Evaluation the Hydraulic Aspects of Stepped Labyrinth Spillway

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ABSTRACT

This study was adopted a new concept to enhance performance of stepped spillway towards more dissipation of kinetic energy along chute face through increases interlocking surface areas between the mainstream and trapping cavity recirculation vortices on the tread of chute steps and each step edge that beneath it, and increasing the interaction of the flow interference over stepped spillway. The aim of this concept is by employment the specification of a labyrinth weir by configured as a stepped spillway, to produce new steps named as Labyrinth stepped spillway. Experiments were restricted in skimming flow regimes, it have been carried out on four physical models with chute angles (35°). Where models are classified into three labyrinth stepped spillway models of three different magnification length ratios L_T/W=1.1, 1.2, and 1.3, additionally; a traditional or conventional shape models were used for comparison. All physical models assembled with step height 4 cm, eight steps constructed for a total height of 32 cm and width of 30 cm .The results generally show that the energy dissipation with labyrinth shape stepped spillway was more than resulted with the traditional shape. As the magnification ratio increase, the energy dissipation observed to increase compare with traditional model.

Keywords: Stepped Spillway, Labyrinth Weir, Skimming Flow, Dissipation Energy

تقيم السمات الهيدروليكية للمطفح المتعرج المتدرج

الخلاصـــة

هذه الدراسة تبنت فكرة جديدة لتحسين أداء المنحدر المدرج لزيادة قابليته على تشتت الطاقة الحركية على طول وجه المنحدر من خلال زيادة المساحات السطحية للتداخل بين التيار , والدوامات المحصورة على الوجه الأفقي للدرجات وحافات الدرجات الخارجية التي تقع أسفلها ، مع زيادة تداخل الجريان على طول وجه المنحدر. تهدف هذه الدراسة إلى استخدام مواصفات (Labyrinth weir) بتشكيل كافة درجات المنحدر ليطلق عليه تسمية (Labyrinth stepped chute). اقتصرت التجارب على نظام (Skimming flow)، التي تم إجرائها على ثلاثة نماذج مختبرية بزاوية ميل المنحدر 35 ° . حيث صنفت لثلاثة نسب مختلفة لطول التكبير L_T/W (Magnification length ratio) (1.3, 1.2, 1.1) بالإضافة إلى نموذج للشكل التقليدي لغرض المقارنة. جميع النماذج تتكون من ثماني درجات إرتفاع الواحدة منها4سم مما يعطي إرتفاعاً كلياً قدره 32 سم وبعرض 30سم . أظهرت النتائج عموما , أن الشكل labyrinth للمنحدر في هذه الدراسة ذو قابلية أعلى لتشتيت الطاقة من تلك المستحصلة باستخدام الشكل التقليدي وأن كفاءة تشتيت الطاقة تتزايد بازدياد نسبة طول التكبير للنماذج.

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LIST OF SYMBOLS

Symbol	Dimension	Definition
B	[L]	length of labyrinth weir in flow direction
E_{min}	[L]	critical energy over crest
E_o	[L]	total energy of flow at U/S
E_1	[L]	total energy of flow at a toe of spillway
F_b	[-]	Froude number at brink of the chute crest
H_{dam}	[L]	dam height
H_T	[L]	Un submerged total upstream head on weir
H_T/p	[-]	Headwater ratio
L_c	[L]	length of a weir crest for a single cycle
L_T	[L]	total length of the labyrinth weir/ Magnification step length
N_s	[-]	number of steps
Q	$[L^3/T]$	discharge
R_b	[-]	Reynolds number at brink
V	[L/T]	velocity
V_0	[L/T]	U/S flow velocity
V_b	[L/T]	velocity at brink of the crest
W	[L]	width of chute
a	[L]	half-length of the tip sections of weir
d	[L]	depth of water normal on the chute slope
g	$[L/T^2]$	gravitational acceleration
h	[L]	step riser height
h_u	[L]	depth of water over the weir labyrinth crest
k_s	[L]	step roughness height perpendicular to the pseudo bottom
l_c	[L]	length of transverse side for labyrinth shape
n	[-]	number of labyrinth weir cycles
p	[L]	height of labyrinth weir
q	$[L^2/T]$	discharge per unit width
s	[L]	step tread length
y_b	[L]	depth of water at brink
y_c	[L]	critical depth
y_1	[L]	upstream initial depth of hydraulic jump
y_2	[L]	sequent depth downstream of hydraulic jump
α	[-]	inclination of a side wall to flow direction
α_{max}	[-]	angle that corresponding to the triangular plan form.
γ	$[M/L^2T^2]$	Weight density of the flowing fluid
$\triangle E$	[L]	difference in the energy between upstream and downstream of
θ	[-]	chute slope
μ	$[M/L^1T^1]$	Fluid dynamic viscosity
ν	$[L^2/T]$	kinematic viscosity
ρ	$[M/L^3]$	mass density of the flowing fluid
ω	[L]	cycle-width of the labyrinth weir

INTRODUCTION

Since the development of RCC techniques for the construction of concrete dams, the behavior of aerated flow on traditional stepped chutes was investigated by numerous researchers over the world. In spite of this widely employment and variety, it still needs much knowledge of the hydraulic behavior and performance about this kind of chutes or spillways. The key feature associated with steps, is the amount of energy dissipation by flow over it producing cost saving in the size of the energy dissipater. This simple fact has led to investigate the best configurations and features to provide standardized hydraulic design criteria.

