Eng. & Tech. Journal ,Vol.27 , No. 16 ,2009

Study of Conveniency of Using Stepped Spillway in Roller Compacted Concrete Dams (RCCD)

Dr. Karim K. EL- Jumaily* & Mariam Khudair Al- Lami**

Received on:29/10/2008
Accepted on:6/8/2009

Abstract

A suggested design of Bastora stepped spillway has been taken as a prototype to build a physical wooden model with scale of **1:20** (L_m/L_p). Experiments have been carried out on the model with slope of upward inclined steps of **42^0**, **28^0**, **14^0** and **0^0**. For every slope of the steps, experiments were conducted in three flow regimes, nappe, transition, and skimming. As observed in experiments, the increase in the slope of steps has no significant effect on the flow behaviour over stepped spillway. The hydraulic depths of flow over the model were measured and the energy dissipation rate was calculated. Results show that the energy dissipation decreases with increasing the discharge, and the energy dissipation of flow on stepped spillways with upward inclined steps is more than on the horizontal stepped spillways, it increases with increasing the adverse slope of steps.

Keywords: stepped spillway, energy dissipation, inclined steps.

دراسة مدى ملاءمة استخدام المطفح المتدرج في السدود الكونكريتية المرصوصة بالحدل

الخلاصة

تم تناول التصميم المقترح لمطفح باستورا المتدرج كنموذج حقيقي لانشاء النموذج الفيزيائي من مادة الخشب بمقياس ٢٠:١ ($L_p\backslash\ L_m$). تم اجراء التجارب على النموذج عند ميل مختلف للدرجات المائلة للاعلى (**42^0**، **28^0** ، **14^0**، و٠^0). عند كل ميل للدرجات، اجريت التجارب لأنظمة الجريان الثلاثة (nappe ، transition ،and skimming). وكما لوحظ في التجارب، فأن الزيادة في ميل الدرجات ليس لها تأثير كبير على سلوك الجريان فوق المطفح المتدرج. تم قياس الاعماق الهيدروليكية للجريان فوق النموذج وتم حساب معدل تشتيت الطاقة. تبين النتائج ان تشتيت الطاقة يقل بزيادة التصريف، وان تشتيت طاقة الجريان على المطافح المتدرجة بدرجات مائلة للأعلى يكون اكثر من المطافح المتدرجة بدرجات افقية، فهي تزداد بزيادة الميل العكسي للدرجات.

Introduction

Stepped spillway have been used for centuries [1]. In the 1970s, the regain of interest for the stepped spillway design has been associated with the development of new construction materials (e.g., roller compacted concrete (RCC)) [2]. The advantages of using a stepped spillway compared with equivalent smooth spillway are compatibility with the RCC placement method, a significant increase in the rate of energy dissipation taking place on the spillway face, reduction of the dissipation basin size and the risks of

---

* **Building and Construction Engineering Department, University of Technology / Baghdad**
** **College of Engineering/ University of Mustansirya / Baghdad**

scouring, reduction in the risk of cavitation, an increase in the discharge capacity and low cost [3].

The step geometry can be horizontal, inclined (upward or downward) or pooled [4].

Flows over stepped spillways are complex, consequently, most hydraulic studies of such flows are performed on physical models. Viscous forces cannot be ignored when modeling highly turbulent air-water flow and must be considered when determining the scale of a Froude model for stepped spillways [5]. Two sets of tests on modeled stepped spillways, 1:10 and 1:20 scale models are conducted by [6]. Based on the results of the sequent depth of the hydraulic jump at the toe of the spillways, he reported that models at scales of 1:20 and larger (e.g., 1:10, 1:15) could represent the prototype behaviour of stepped spillways. Then, gravity effects are predominant but it is recognized that surface tension scale effects can take place for $L_r > 10$ to 20 [7-8].

Energy dissipation can be estimated by the indirect (hydraulic jump) method, it consists of measuring the sequent depths of a hydraulic jump forced in a stilling basin at the base of the chute [9].

Experimental work:

The section of Bastora stepped spillway which is suggested by Al-Ghazali (2008) is used as a prototype in the present study. The physical model of Bastora dam spillway is made of high density overlay plywood ,Fig. (1). the scale of this model is selected to be 1:20 (L_m/L_p) to prevent scale effects.

By using the geometric similarity, the vertical height of the model (difference between the crest and toe elevation) is 412.5 cm ,Fig. (2). The horizontal length between the upstream and downstream of model is 457.5 cm . The width of model is 31.3 cm . The downstream slope of model is 1:1.11 .

This model consists of 92 steps with bottom adverse slope (inclined upward) with slope (ά) 42^0 for each one. All steps are with height of 4.5 cm and length of 5 cm except the first step, near a crest, which is with height of 2 cm and length of 2.7 cm .

The kinematic similarity is used to convert the maximum flow passing over the prototype (design discharge) to the equivalent flow passing over the model, as a result, it equals (0.01028 m^3/s) (10.28 l/s). The maximum head above the model crest (at this discharge) is (5.75 cm.). At the maximum discharge, the residual energy equals (42.65 cm.).

