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ORIGINAL ARTICLE

Impact of the Number of Drop Stairs on Energy Dissipation in Stepped Drops

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ABSTRACT
Due to the simplicity of construction and operation, drops are among the most common water buildings to reduce water flow energy in irrigation systems which usually in combination with a variety of obstacles and aprons in the downstream can constitute varied modes of energy dissipation hydraulic structures. Due to the role of stairs in making large roughness and the impact of structure energy dissipation in reducing the dissipating structures in downstream, stepped drops and stepped spillways are of particular importance in recent years. So this research has studied the impact of structure slope, the number of stairs and the structure height on energy dissipation rate in stepped drops. Experimental models used in 2, 20 and 30 cm height and 2, 26.5 degree slope channels (1 to 2) and 33.3 degrees (1 to 1.5) and in (3, 5, and 7) stairs were built. With the establishment of four different rates (10, 13, 15 and 20 liters per second) and performing 48 experiments, the effect of the structure slope on energy dissipation was investigated. All tests were done in the laboratory flume, Islamic Azad University of Ahvaz with a length of 13 m, width 50 cm and depth of 60 cm. The results showed that by increasing the amount of $\frac{y_c}{\Delta z}$ *the energy dissipation rate will be reduced. It can be also seen that for a certain value of* $\frac{y_c}{\Delta z}$*, the increase in the number of stairs reduces the amount of relative energy dissipation. Results showed that increasing the slope, the relative energy dissipation rate increases. In this study, the maximum amount of relative energy dissipation for a model with a slope of z = 2 and a height of 30 cm obtained0.761 and the minimum amount of relative energy dissipation for a model with a slope of z = 1.5 and a height of 20 cm obtained0.604.*
Keywords*: stepped drop, energy dissipation, structure slope.*

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INTRODUCTION

In channels with steep slope, the flow regime was supercritical and flow high speed erodes the channel bed and banks particularly the earth channel. The nappe section or drop associated with its downstream stilling basin is among effective hydraulic structures to balance slope and energy dissipation in channels built in lands with steep slope. The presence of drop will eliminate water destructive power in three forms of mixing up the flow with the air, collision of the flow with the downstream channel floor and water swirl in the vortex basin. A large percentage of the energy flow is amortized as a result of hydraulic jump at the downstream of drop building and another significant percentage will be wasted while crossing a drop and before jump. There are different types of drops including vertical drop, baffled drop, rectangular inclined drop, circular inclined drop and stepped drops. Based on USBR Institute criteria for the height difference less than 0.9 m (3 feet) vertical drops and 0.9to 4.5 m (3 to 15 ft.) rectangular and circular inclined drop, (slides) will be used. For more height difference, a series of continuous drops or a chute can be used. Given the role of stairs in creating large roughness in recent years, stepped drops have special significance. Better recognition of the effective parameters in estimating the flow hydraulic properties including energy dissipation caused by drop structure or jump energy loss reduced the construction dimensions of the hydraulic structures and its downstream basin and in this regard, it is associated with a significant economic savings. The idea of using stepped drop was proposed when it was observed that stairs lead to greater energy dissipation by creation of large roughness in the flow path. In Figure 1 different geometric parameters of this kind of drop are given.

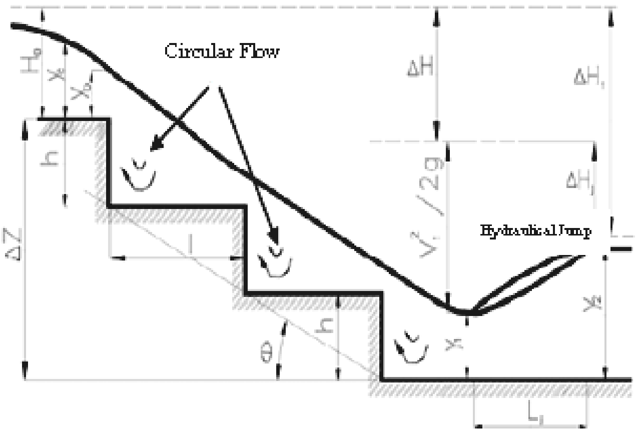

Figure 1. Introducing stepped drop and its components

In this figure y_c, y_2, y_1, y_b and y_p are depth on the edge of drop, the depth before hydraulic jump, jump sequent depth, critical depth before drop and depth under falling jet of flow, respectively. Also $\Delta Z, \Delta H_1, \Delta H_j, \Delta H, \Delta H_0$ and ϕ are specific energy of flow before drop, structure energy dissipation, jump energy losses, total energy losses, drop geometric height and angle of falling jet to the underlying basin, respectively. In this figure, *h* is the vertical height and *L* is the horizontal length of any stairs. In moving water falling from the stairs, three types of flow regimes are recognized including nappe, skimming and transition regime, which intermediates two prior regimes.