Most stepped spillway structures had flat horizontal steps, but some were equipped with devices to enhance energy dissipation. Some spillways had pooled steps with vertical walls (Sorpe dam, 1932) or rounded edges (Le Pont dam, 1882) (Gonzalez A., & Chanson H.(2007).

To improve the hydraulic performance, some researchers conducted a modification to the traditional configuration of stepped chute and studied their performance towards increasing the dissipation efficiency of kinetic energy and/ or enhancing the resistance against cavitation by getting a valueless pressure over it. Such modification to design of flat steps are; inclined upward steps, end sills, adding baffle row or blocks at the downstream end of step, turbulence manipulators, and Macro-roughness systems consisting of concrete blocks (Peyras et al., 1991; Manso & Schleiss, 2002; Andre et al. , 2004; Gonzalez A. & Chanson H.(2007); Al-Lami& EL-Jumaily, 2008).

All The modifications mentioned may effectively enhance flow resistance but their attractiveness is counterbalanced by increasing a structural load to the stepped chute. However, the additional average of energy dissipation May not cover the increases in cost due to the needs of extraordinary placement methods and length of periods required to their construction (Gonzalez & chanson, 2007). The present adopted a new physical model that doesn't previously introduction by investigates or in construction techniques to improve the energy dissipation by increasing the interlocking surface areas between the mainstream and that spread laterally due to like zigzag configured steps as a labyrinth shape weir. This configuration will be combining the hydraulic of specification labyrinth weir with the stepped spillway.

Skimming Flow

Chanson (1994a, 1996) and Khatsuria (2005) indicated that; the skimming flow occurs, with as considered the high discharges. The water flow down the stepped face as a coherent stream skimming over the steps, the air cavity beneath the falling nappe completely filled with water along the entire length of the stepped chute . Chamani & Rajaratnam (1999), established that; at an incipient skimming flow in stepped chute, the jet becomes parallel to the slop of the chute, but Sánchez-Juny & Dolz(2005) indicated that the jet becomes parallel to the slop of the chute fits quite well with the experimental results obtained only in stepped spillway with high slopes (θ **> 45°**).

The external edges of the step form a pseudo-bottom over which the flow passes. Beneath the pseudo-bottom, horizontal axis vortices have been develop and are maintained through the transmission of shear stress from the water flowing past the edge of the steps, as shown Fig.1 .

ENERGY DISSIPATION

When flow discharging over a stepped chute, the rate and amount of the kinetic energy dissipation along the chute expected to be considerably increases comparing with a smooth surface. Accordingly a stepped chute should be eliminate or reduce greatly the needs for a sizeable energy dissipaters and structures at the toe of the chute (Chanson, 1994a; ₋, c). Generally , the amount of a hydraulic energy dissipation along of the stepped chute can be expressed as a difference between the energy at chute crest and the residual energy at toe of the stepped chute.

$$\Delta E = E_o - E_1 \qquad (1)$$

The energy at a chute crest , E_0 , influenced by the height of the dam , where the potential energy component increases as the crest height increase .The available hydraulic energy at a crest has been expressed as:

$$E_0 = y_0 + \frac{q^2}{2gy_0^2} \qquad (2)$$

Where $\mathbf{y_0}$ is depth of water at upstream measured at a distance far enough from the influence of back water curve, **q** is the unit discharge, and g is the gravitational acceleration (see Fig.2). The mechanisms of energy loss along chute surface are quite different between the smooth and stepped configuration .

Energy Dissipation with Skimming Flow Regime

In a skimming flow regime, the steps act as large roughness elements. Most of energy was dissipated to maintain stable horizontal vortices beneath the pseudo-bottom formed by the external edges of the steps. The vortices are maintained through the transmission of turbulent shear stress between the skimming stream and the recirculating fluid underneath (Chanson, 1994a; b; c; 1996; Al-Ta'i, 2010; Al-lami, 2008) .