At the bottom of the stepped spillway, a horizontal channel, placed attached to the base of the last step, to represent a stilling basin ,Figs. (2), (3), and (4). At the downstream end of the basin, an adjustable weir allows a hydraulic jump to be formed at the toe of the stepped model ,Fig. (5). Hence with this present facility, the residual energy has been estimated indirectly by measuring the downstream sequent depth (Y_2) of the hydraulic jump by using a point gauge.

This model was painted such that its roughness coefficient becomes very low, in agreement with the concrete roughness coefficient.

As shown in ,Figs. (3), and (4), an underground storage tank with capacity more than ($1m^3$) was made from concrete beside model to represent a water supply storage for the model. Electro pump with (12 l/s) capacity was used to supply energy for transfer water from the concrete storage tank through a (3) inches pipe to the (25×75×31.3 cm) acrylic channel located upstream the model. To reduce turbulence in the flow, an acrylic sharp crested weir with height of (12 cm) was installed at the mid-distance in the upstream channel.

Flowmeter and control valve are installed in the supply line to measure the quantity of discharge and control on it, respectively ,Figs. (3), and (4).

To investigate the effect of step inclination on the amount of energy dissipation, four angles of steps (ά) were tested, three of which were upward angles of inclined steps, (42^0, 28^0, and 14^0), and the fourth angle is (0^0) (horizontal steps)

Four stages of runs were carried out on the stepped spillway model depending on the changing in the steps inclination. (25) runs were carried out in each stage to cover the three types of flow ranging from (0.0015 m^3/s) at nappe flow regime to (0.011 m^3/s) at skimming flow regime, including the design discharge (0.01028 m^3/s). At any discharge of these runs, a hydraulic jump was forced in the rectangular stilling basin at the base of the model to measure the sequent depth (Y_2).

Results and discussion:

For low discharges, free falling nappe is found at the brink of the inclined steps, an air cavity, and a pool of recirculating water are observed at each step which are the same as the flow behaviour on horizontal steps ,Fig. (6).

For intermediate discharge, the succession of free jet disappeared. The free surface of the flow is wavy with spray and the flow is characterized by presence of air cavities for some steps and onset of vortices in a filled step for the rest ,Fig. (7).

dam crest and disappears at so-called inception point, where, the air entrainment is started ,Fig. (8).

At these discharges which are included the design flow (0.01028 m^3/s), the vortices are trapped inside the steps, above it, the flow skims as a coherent stream over a pseudo-bottom is formed by the outer edge of the steps. When, the slope of steps increases, these vortices become larger with more spray and more stable than those in the smaller slopes of steps ,Fig. (9).

The measured downstream sequent depths (Y_2) of the hydraulic jump are used in the following equation to calculate the upstream sequent depths (Y_1) of the hydraulic jump.

$$Y_1 = \frac{Y_2}{2}\left(\sqrt{1+8Fr_2^2}-1\right) \qquad (1)$$

with $Fr_2^2 = \frac{q_w^2}{gY_2^3}$, the Froude number of the downstream section.

The residual energy (H_{r1}) is calculated by using the following equation.

$$H_{r1} = Y_1 + \frac{aq_w^2}{2gY_1^2} \qquad (2)$$

With α the kinetic correction coefficient, for turbulent flow, generally, α = 1.1, q_w the unit water discharge and g is the Gravitational acceleration.

The residual energy (H_{r1}) is plotted versus the discharge as shown in ,Fig. (10).

As observed in ,Fig. (10), at low discharges (nappe flow regime), the residual energy at the toe of model is small and decreases slightly with increase in the slope of steps where, most of the flow energy is dissipated because of jet breakup and jet mixing on the step. The residual energy increases as the discharge increases. It becomes the largest for well developed skimming regime, because the steps become less efficient to energy dissipation as the discharge increases. Their influence is cushioned by the large skimming layer. As the angle of the steps increases, the residual energy decreases because the upward inclined steps obstruct the flow, trapping recirculation vortices on the chute steps.

The energy dissipation is estimated by using the following equation.

$$\frac{\Delta H}{H_{\max.}} = \frac{H_{\max.} - H_{r1}}{H_{\max.}} \qquad (3)$$

where $H_{max.}$= H_{sp} + 1.5 y_c is the total energy head at the crest of the dam, H_{sp} the total height of spillway above the downstream toe, and y_c the critical depth which is measured at the crest of model at all discharges [11].

As shown in ,Fig. (11), and in agreement with [12] the nappe flow is the most dissipative regime. In this regime of flow, the increase in angle of steps has little effect upon ($\Delta H/H_{max.}$). The greatest angle of inclined steps ($\acute{\alpha}=42^0$) increases the energy dissipation by less than (3%) compared with horizontal steps ($\acute{\alpha}=0^0$), as most of the flow energy is dissipated by jet disintegration and nappe impact.

