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Experimental study of effect of installing deflector on replacement of inception point of air entrainment in stepped spillways

Safarpour Mojtaba [1,*], Mousavi Jahromi Habib [2], Shafaei Bajestan Mahmood [3], Masjedi Alireza [4], Kashkouli Heidar Ali [4]

[1]*Department Water Science and Engineering, Khuzestan Science and Research Branch, Islamic Azad University, Ahvaz, Iran*
[2]*Department Water Science and Engineering, Tehran Science and Research Branch, Islamic Azad University, Tehran, Iran*
[3]*Department Water Science and Engineering, Shahid Chamran University, Ahvaz, Iran*
[4]*Department Water Science and Engineering, Ahvaz Branch, Islamic Azad University, Ahvaz, Iran*

Abstract: obtained improvement in field of building stepped spillways-RCC method- has made stepped spillways and conditions of passing flow, problems that have attracted much attention of researchers. In this paper - according to limitation of water discharge per unit width of stepped spillways- we not only examine effect of deflector installing on flow condition in inception point, but also seek a hydraulic solution in order to shorten length of inception point and increase pressure on steps. Obtained result of experiments present that simultaneous installing deflector and aerator in first steps of spillway is one of effective tactics to increase passing discharge of spillway.

Key words: Stepped spillway; Inception point; Deflector; Energy dissipation; Cavitation index

1. Introduction

Building dams and spillway over them is one of ways to manage water resources. In recent years and with improvement of technology in building dams with RCC method applying stepped spillways have considered special attention, although building this kind of spillways dated back to 1500 years ago. Many scientists like Chanson have done relatively comprehensive studies of stepped spillways. The most important advantages of stepped spillway include: a)simplicity of building and cost-effectiveness, b)decrease in risk of cavitation through entrance of air into flow, c) decrease in dimensions of stilling basin in toe of dam through increase of energy dissipation of flow by stepped spillway (Boes et al., 2003) But one of properties of stepped spillway is limitation (water discharge per unit width) of flow passing over it, that this value has been stated *(25-30m³/s/m)* by researchers. Whereas, this value in flat spillways equals *(q=100m³/s/m).* Such property is main cause of creating limitation in applying stepped spillway (Shvainshtein, 1999; Pfister et al., 2006). Reason of limitation in discharge per unit width, is dominance of skimming flow on spillway and formation of non-aeration zone (black water) from crest of spillway to inception point. Result of this phenomenon is decrease of pressure on steps and creating cavitation over them. After inception point, risk of cavitation will be decrease effectively due to natural entrance of air into flow and increase in air concentration near to down stream bed. Hager et al. (2003) stated that one of ways to reduce risk of cavitation in upper part of spillway and before inception point, is

Installing deflector and aerator on first step of stepped spillway that through this way, air would enter into flow and reduce the risk of cavitation by increase pressure (Zamora et al., 2008). Final result of this action is increase in capability of stepped spillway to pass water discharge more than *(q=25m³/s/m)*. Chanson,, stated that by passing skimming flow on steps, there is no air in upstream flow of spillway and flow is relatively clear and crystalline. Turbulence is created because of contact of flow particles with step surface and it developed a boundary layer close to bed of spillway. When outer edge of boundary layer approaches surface of water flow, reaction between boundary layer and free surface, causes entrance of air into flow. Place of starting this phenomenon -in a certain distance from crest of spillway- has been called inception point of aeration. Characteristics of this point are defined with parameters such as x_I- distance between starting point of boundary layer to inception point- and d_I - depth of water in that point (Chanson, 2006).

2. Experimental facilities

In this research effect of installing types of deflector have been studied on replacement of inception point, as well as increase in passing water discharge. experiments have been done on two models of stepped spillways of Plexiglas material

* Corresponding Author.

which their characteristics have been written in table1. Where; N=number of step's=width of spillway; l=horizontal step length; h=step height and Θ=slope of stepped channel. Water flow has been entered to a tank in dimensions of(11×11×5) through pumps of existing channel passing stepped chute and stilling basin of downstream, entered wooden flume and again returned to channel. In order to water discharge measure gauge available beside spillway, as well as Sharpe edge rectangular spillway in downstream chute has been used, by which rating curve has been prepared for these stepped spillways.