The study that have been done by Barani et.al (2005) for models having the height of step and width of spillway similar to the models of a present study, while the angle of spillway adopted by the authors were (**41.63°**).the number of steps and the height of crest referenced to the bed were **21** and **84 cm** respectively compared with those adopted in present works (**8, 32cm**). These number of steps and height of crest having in fact a positive influence for increasing the dissipation of energy if compared with another model have a less number of steps and height of crest for the same flow conditions. The average increases in the energy dissipation for model with tread of steps inclined **(45°)** upward (which is considered as the most efficient between those adopted by Barani et.al, (2005)) , was (**7.6%**) under the flow condition ranged between (**6 l/s to 10 l/s**) compared with the energy which dissipated along a conventional (i.e , 0^o tread inclination) stepped spillway .

LABYRINTH WEIR

A labyrinth weir is characterized by a broken axis in plan (zigzag) so that the water flow with a greater path length of crest compared with a normal weir crest occupying the same width of waterway; Fig.3 is a well illustrate this kind of weir. The need to use this configuration is to increase the discharge per unit width of structure waterway for a given operating head (Hay &Taylor, 1970; Crookston &Tullis, 2011). Because the labyrinth weir has a high discharge capacity, it allows the design maximum flood flow to be discharged at a shallower water depth. This will eventually reduce the maximum water level of the reservoir, which can reduce the crest height and eventually reduce the cost (Hay &Taylor, 1970; Khode et.al., 2010). There are a number of studies that presented a hydraulic design or a design curves (e.g., Hay and Taylor 1970; Lux 1984, 1989; Lux & Hinchliff 1985) .

Labyrinth Parameter

The published studies have been developed a numerous design parameters to aid the engineers for a suitable selection feature and design of labyrinth weirs according to a case needed . This section is discuss the influence of related parameters on the discharge capacity of a labyrinth weir; as illustrated in Fig.3 .

- Headwater Ratio (H_T/P) , the headwater ratio is the total head ($\mathbf{H_T = h_u + V_0^2/2g}$), (**$h_u$**) , depth of water measured relative to the weir crest elevation , it located at gauge station upstream of the weir, (**P**) , is the weir crest height above bed. This ratio is well relating the hydraulic performance of a labyrinth weir. An upper limit of HT/P as recommended by several researchers is based upon the declination of a hydraulic efficiency noted in their experimental results. The entire model tests served to determine the significance of this parameter, are clearly appear that for small values of HT/P, a labyrinth weir behave almost ideally (Hay & Taylor, 1970) . The upper limits of 0.9 were recommended by Tullis et al. (1995) is solely based upon the limit of the experimental results.

- Cycle Width Ratio (ω/P) , or vertical aspect ratio was considered by Hay & Taylor, (1970) to show the influence of nappe interference. They recommended that **ω/P** should be greater than **2.0** in the case of trapezoidal plan-form weir, and not less than **2.5** in the case of triangular plan-form weirs.

- Sidewall Angle (α) , it is representing the inclination of a side wall (in plan) of the labyrinth weir relative to the cycle center line (see Fig.3) . The triangular plan form weirs offer better hydraulic performance with as large a sidewall angle as possible (Crookston, 2010; Hay & Taylor, 1970), but, nappe interference is a greater in triangular plan form more than trapezoidal (Hay & Taylor, 1970). If a trapezoidal plan form is to be used, Hay & Taylor (1970) recommended that the sidewall angle should not be smaller than **0.75**α_{max} angle that corresponding to the triangular plan form.

- Length-Magnification Ratio (Lc/ω) , it is the ratio of the length of a weir crest for a single cycle (**Lc**) to the cycle-width (**ω**). Hay and Taylor (1970) indicated that the increase in the length magnification ratio of weir having an influence to magnifying the performance flow, also they noted that for setting **Lc/ω ≥ 8** the little gain performance is unlikely in practice to justify the extra structural costs involved, thereby the authors recommended that the length-magnification equal 2 has an ideally behavior, relative to increasing the flow magnification, within a wide range of **h_u/p**. While, the length-magnification must not exceed 4 when the weir operated at **h_u/p = 0.5** , at the same time the **Lc/ ω > 6** give a little return when designed with **h_u/p** > **0.25.**

In present work the trapezoidal (in plan) labyrinth shape weir have been adopted for each step of stepped spillway to employ the length-magnification ratio hydraulic performance action for improving the ability of chute surface toward increasing the dissipation of kinetic energy .