Fig. (11) shows that for well developed skimming regime, the steps become less efficient to energy dissipation as the discharge increases. Their influence is cushioned by the large skimming layer. An inclined step increases the energy dissipation by about (6%) for the greatest angle of inclined steps ($\acute{\alpha}=42^0$). As the upward angle of the inclined steps increases, the energy loss increases because the steps obstruct the flow, trapping recirculation vortices on the chute steps. Larger flow circulations result, which are more stable than those in the smaller angles of inclined steps. Therefore, more energy is dissipated on this kind of structure.

As shown in ,Fig. (12), at nappe flow, an inclined steps increase slightly the energy dissipation, where at any stage of increasing of steps slope, the energy dissipation increases by less than (1%), because most of the flow energy at this regime is dissipated over the steps by jet breakup and jet mixing on the steps.

As transition flow, the energy dissipation rate becomes more sensitive to the increasing in the angle of steps as shown in ,Fig. (12). While the greatest effect of increasing in the slope of steps on energy dissipation rate is observed at large discharges (skimming flow). at any stage of increasing of steps slope, the energy dissipation increases by about (2%)

until the increases become about (6%) at the greatest angle of upward steps ($\acute{\alpha}=42^0$), where the flow is characterized by more spray and larger vortices are trapped inside the inclined steps, therefore, more energy of flow is dissipated.

Conclusions:

1. The flow behaviour over the model with horizontal steps at the design flow (0.01028 m^3/s) corresponds to its behaviour which is described over the prototype by [10] where the flow regime at this discharge is skimming flow with trapping the vortices inside the steps.
2. Flow regimes on chutes with upward inclined steps can be classified as those are found in horizontal steps, nappe flow, transition flow, and skimming flow regimes.
3. The increasing of slope of steps has no significant effect on the upper limit of nappe flow, but results in a small increment in the lower limit of skimming flow where more discharge is needed to establish the onset of skimming flow.
4. For dams with low discharge over the spillway, stepped shape spillway can be dissipated most of the flow kinetic energy (about 99%), and the need for construction of stilling basin at the toe of spillway becomes negligible.
5. At low discharges, increase in the slope of steps has no significant effect on the energy dissipation where the horizontal steps dissipate most of the energy.
6. For dams with large discharges over the spillway, the upward inclined type of stepped spillway can be more effective than horizontal type where an upward inclined step causes more energy dissipation than horizontal steps (about 6% at $\acute{\alpha}=42^0$).

References:

1.Murillo, R.E., “Experimental Study of the Development Flow Region on Stepped Chutes.” Ph.D. Dissertation, University of Manitoba, Canada, (2006).

2. Chanson, H. and Toombes, L., "Experimental Investigation of Air Entrainment in Transition and Skimming Flows down A Stepped Chute." Can. J. of Civil Eng., 29: 145-156, (2002).

3. Chanson, H. and Gonzalez C.A., "Physical Modelling and Scale Effects of Air-Water Flows on Stepped Spillways." J. of Zhejiang University Science, 6A (3):243-250, (2005).

4. Gonzalez, C. A. and Chanson, H., "Stepped Spillways for Embankment Dams: Review, Progress and Developments in Overflow Hydraulics." Intl. Conf. on Hydraulics of Dams and River Structures, Tehran, Iran, 287-294, (2004).

5. Frizell, K.H., " Research State-of-the-Art and Needs for Hydraulic Design of Stepped Spillways" US Bureau of Reclamation, Denver, Colorado, USA, (2006).

6. Pegram, G.G.S., Officer A.K., and Mottram, S.R., "Hydraulics of Skimming Flow on Modeled Stepped Spillways." J.Hydr. Eng., ASCE, 125(5): 500-510, (1999).

7. Wood, I. R., " Air Entrainment in Free Surface Flows." Ian Wood (ed), IAHR, Hydraulic Structures Design Manual, Vol. 4, Balkema, Rotterdam, chapter 3, 55-84, (1991).

8. Chanson, H., "Forum Article. Hydraulics of Stepped Spillways:

Current Status." J. of Hydr. Eng., ASCE, 126(9): 636-637, (2000).

9. Andre, S., “High Velocity Aerated Flow on Stepped Chutes with Macro-Roughness Elements.” Ph.D. Dissertation, Ecole Polytechnique Federale de Lausanne (EPFL), Lausanne, Switzerland, (2004).

10. Al-Ghazali, O.S., " Evaluation of some Design Parameters of Bastora Roller Compacted Concrete Dam " Ph.D. Dissertation, University of Technology, (2008).

11. Toombes, L., "Experimental Study of Air-Water Flow Properties on Low-Gradient Stepped Cascades." Ph.D. Dissertation, University of Queensland, Australia, (2002).