Table 1: Characteristics of stepped spillways applied in experiments

Q (lit/s)	Spillway kind	N	b (cm)	l (cm)	h (cm)	Θ (deg)	Model no.
220-240-270-290-310	Ogee crest	84	75	7.2	6	40	1
126-137-155-166-178-192-209	Ogee crest	64	72	4	4.8	50	2

Measuring depth of flow has been done by a Point gauge with accuracy of 1mm and measuring flow velocity by Pitot-static tube. According to condition of each experiment, 10 to 15 cross-sections have been considered and in each cross-section, in three points ($b/4, b/2, 3b/4$), depth and flow velocity have been measured. In order to measure accurate pressure fluctuations, a pressure transducer with six sensors has been used. Experiment time in each point is determined 30 seconds and received data rate is determined 200 data per second. Totally 6000 data in each point is acceptable data to analyze pressure fluctuation. In order to inject air into passing water flow over deflector, an aerator with dimensions of $5.5\times 6cm$ was installed on model no.1 and an aerator with dimensions of $4\times 4cm$ was installed on model No.2. these aerators have suitable cabs and a hole by diameter of $1cm$ to enter ((hot-wire)) device that computed velocity of passing air inside aerator in *m/s*. Measuring partial negative pressure obtained of installing deflector and closing aerator, is computed by a U-tube manometer.

3. Deflectors characteristics and dimensional analysis

In experiments done on model no.1, four types of deflector -types 1, 2 and 4 with triangular cross-section and type 3 with trapezoidal cross-section. on model No.2, deflector type 1 has been installed in end of ogee-spillway and before first step and has $L=6cm$ and angles of $\phi=4,9,14.5,18,22\,(\text{deg})$.Deflector type 2 has been installed on upper part of vertical face of first step and above pseudo bottom and has two slopes $\phi=5,10(\text{deg})$. Deflector type 3 has been installed on upper part of vertical face of first step and under pseudo bottom and has characteristics that have been written in table 2. Deflector type 4 has characteristics as type1 but has been applied as jagged in width of spillway (Fig.1).In order to dimensional analysis to determine depth of flow in inception point, effective parameters are stated

$F(d_I, q, h, \rho_w, \sin\theta, \cos\theta, g, \tan\phi)$.Where: d_I :depth of flow in inception point; θ : spillway slope; q : water discharge per unit width; h :step height; ρ_w :water density; ϕ: deflector slope and g : gravitational acceleration. Finally, by Buckingham Pi method and combining some parameters, we can state effective dimensionless parameters on flow depth in inception point in condition of installing deflector as equation 1:

$$\frac{d_I}{h} = f\left(Fr^*, \sin\theta, \tan\phi\right) \quad (1)$$

Where: Fr^* : roughness Froude number. And similarly equation2 is obtained to determine length of inception point:

$$\frac{L_I}{h} = f\left(Fr^*, \sin\theta, \tan\phi\right) \quad (2)$$

4. Experimental results

Length of inception point of aeration: figure 2 presents length of inception point versus roughness Froude number in conditions of: 1) not installing deflector and 2) installing deflector and closing aerator.

Table 2: Characteristics of deflector type 3

γ (deg)	c/cd	Cd (cm)	C (cm)	L (cm)	Deflector location
20-30-40	0.8-0.9-1	2.9	2.3-2.6-2.9	2.5	Zone 1
20-30-40	0.8-0.9-1	4	3.2-3.6-4	3.5	Zone 2
20-30-40	0.8-0.9-1	5.2	4.1-4.7-5.2	4.5	Zone 3

