet
z	control gate height
α	chute angle
ρ	mass density of the water,
ρ_S	mass density of the bed material
e=	void ratio
n=	porosity
Δ=	s-1
γd =	dry unit weight of the particles
γs =	unit weight of the particles
γw =	unit weight of the water
ν=	kinematic viscosity of water

Abbreviations

DH1	stilling basin without sill
DH2	stilling basin sill height with 0.02 m
DH3	stilling basin sill height with 0.04 m
M1	thin sediment, d_{50}= 3.17 mm
M2	thick sediment, d_{50}= 9.94 mm

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