12. Chamani, M.R. and Rajaratnam, N. ,"Jet Flow on Stepped Spillways." J. Hydr. Eng., ASCE, 120(2):254-259, (1994).

Figure (1) The section of model

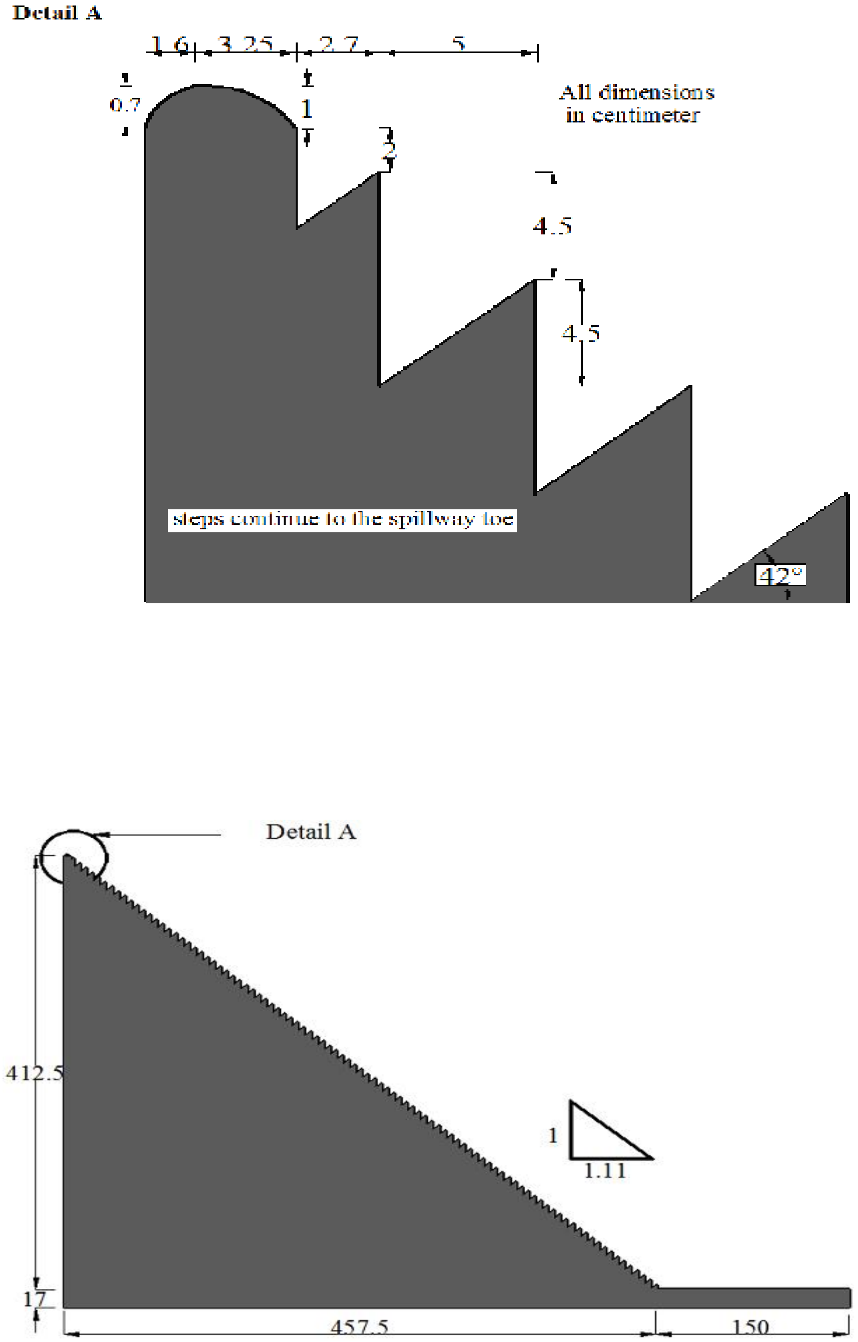


Figure (2) Details of a physical model.