In nappe flow regime, stairs act as a series of vertical drops or downstream pools formed beneath them. In general, the nappe flow in low rates and the stairs relative high height are formed. Many researche shave been done on the nappe flow regime. Based on researches of Chanson(2002), relative energy dissipation in stepped spillways with nappe flow regime having full hydraulic jump in mode of shoots without valve using the theoretical framework and the integration of the proposed relations for drops is derived from the following equation:[1]

$$(1)\ \frac{\Delta H}{H_t} = 1 - \left[\frac{0/54(\frac{y_c}{h})^{0/275} + \frac{3/43}{2}(\frac{y_c}{h})^{-0/55}}{1/5 + (\frac{H_t}{y_c})} \right]$$

In skimming flow regime, flow flows on the stairs as clung. In this regime, the top of the stairs serves as a pseudo bottom. In the wedge-shaped space between the stairs, part of the flow is confined and will have a rotational state. Much of the structure energy dissipation in the skimming flow regime is as a result of the transfer of shear stress from the flow of pseudo bottom to the swirling flow confined in the wedge space among stairs and maintaining it srotation. In the results of these researches which obtained mostly by assuming the formation of a uniform flow of air-water on the stepped channel, by increasing the number of stairs, relative energy dissipation of $\Delta H / H_t$ increases. Also Salmasi (2009) showed that skimming flow by assuming the formation of a uniform water-air flow on the stepped channel per identical geometric and hydraulic conditions, the effect of increasing the number of steps in $\Delta H / H_t$ is rather positive and then negative and a method is provided for obtaining it [2].

There is a flow regime that is intermediate between the nappe and skimming flow with a high rate. This type of regime is called transition. Transition flow regime has highly irregular behavioral characteristics associated with rapid changes in the flow characteristics on each stair. Given that transition condition is affected by the severe hydrodynamic fluctuations, in practice its occurrence condition should strictly be avoided. So far, predicting flow characteristics in transition regimes were not feasible due to the theoretical foundations and only brief details based on the observations by the University of Queensland

is available. Thus, the transition flow is better to occur at low rates and in the area where there is a possibility of transition flow; circumstances must be evaluated by physical modeling.
Relative energy dissipation function $(\Delta H / H_t)$ for stepped drops is summarized as follows:

$$\text{(2)}\quad \frac{\Delta H}{H_t} = f(R_n, F_r, D_r, \Delta Z/Y_C, N)$$

Rouse (1943) using the principles of momentum has provided equation (3) to determine the ratio of y_p / y_u:

$$\text{(3)}\quad \frac{y_p}{y_u} = \sqrt{(\frac{y_1}{y_u}) + 2Fr_u^2 \frac{y_u}{y_1} - (2Fr_u^2 + 1)}$$

That in this equation Fr_u is the Froude number of drop upstream flow. Other parameters in the equation have been previously defined [3].

In drop upstream, if using equation(3) in the case of subcritical flow is raised, the depth of y_u is equal to the flow critical depth y_c and $Fr_u = 1$. When using equation (3) for supercritical flow conditions due to the lack of the oreticalimpact of drop on water surface profiles, y_u can be considered as upstream channel normal flow depth.
White (1943) provided the following equation to estimate the depth of y_1 before jumping in drops which is used for designing in USBR standard.

$$\text{(4)}\quad \frac{y_1}{y_c} = \frac{\sqrt{2}}{1/061 + \sqrt{1/5 + \Delta Z/y_c}}$$

Using the above equation, the flow energy in the pre-jump section, (H_1) is obtained from the following equation:

$$\text{(5)}\quad \frac{H_1}{y_c} = \frac{\sqrt{2}}{1/061 + \sqrt{1/5 + \Delta Z/y_c}} + 0/25\left(1/061 + \sqrt{\frac{\Delta Z}{y_c}} + 1/5\right)$$