DIMENSIONAL ANALYSIS

A method of evaluation the effects of magnification length and other variables in stepped spillway under skimming flow condition, which may be used in such general evaluation or analysis, are presented herein. In the analysis of the problem, the upstream velocity **V_0** can be eliminated where it implicit within the total upstream energy. The residual energy at toe of spillway is a function of governing hydraulic and geometric parameters as the following functional relationship :-

$$\mathbf{E_1 = f_1(E_0, y_0, y_b, V_b, y_c, h, s, L_T, W, \theta, N, \rho, \mu, \gamma)} \ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(3)}$$

With the help of the Pi-theorem and with the selection of $\mathbf{y_b}$, $\mathbf{V_b}$ and γ as a repeating variable factors may be combined , allowing the problem to restated as:

$$\mathbf{\frac{E_1}{y_b} = f_2\left(\frac{E_0}{y_b}, \frac{y_0}{y_b}, \frac{y_c}{y_b}, \frac{h}{y_b}, \frac{s}{y_b}, \frac{L_T}{y_b}, \frac{W}{y_b}, \theta, N_s, \frac{\rho V_b^2}{\gamma y_b}, \frac{\mu V_b}{\gamma y_b^2}\right)} \ldots\ldots\ldots\ldots \mathbf{(4)}$$

By using the process of elimination and delimitation permit the Eq.(4) to take the form :

$$\mathbf{\frac{\Delta E}{E_0} = f_3\left(\theta, N_s, R_b, \frac{y_c}{h}, \frac{h}{s}, \frac{L_T}{W}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(5)}$$

If one assumes that the force of fluid viscosity are insignificant as compared with those of inertia for open channel flow (Chow, 1959), the Reynolds number, $\mathbf{R_b}$, could be eliminated .

The number of steps were fixed in this study, that permit the elimination of $\mathbf{N_s}$, however the angle, ($\boldsymbol{\theta}$), can be expressed implicitly with a step height, where ($\mathbf{h/s}$), representing the tangent of spillway angle ($\boldsymbol{\theta}$).

From the elimination and the delimitation, permit the terms restated as:

$$\mathbf{\frac{\Delta E}{E_0} = f_4\left(\frac{y_c}{h}, \frac{h}{s}, \frac{L_T}{W}\right)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(6)}$$

EXPERIMENTAL WORK

Experiments were restricted in skimming flow regimes, it have been carried out on four physical models with chute angles (**35°**). Where models are classified into three labyrinth stepped spillway configuration represent a three different magnification length ratios $\mathbf{L_T/W}$**=1.1, 1.2,** and **1.3**, and the fourth configured a traditional or conventional shape model used for results comparison . All physical models assembled with eight steps of 4cm height , to give a crest height of **32 cm**. Table (1) demonstrate the characteristics of these models tested . The maximum unit flow rate passing over a selected models was **0.06 m3 /s.m**, as a result, the maximum flow passing the model equals **0.018 m3/s(18 l/s)** , with maximum head above the model crest was **13 cm**. The length of crest of physical model was equal to the width of flume, **30cm**, and this dimension is larger than the minimum length of crest **15cm** for two-dimensional models that should be for models investigations as recommended by the United States Bureau of Reclamation ,USBR, (Spiegel, 1961; cited by Barani et al., 2005).

The trapezoidal plan of labyrinth shape was chosen in present study because its construction easily feasible (Hay and Taylor 1970) and it is chime with configuration and function of the stepped spillway. The labyrinth shape is designed based on the recommendation proposed by the previous studies in this field (e.g; Hay & Taylor 1970; Lux 1985, 1989; Lux and Hinchliff 1985and Tullis et al. 1995). Three different magnification ratios $\mathbf{L_T/W}$=**1.1, 1.2,** and **1.3**, undertaken to investigate its influence on hydraulic performance of the stepped spillway. It must remembered here that the slashes angle with the direction of flow for a transverse side of the step edge (α) is involuntary varies as magnification ratios change, but it must still within a recommendation of previous studies {i.e.$(\alpha/\alpha_{max}) \geq 0.75$ where α_{max} angle that corresponding to the triangular plan form} (Hay & Taylor, 1970). The vertical aspect ratio (ω/h) was fixed at 2.5 for all labyrinth shape models tested. Figs.4 and 5 illustrate the design parameters of labyrinth shape compared with a traditional one. Five runs were conducted for all models as listed in Table (2) to simulate a variations of discharge within limitations of the flume capacity and dimensions. Discharges were measured using electromagnetic flowmeter, mounted with flume. After making the required adjustments to stabilize the flow, the measurements are conducted for a necessary need, such as flow depths at U/S and at a toe of spillway

RESULT AND DISCUSSION

From analyzing the experimental results it was observed generally that the magnification length ratio having the advantageous influences on energy dissipation efficiency compared with conventional stepped spillway. However ,where the increases in a magnification ratios lead to sensitive dramatic increase in the energy dissipation under the flow conditions between (6 l/s to 16 l/s), as well illustrated in Table (3) and Fig.6 .