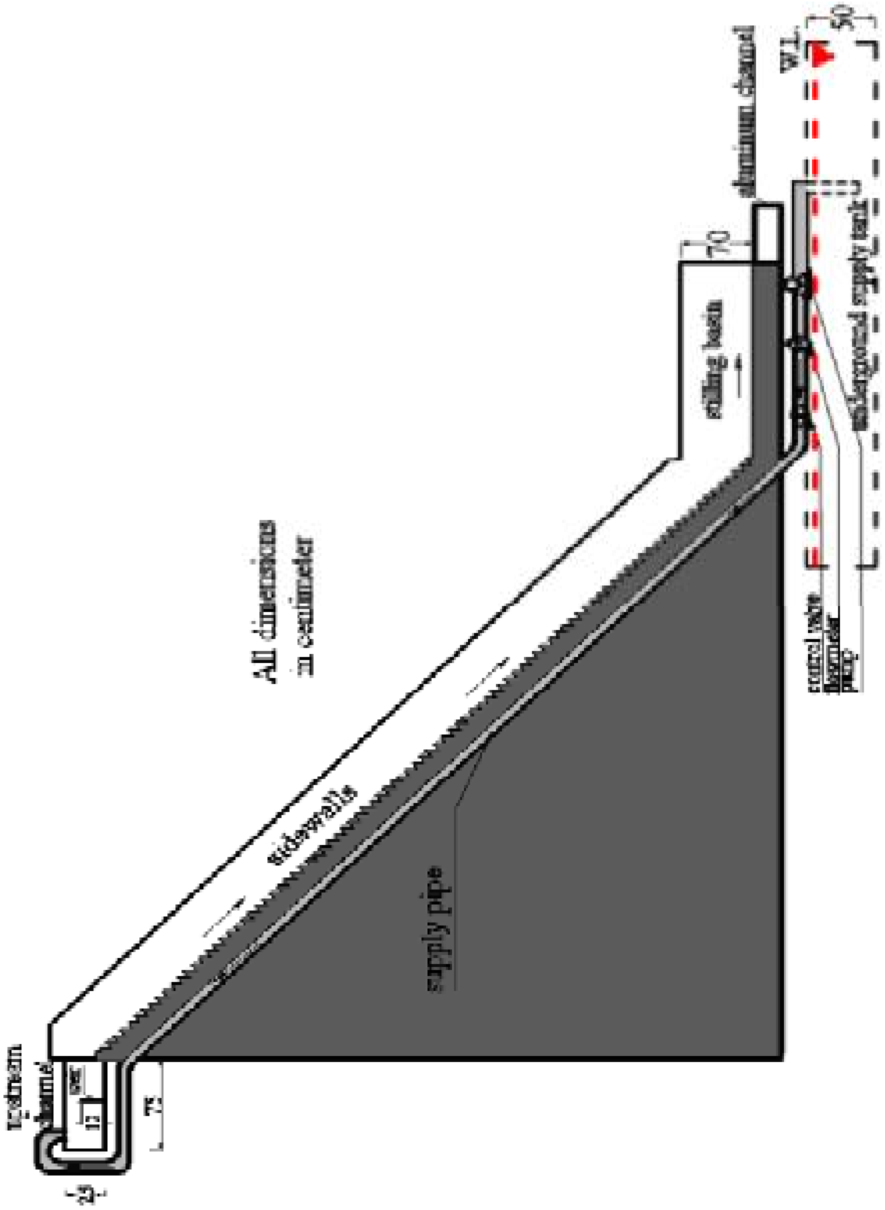


Figure (3) A schematic side view of experimental arrangement for stepped spillway model.