On the other hand, total energy flow before drop (H_t) can be written in the upstream subcritical regime as follows:

$$\text{(6)}\quad H_t = \Delta Z + 1/5 y_c$$

Finally, the relative rate of energy dissipation of drop structure can be calculated by $\left(\frac{\Delta H}{H_t} = \frac{H_t - H_1}{H_t}\right)$ [4].
Chinnarasi and Wongwises (2006) by performing some studies and modeling different types of stairs (horizontal, inclined and stairway with terminal appendages) on chute with different number of stairs examined the energy dissipation and its relation to the relative critical depth. The results showed that the stairs with terminal appendage shave a significant impact than the other two stairs on energy dissipation and the relative depth [5].
Felder and Chanson (2009) performed experiments on physical model of stepped spillway with a height of one meter and a slope of 26.6 degree. 5 different modes were considered for the stairs and the residual energy was measured at downstream of the spillway. Although the results show that the number of steps has not a large effect on the residual energy in spillway downstream, but the spillway has 10 steps while each step with 10 cm high has less residual energy downstream, and this matter indicates more energy dissipation in this spillway [6].

MATERIALS AND METHODS

To investigate the effect of drop geometry and its hydraulic flow in the structure energy dissipation, after determining the effective geometric and hydraulic parameters, 12 physical models of stepped drops was made of plexiglass. Drops were made with a width of 50 cm in two heights of 20 and 30 cm, 2 structure slopes(1: 1.5 and 1: 2) and with 3, 5, 7 stairs. With the establishment of different hydraulic conditions in each model four different flow rates of 10, 13, 15 and 20 liters per second in the experiments were planned. The practical procedures and tests of this study were done in the laboratory of Islamic Azad University of Ahvaz, located in Chonibeh. In laboratory flume with a length of 13 m, width 50 cm and depth of 60 cm, after installing the built models and establishing steady-state conditions, flow different parameters were measured. Measuring the depth or elevation of flow level at each section was performed using level meter or vernier with an accuracy of 1.0 mm. To measure the flow rate through a 60 degree triangular weir were used which was calibrated before the start of experiments. A view of equipment used in research is given in the Figure(2). A summary of the various models of weir was planned with the conditions provided in Table 1. Figure (3) shows an example of the experiments.

Figure (2) A view of the 13 m flume

Figure (3) A view of the spillway with 3 steps, 20 cm height and a slope of 1: 2

Table (1) various models of spillway tested

Slope	Number of steps	Model height(cm)	Model Number
1: 1.5	3	20	1
1: 2	3	20	2
1: 1.5	5	20	3
1: 2	5	20	4
1: 1.5	7	20	5
1: 2	7	20	6
1: 1.5	3	30	7
1: 2	3	30	8
1: 1.5	5	30	9
1: 2	5	30	10
1: 1.5	7	30	11
1: 2	7	30	12

After assuring of the tightness of the model installation, we first activate the pump after air bleeding and open the flow regulator gradually to regulate the desired flow rate of triangular spillway upstream. Then given the installation of different scales in specified places, H_0, y_c, y_2, y_1, y_b was read.

Due to the occurrence of critical depth before the drop edge at the upstream and measuring the flow rate, the amount of flow energy in upstream is obtained through equation (6), that in this equation Htis the total flow energy in upstream of each model, ΔZ is the exact height of each model and yc is the critical depth of the flow of models and it is obtained from $y_c = \sqrt[3]{\frac{q^2}{g}}$.

By measuring the energy at the structure downstream and energy difference in upstream and downstream, structure energy dissipation is obtained that the result of combined effects of model geometry and flow conditions is in it. To determine the energy rate at the downstream of models, two methods including direct measurement of the depth before jump y_1 and measuring jump sequent depth $y_2$and calculation of $y_1$are used. Preliminary results and using the experiences of previous researchers showed that direct measurement of the initial depth of jump due to high velocity of supercritical flow in this section and greater depth measurement error due to the penetration of air flow will show the structure energy dissipation rate more than reality, therefore the second method, i.e. measuring y_2 and calculating y_1, due to decreased air entry in the jump downstream as a more accurate method was chosen and was a criteria for energy calculations in all the models. Jump conjugate depths equation is as follows:

(7) $$\frac{y_2}{y_1} = \frac{1}{2}\left(\sqrt{1+8Fr_1^2}-1\right)$$

Then through y_1 with the help of energy relation $H1 = y1 + V1^2/2g$the value of H_1 obtains and due to obtaining the value of H_t, $H_t - H_1$ $\Delta H =$ is computed.