As mentioned for the study conducted by Barani *et.al*, (2005) , the efficiency of energy dissipation with tread of steps inclined **(45°)** upward was **7.6%** , if compared with the present results performed by labyrinth shape steps it nearly equal this resulted with the lowest length-magnification ratio **L_T/W=1.1** this was **6.7%** for at the same flow conditions. While , as illustrated from Fig.6 , the **L_T/W=1.1** give a smallest efficiency compared with other ratios , where with **L_T/W=1.3** the dissipation efficiency increases up to **17.3%** . Accordingly , that emphasize the advantageous of employment the labyrinth shape as a steps of stepped spillway to enhancement its ability for energy dissipation . The positive proportional increases in energy dissipation with a higher length-magnification ratios may be attributed to the increasing the interlocking surface areas between the mainstream and trapping cavity recirculation vortices on the spillway steps and each step edge that beneath it. Also, the energy dissipation increases due to the interaction of the flow interference that appears over transverse sides of the steps edge of slashes angle (α) with the direction of flow for a labyrinth shape step ,see Fig.7 . Therefore, more energy has been expected to be dissipated with employment of this kind of structure.

CONCLUSIONS

1- The energy dissipation of flow over stepped chute models with the new labyrinth shape is more than this resulting along traditional shape stepped chute for the same hydraulic conditions .

2- In comparison with the results of Barani et.al (2005) for nearly the same hydraulic conditions and dimensional formation, the labyrinth shape of stepped chute have a perceptible contribution for increasing the efficiency of energy dissipation along chute more than the model adopted by Barani et.al with steps inclined upward at (45°), which is considered by authors as the most efficient for increasing a dissipation.

3- As the length-magnification ratio increase, the energy dissipation observed to increase up to 17.3% where it recorded with **L_T/W=1.3** , that may be attributed to the increasing the interlocking surface areas between the mainstream and trapping cavity recirculation vortices on the chute steps and each step edge that beneath it. Also, the energy dissipation increases due to the interaction of the flow interference that appears over transverse sides of the steps edge of a slashes angle (α) with the direction of flow.

REFERENCES

[1]Al- Lami, M. K.(2008)," Study of Conveniency of Using Stepped Spillway in Roller Compacted Concrete Dams (RCCD)". M.Sc. Thesis, University of Technology, Baghdad, Iraq.

[2]Al-Ta'I, M. A.(2010)," Hydraulic Model Investigation of Different Configurations of Stepped Spillway". M.Sc. Thesis, University of Baghdad, Baghdad, Iraq.

[3]André, S., Boillat, J.L., Schleiss, A.J., & Matos, J. (2004). "Energy Dissipation and Hydrodynamic Forces of Aerated Flow over Macro-Roughness Linings for Overtopped Embankment Dams." Proc. Intl Conf. on Hydraulics of Dams and River Structures, Tehran, Iran, Balkema Publ., The Netherlands, pp. 189-196.

[4]Barani, G., Rahnama, M., & Sohrabipoor, N. (2005). "Investigation on Flow Energy Dissipation over Different Stepped Spillways" . American Journal of Applied Sciences , Vol.2, No.6 , pp.1101-1105.

[5]Chamani, M.R., & Rajaratnam, N. (1999).“Characteristics of Skimming Flow Over Stepped Spillways”, Journal of Hydraulic Enggineering, ASCE,125(4), pp. 361-367.

[6]Chanson, H. (1994a), "Hydraulics of Stepped of Spillway and Cascades", National Conference Publishers No: 94/1; The Institution of Engineers, Australia.

[7]Chanson, H. (1994b). "Comparison of Energy Dissipation in Nappe and Skimming Flow Regime on Stepped Chutes", Journal of Hydraulic Research, Vol. 32, No. 2, pp. 213-218.

[8]Chanson, H.(1994c)."Hydraulics of skimming flows over stepped channels and spillways". IAHR, Journal of Hydraulic Research, Vol.32,No.3, pp.445-460.

[9]Chanson, H. (1996). "Prediction of the Transition Nappe/Skimming Flow on a Stepped Channel". Journal of Hydraulic Research, IAHR , Vol.34, No.3 , pp.421-429.

[10]Chow,V. T.(1959). "Open Channel Hydraulics". McGraw-Hill, New York, USA.

[11]Crookston, (2010) Brian Mark, "Labyrinth Weirs". Ph.D. Thesis, University of Utah State, Utah, USA.

[12]Crookston, B.M., & Tullis, B.P. 2011. The Design and Analysis of Labyrinth Weirs. Proc.31st Annual USSD Conference, San Diego, California, April, 2011.

[13]Gonzalez Carlos A., & Chanson H.(2007)." Hydraulic Design of Stepped Spillways and Downstream Energy Dissipators for Embankment Dams". Dam Engineering, Vol. XVVII, Issue 4,pp.223-244.

[14]Hay, N. and Taylor, G. (1970). “Performance and Design of Labyrinth Weirs”. Journal of Hydraulic Engineering, Vol.96, No.11, pp.2337-2357.