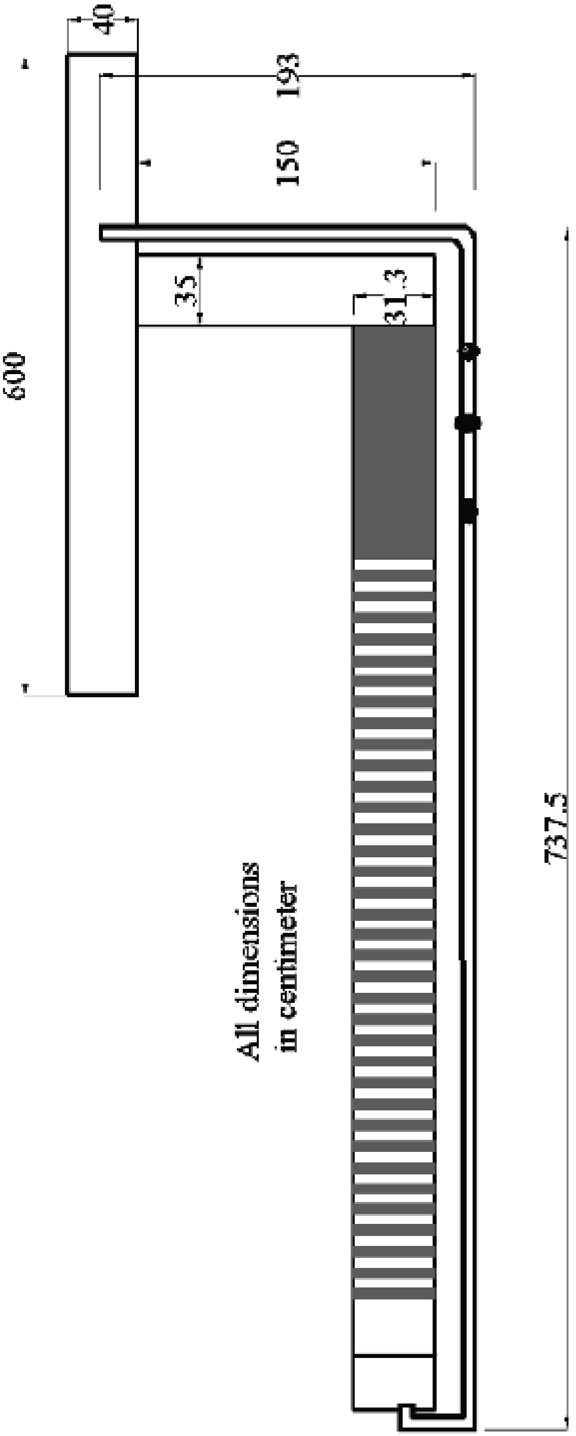
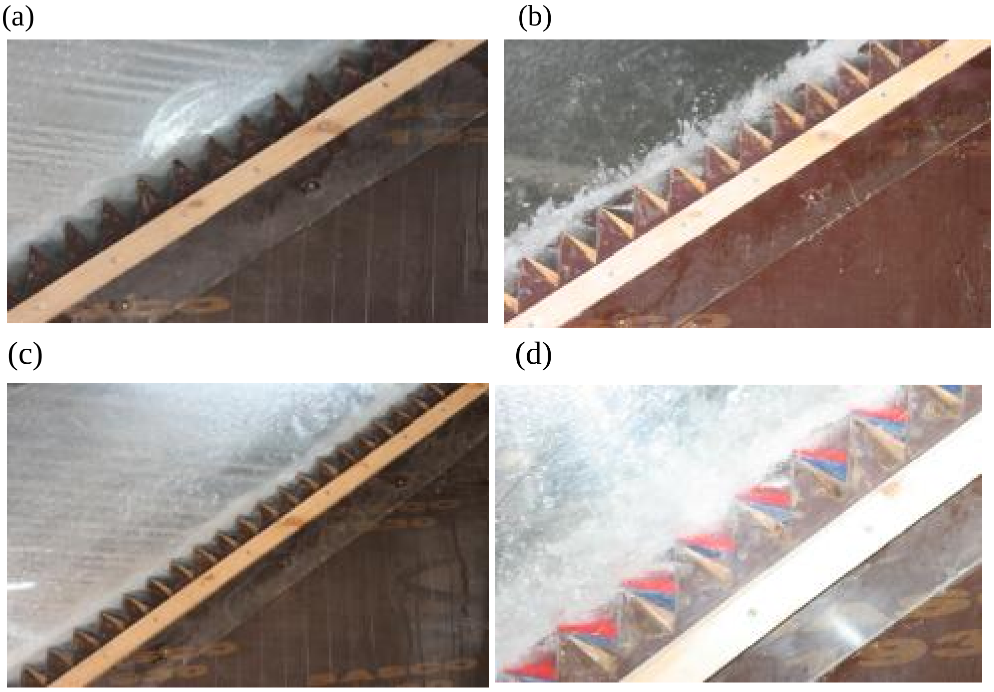


Figure. (4) A schematic top view of experimental arrangement for stepped spillway model.

Figure (5) The hydraulic jump forced at a stilling basin.



(a) (b) (c) (d)

Figure.(6) The nappe flow regime on model at (Q=0.003 m^3/s).

(a) ά=42^0. (b) ά=28^0. (c) ά=14^0. (d) ά=0^0.

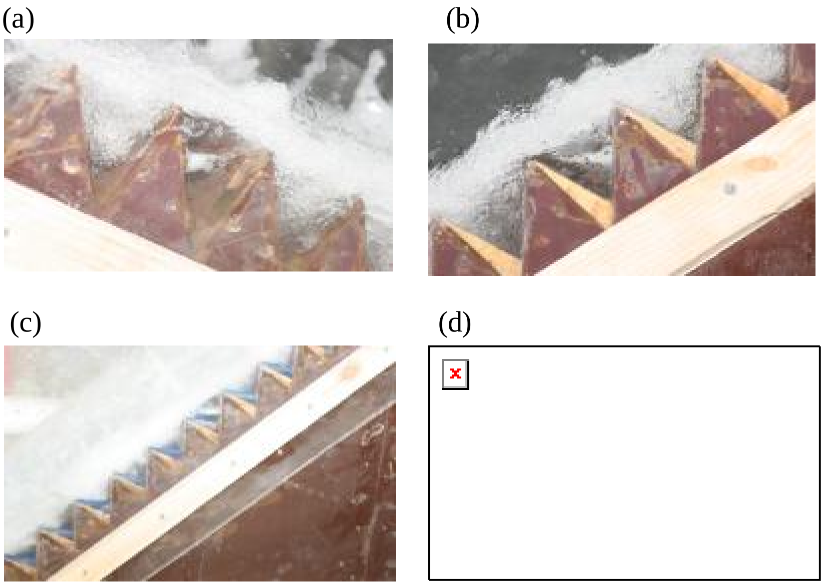


Figure (7) The transition flow regime on model at (Q=0.006 m^3/s).