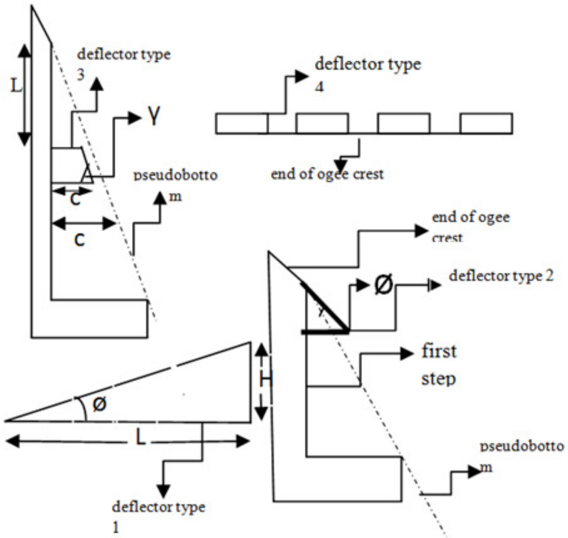

Fig. 1: details of types of deflectors

Deflector type 1: results of experiments state that: a) in not installing deflector condition, length of inception point increases with increase in flow discharge) results obtained in experiments in not installing deflector condition, have a good consistency with equation suggested by Hager (2003). In other word, Hager equation would anticipate length of inception point in stepped spillway in condition of not installing deflector well but Chanson equation (1994) underestimates this value. c) For a deflector with constant dimension, length of inception point increases with increase in water discharge. Because with increase in discharge, existing energy in flow will increase and flow feel deflector on its way less and finally will have less effect on developing boundary layer. This phenomenon causes movement of inception point into downstream of spillway. d) In a constant water discharge, length of inception point will decrease with increase of deflector dimensions. That reason of this phenomenon is contact of flow with greater obstacle and creating oscillation and turbulence in boundary layer. This turbulence causes faster growth in boundary layer and decreases distance to arrive this layer into flow free surface.

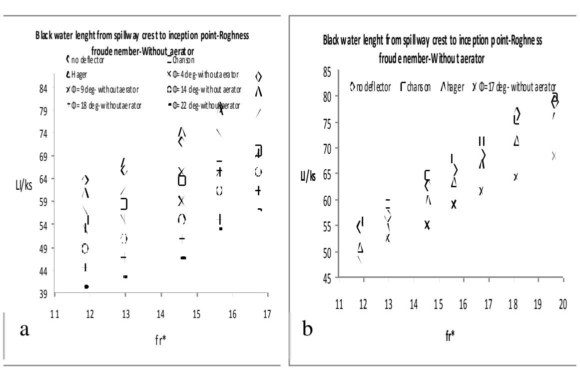

Fig. 2: Length of inception point versus roughness Froude number for different water discharges in both conditions of:1) not installing deflector and 2) installing deflector and closing aerator: a)model No.1, deflector type1; b)model No.2, deflector type1.

Deflector type 2: in this condition, deflector is installed on vertical face of first step above pseudo bottom. Similar to type 1, length of inception point will increase with increase in dimensions of deflector. In experiments related to deflector type 2, ultimate angle of deflector is 10 degree and with increase in this angle, incidence of severe contact of flow with deflector and creating turbulence and forming irregular waves in flow surface, is observed. Deflector type 3*:* in this condition that deflector is installed on vertical face of first step under pseudo bottom, it IA observed that in a constant water discharge with replacement of deflector in different points, overlap is seen between results. In other word, when aerator is closed, deflector type 3 has insignificant influence on replacement of inception point and in this condition; deflector has the least influence on growth and development of boundary layer. Deflector type 4*:* in this condition, jaggedness of deflector makes width of spillway less so it reduces flow passage from cross-section. observations present that flow while passing over deflector, strikes downstream steps as falling jet and produces severe waves and oscillation. It is necessary to state that comparison between different types of deflectors-in this study- is impossible, because of their different shapes. In order to examine effect of deflector type 1, a deflector with ϕ=17deg in model no.2 has been tested that its results have been presented in figure 2.

Fig.3 presents length of inception point versus to roughness Froude number, in condition of installing deflector and opening aerator in different models. Deflector type 1: results of experiments state that: a) for a deflector with constant dimensions, length of inception point increases with increase in discharge. b) In a constant discharge, length of inception point decreases when dimensions of deflector increase. So this causes contact of flow with a bigger obstacle and produces greater oscillation and turbulence in boundary layer. That makes this layer bigger and arrives sooner to flow free surface.