[15]Khatsuria .R. M.(2005)." Hydraulic of Spillway and Energy Dissipators", Marcel Dekker, New York, USA.(ISBN: 0-8247-5789-0)

[16]Khode B.V., Tembhurkar A.R., Porey P.D., & Ingle R.N.,(2010)." Determination of Crest Coefficient for Flow over Trapezoidal Labyrinth Weir". World Applied Sciences Journal, Vol.12, No.3, pp.324-329, 2011, (ISSN 1818-4952),© IDOSI Publications, 2011

[17]Lux, F. (1989). “Design and Application of Labyrinth Weirs”. Design of hydraulic structure 89, Edited By Alberson, M.L., and Kia, R.A., Balkema/ Rotterdam/ Brookfield.

[18]Lux, F. (1985)."Duscussion on ' Boardman Labyrinth Crest Spillway'". Journal of Hydraulic Enggineering, ASCE , Vol.111, No.6, pp.808-819.
[19]Lux, F.; Hinchliff, D. L.(1985) "Design and construction of labyrinth spillway". 15th ICOLD,Lausanne, Switzerland: see reference of Khatsuria .R. M.(2005).
[20]Ohtsu, I., Yasuda, Y., & Takahashi, M. (2004). "Flow Characteristics of Skimming Flows in Stepped Channels." Journal of Hydraulic Engineering, ASCE, Vol.130, No.9, pp.860-869.
[21]Peyras, L., Royet, P., & Degoutte, G. (1991). "'Ecoulement et Dissipation sur les Déversoirs en Gradins de Gabions." ('Flows and Dissipation of Energy on Gabion Weirs.')'" Journal La Houille Blanche, No. 1, pp. 37-47 (in French).
[22]Sánchez-Juny M. & Dolz J.(2005) "Experimental Study of Transition and Skimming Flows on Stepped Spillways in RCC Dams: Qualitative Analysis and Pressure Measurements". Journal of Hydraulic Research Vol. 43, No. 5, pp. 540–548.
[23]Spiegel, M.R., (1961)."Statistics schemes outline series". McGraw Hill Book Company.
[24]Tullis, J. P., Amanian, N. & Waldron, D. (1995). "Design of Labyrinth Spillways".Journal of Hydraulic Engineering, ASCE, Vol.121, No.3, pp.247-255.

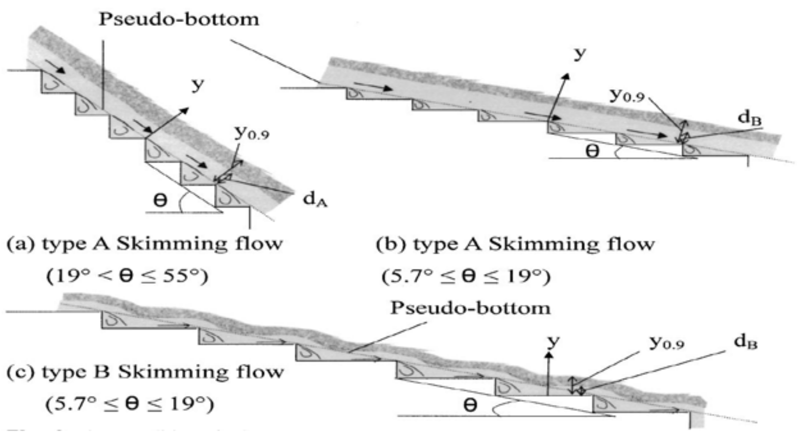
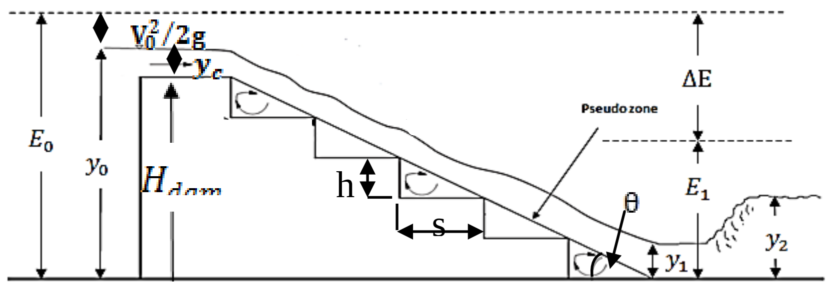


Figure (1) Different faces of skimming flow over stepped spillway (after Ohtsu Y.Yasuda and M. Takahashi , 2004)