(a) ά=42^0. (b) ά=28^0. (c) ά=14^0. (d) ά=0^0

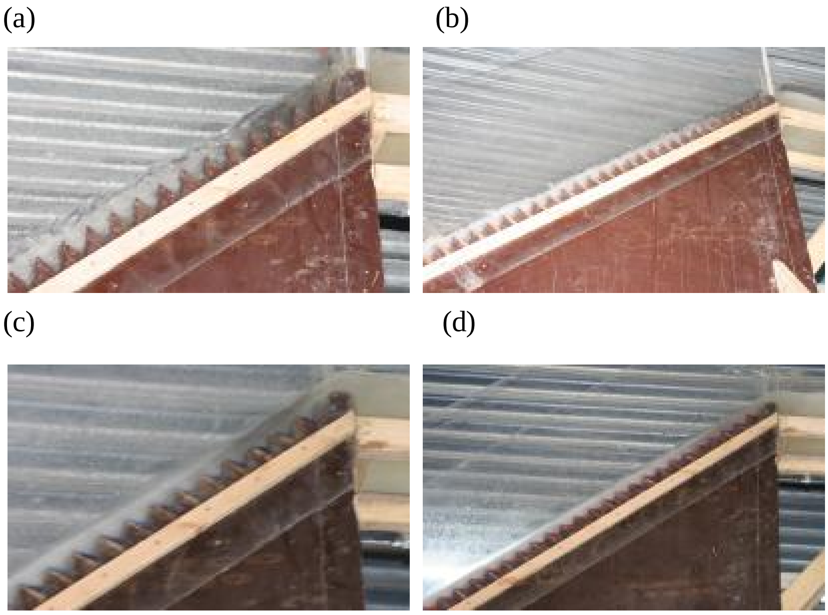


Figure (8) The appearance of inception point at (Q=0.01028 m^3/s).

(a) ά=42^0. (b) ά=28^0. (c) ά=14^0. (d) ά=0^0.

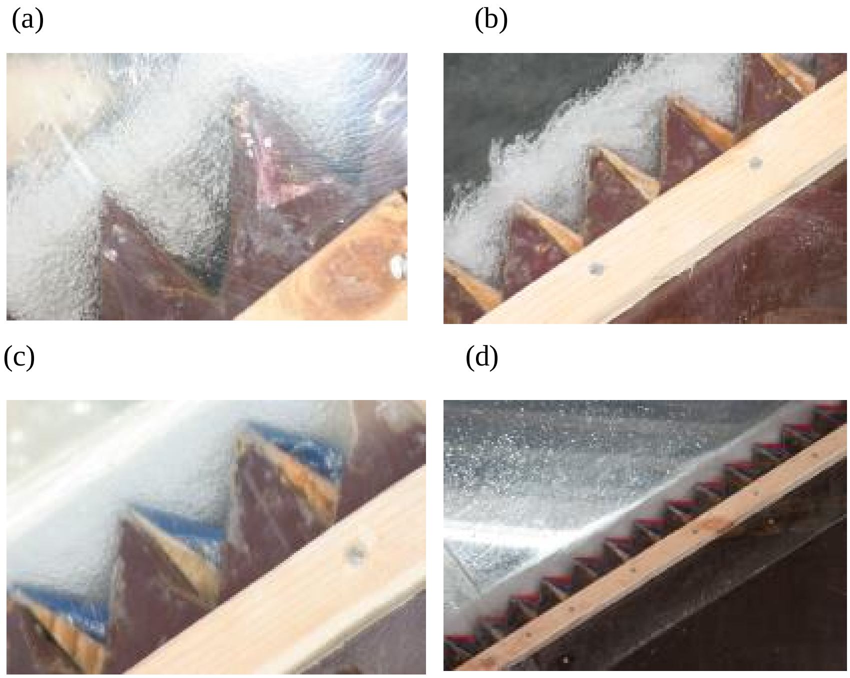


Figure (9) The skimming flow regime on model at ($Q=0.01028\ m^3/s$).
(a) ά=42^0. (b) ά=28^0. (c) ά=14^0. (d) ά=0^0.

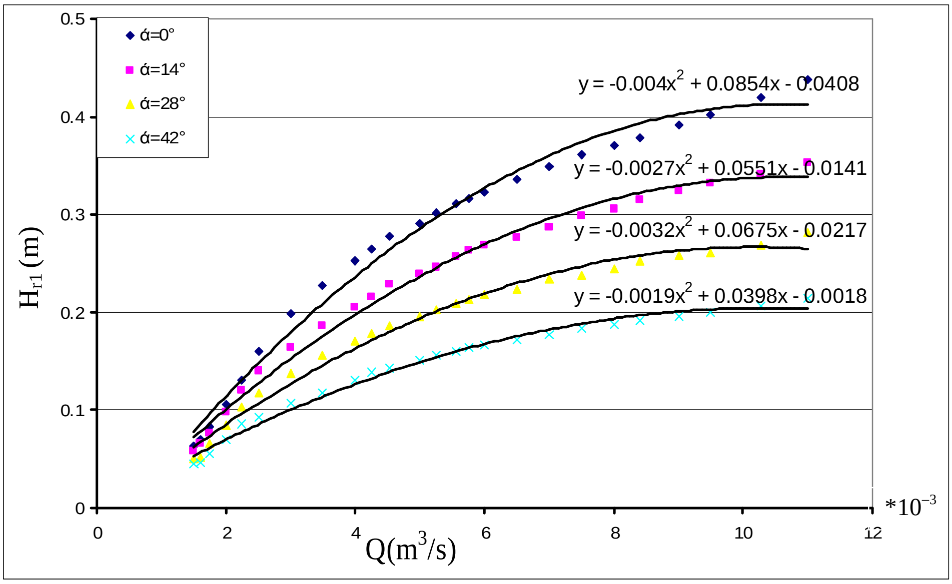


Figure (10) The residual energy at the toe of stepped spillway versus discharge for different slopes of steps