RESULTS AND DISCUSSION

Figure (4) shows the changes of $\frac{\Delta H}{Ht}$ to $\frac{yc}{\Delta z}$ for a model with a slope of z = 1.5 and a height of 20 cm and Figure (5) shows the changes for a model with a slope of z = 2 and a height of 20 cm.

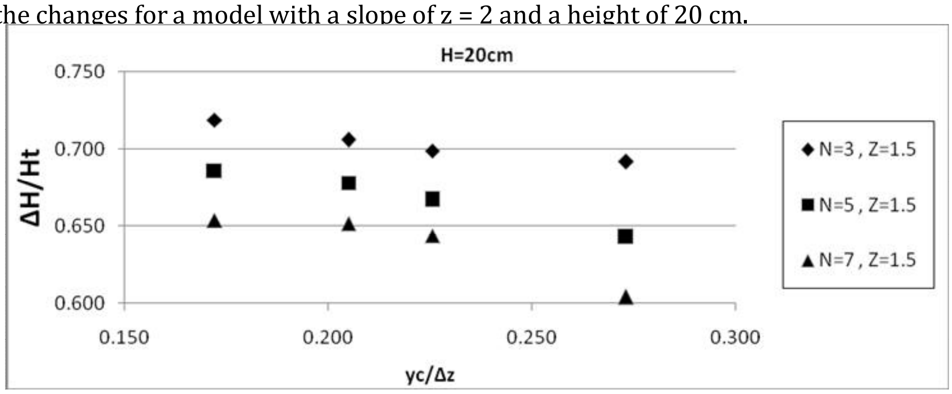

Figure (4) $\frac{\Delta H}{Ht}$ changes to $\frac{yc}{\Delta z}$ for a model with a slope of z = 1.5 and a height of 20 cm

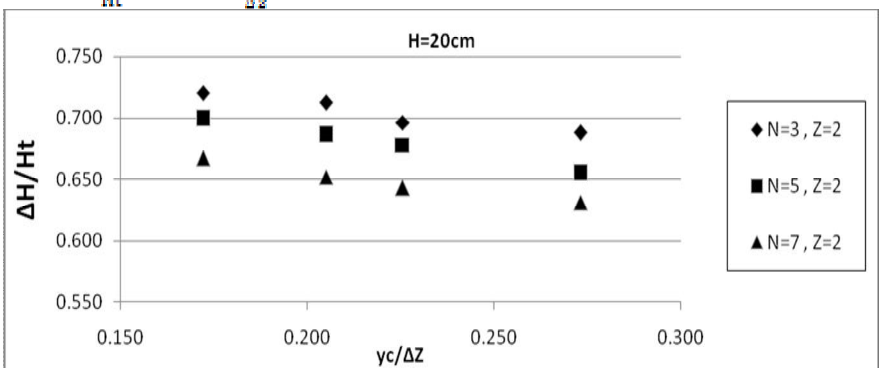

Figure (5) $\frac{\Delta H}{Ht}$ changes to $\frac{yc}{\Delta z}$ for a model with a slope of z = 2 and a height of 20 cm

As can be seen in these two figures, the rate of energy dissipation will be reduced by increasing $\frac{yc}{\Delta z}$. It can be also seen that for a certain value of $\frac{yc}{\Delta z}$, the increase in the number of stairs reduces the amount of relative energy dissipation. This is exactly opposite the conclusion of Chanson [1], and Chamani and Rajaratnam [7] about the nappe flow regime with low channel slope on the impact of the number of steps. Since the above relations are analyzed and concluded by assuming complete hydraulic jump on each stair, it seems that the cause of the fundamental difference lies in this case because the steep slope of the channel chosen for the present study and thus the low length of the steps don't provide the necessary conditions for hydraulic jump on any stair of the nappe flow regime experiments in this study. In fact energy dissipation on each step in nappe flow regime includes both the loss caused by nappe from previous stair and the hydraulic jump on the stair. It is obvious that by increasing the channel slope the impact of first and second parts will be reduced. This analysis is also true for the 30cm drop which result sare presented in Figures (6) and (7).