Figure(2) Typical scheme of a stepped spillway

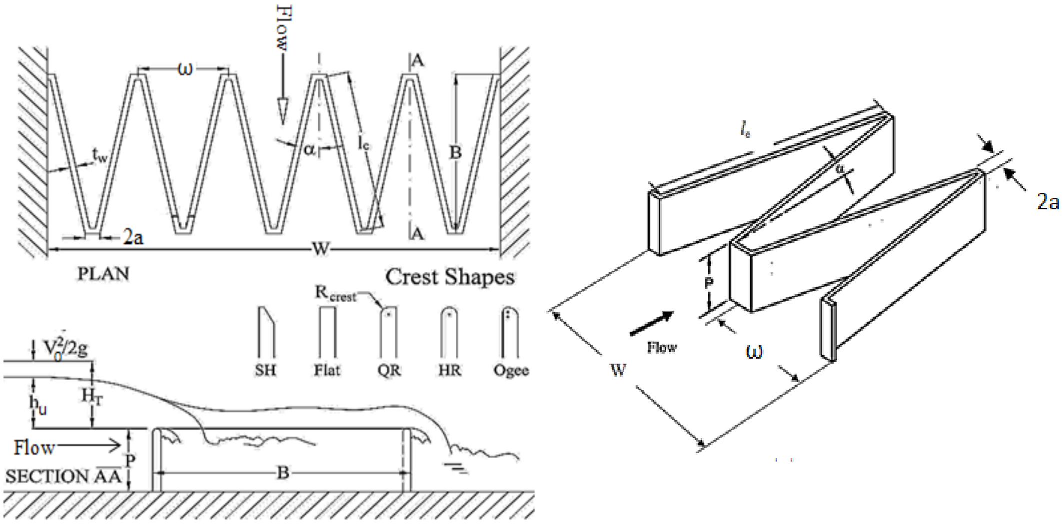
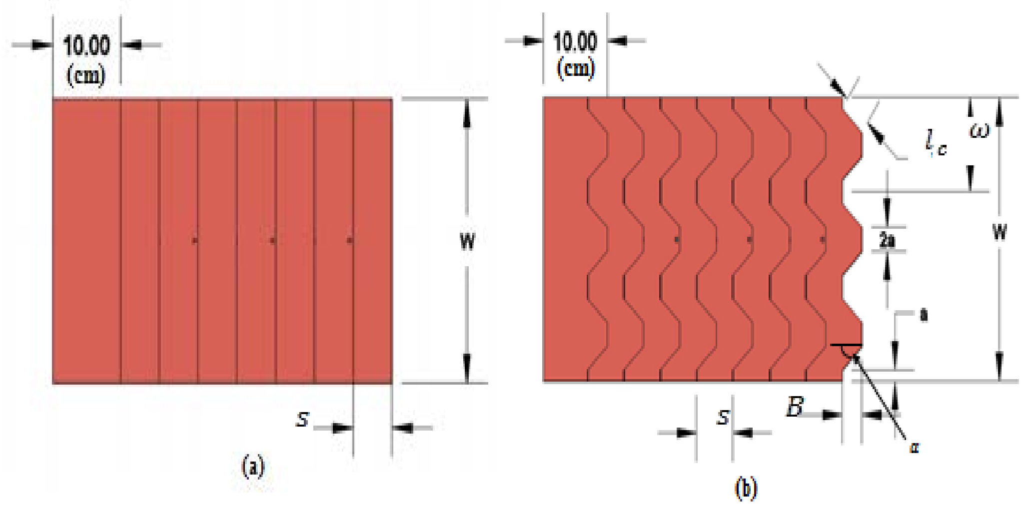
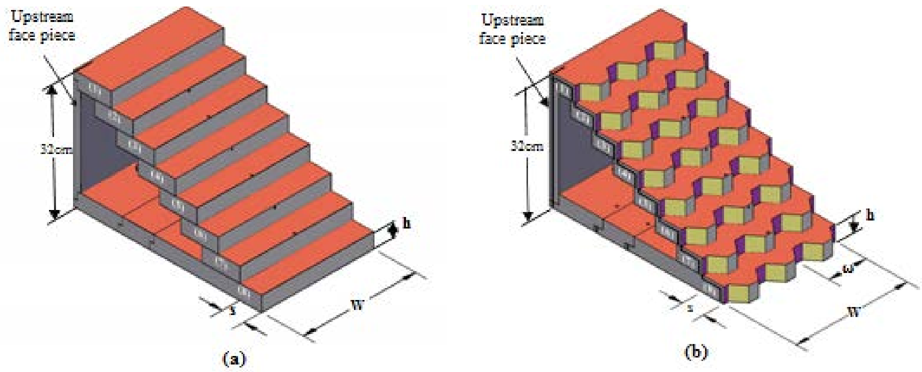


Figure (3) labyrinth weir with related design parameter (Crookston, 2010)



Figure(4) drawing of configuration (a) Traditional shape (b) Labyrinth shape



Figure(5) Detail drawing show pieces comprise physical model (a) Traditional shape (b) Labyrinth shape