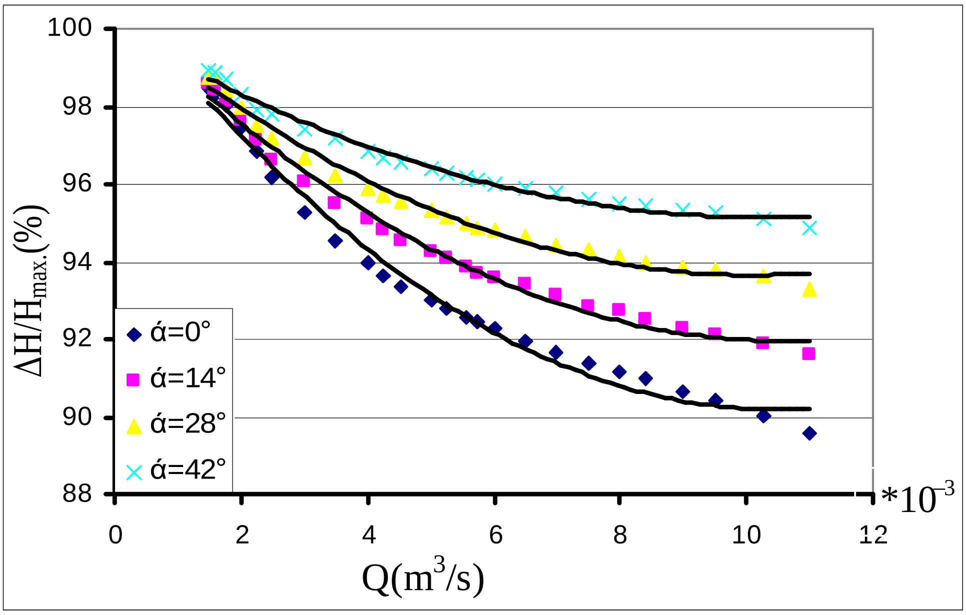


Figure (11) The energy dissipation rate of flow over the stepped spillway versus discharge for different slope of steps

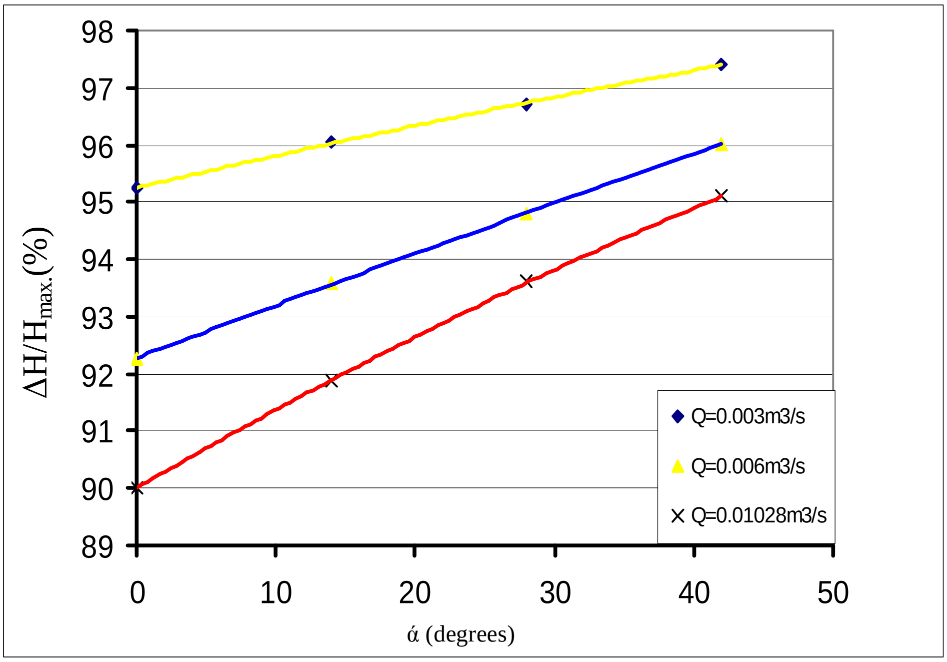


Figure (12) Effect of increasing of steps inclination on energy dissipation rate ($\Delta H/H_{max.}$) for the stepped model