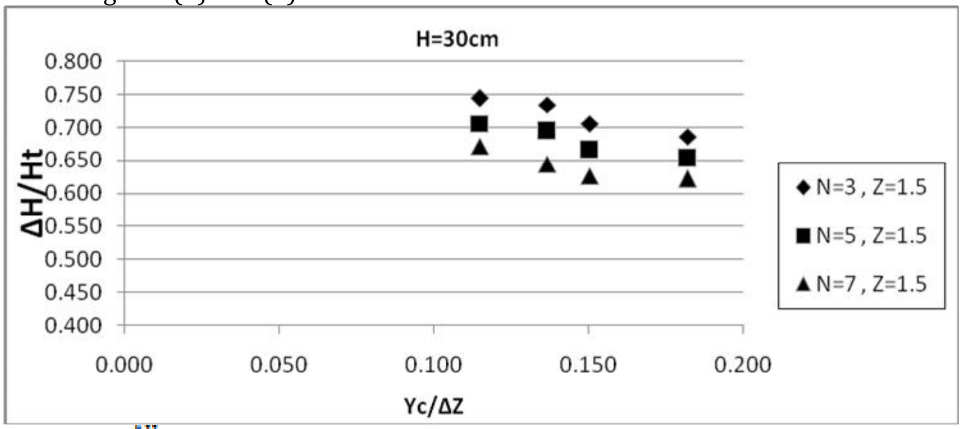

Figure (6) $\frac{\Delta H}{Ht}$changes to$\frac{yc}{\Delta z}$for a model with a slope of z = 1.5 and a height of 30 cm

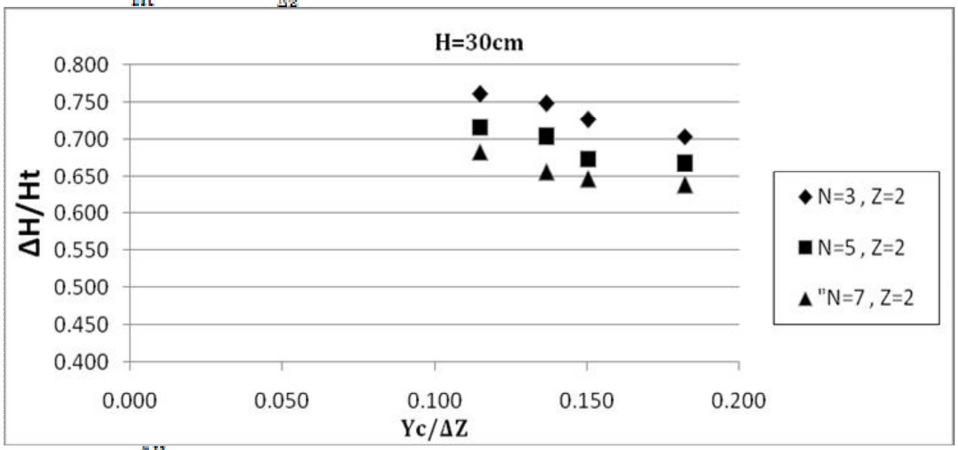

Figure (7) $\frac{\Delta H}{Ht}$changes to$\frac{yc}{\Delta z}$for a model with a slope of z = 2 and a height of 30 cm

Given the figures (4) to (7) it is concluded that increasing the slope, the relative energy dissipation rate increases. In this study, the maximum amount of relative energy dissipation for a model with a slope of z = 2 and a height of 30 cm obtained0.761 and the minimum amount of relative energy dissipation for a model with a slope of z = 1.5 and a height of 20 cm obtained 0.604.

CONCLUSION

In this research, to study the parameters effective in the relative energy dissipation ($\frac{\Delta H}{Ht}$) of flow through stepped drop, 12physical model of plexiglass were made. Drops were made with a width of 50 Cm in two20 and 30 cm height, 2 slope structures (1: 1and 1: 2) and with a number of 3, 5, 7 stairs. With establishment of different hydraulic conditions in each model, four different flow rates (10, 13, 1, 5 and 20) Liters per second, the experiments were planned.

Results showed that increasing the rate of$\frac{yc}{\Delta z}$ energy dissipation is reduced. Also increasing the number of stairs and reducing the channel angle in the range of studied variables of the present study reduced the relative rate of energy dissipation. Also the effect of changes in the number of stairs on the relative energy dissipation in stepped drop models in the present research compared with previous researches on the stepped spillways shows different results. It seems that the cause of the fundamental difference lies in the fact that the steep channel slope chosen for the present study and thus the low staircases length don't provide necessary conditions for the occurrence of hydraulic jump on each stair in any of the nappe flow regime tests in the present study.

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