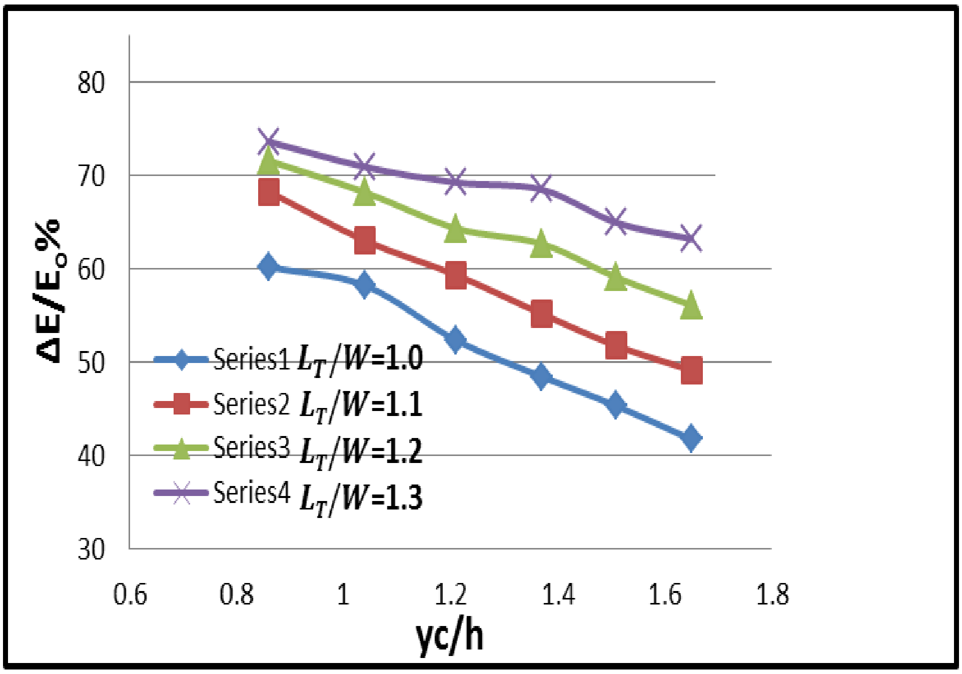


Figure (6)Percentage of energy dissipation with different flow conditions for 35° spillway

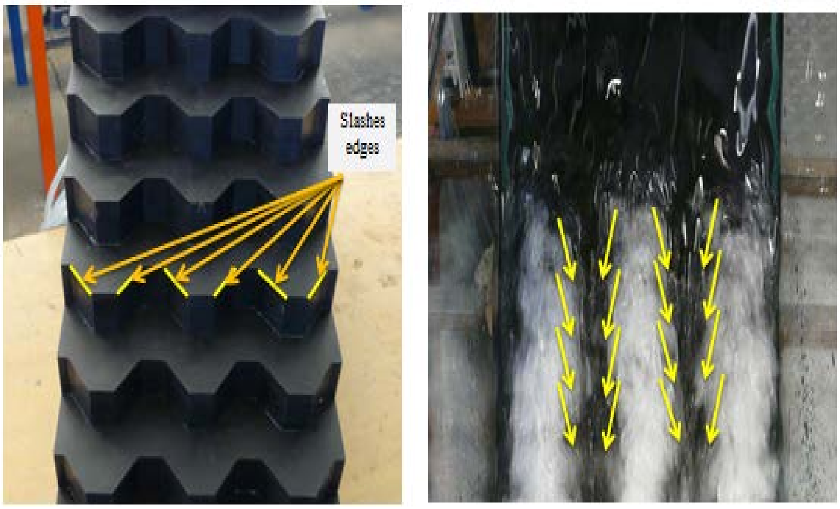


Figure (7) The flow interference over transverse sides of the steps slashes edges

Table 1: Physical models characteristics of Labyrinth stepped spillways tested

Labyrinth geometric							
L_T/W	n	ω/h	a (cm)	l_c (cm)	B (cm)	α Deg.	$\frac{\alpha}{\alpha_{max}}$
1.0	-	-	-	-	-	-	-
1.1	3	2.5	0.75	4	1.94	61.1	0.93
1.2	3	2.5	1	4	2.65	48.6	0.86
1.3	3	2.5	1.25	4	3.12	38.7	0.77

Table 2: Discharges over stepped spillway physical models

Run	1	2	3	4	5
Discharges (l/s)	8	10	12	14	16
y_c/h	1.042	1.210	1.366	1.514	1.655

Table 3: Energy dissipation variation with magnification ratio

	Average of energy dissipation %				Additional dissipation%		
L_T/W	1.0	1.1	1.2	1.3	1.1	1.2	1.3
angle							
35°	51.1	57.8	63.7	68.4	6.7	12.6	17.3