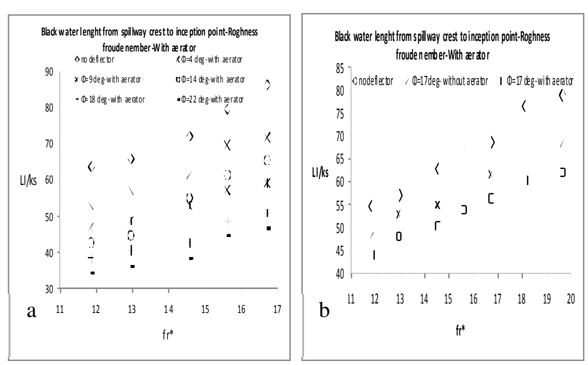

Fig. 3:.Length of inception point versus roughness Froude number, for different discharge in condition of installing deflector and opening aerator: a) model No.1, deflector type1; b) model No.2, deflector type1

c) in a constant discharge, length of inception point in this condition has been reduced relative to condition of closed aerator since due to simultaneous existence of deflector and entering air from aerator in upper part of spillway, water flow passes deflector as free jet that finally rate of growth in boundary layer increases and this layer approaches flow free surface sooner. In deflector type 2 like type 1, in a constant discharge, length of inception point decreases as dimensions of deflector increases and in deflector type 3, with existence of efficacy on decreasing length of inception point relative to not installing deflector condition, obtained results present that replacement of deflector in each three zones (1, 2, 3), have similar effect on decreasing length of inception point. By examining results obtained of experiments, following equations can be stated in order to anticipate length of inception point of aeration in stepped spillways: a) not installing deflector condition; b) installing deflector and close aerator condition; c) installing deflector and onen aerator condition:

a) $$\frac{L_I}{h\cos\theta} = 9.719(\sin\theta)^{0.076} F_*^{0.733} \qquad (3)$$

b) $$\frac{L_I}{h\cos\theta} = 9.72(\sin\theta)^{0.078} F_*^{0.72} (\tan\phi)^{0.0945} \qquad (4)$$

c) $$\frac{L_I}{h\cos\theta} = 9.718(\sin\theta)^{0.083} F_*^{0.689} (\tan\phi)^{0.1109} \qquad (5)$$

Depth of flow in inception point of aeration**:** By studying the experiment results, it can be stated that:

.Deflector type 1: a) in not installing deflector condition, flow depth in inception point increases as discharge increases. b) Results obtained of experiments in not installing deflector have a very desirable consistency with equation offered by chanson. In fact, chanson equation anticipates flow depth in inception point in stepped spillway without installing deflector well, whereas Hager equation predicts this parameter more than observed value. c) For a deflector with constant dimensions, flows depth in inception point, increases with increasing discharge. d) In a constant discharge, with growth in dimensions of deflector, flow depth increases, because as it was stated before, flow comes into contact with a bigger obstacle and greater oscillation and turbulence increase in boundary layer and velocity of approaching into flow free surface increase with growth and development of this layer. Finally, this action -air entrance into water flow- is done in less distance from spillway crest. *deflector type 2*, flow depth also increases as dimensions of deflector increase in a constant discharge but in deflector type 3 there is overlap between data because for little effect of this type of deflector on reducing length of inception point and so flow depth in this point. In order to examine effect of deflector type 1, a deflector was selected and tested with $\phi = 17\deg$ in model no.2. By studying the experiment results in condition of opening aerator, it can be stated that: for a constant discharge, efficacy of deflector type 1 and 2 has increased on flow depth in inception point relative to closed aerator condition that is because of air entrance from aerator in upper part of spillway, generating free jet because of simultaneous existence of deflector and aerator, increase in rate of growth in boundary layer and shortening distance of approaching this layer into flow free surface. In deflector type 3, overlap is seen between data and it's for little effect of this deflector on reducing length of inception point and so less efficacy on flow depth in this point. The results present that flow depth in aeration condition is more than other conditions of not installing deflector and also closed aerator. Totally effect of deflector on reducing length of inception point which is related to nature of flow passing on spillway. In order to study effect of deflector type 1, a deflector with $\phi = 17\deg$ in model No.2 has been selected and tested. By examining results obtained from experiments, following equations have been suggested to anticipate flow depth in inception point of aeration in stepped spillway: a)not installing deflector condition; b)installing deflector and close aerator condition; c)installing deflector and open aerator condition:

a) $$\frac{d_I}{h\cos\theta} = \frac{0.405}{(\sin\theta)^{0.0401}} F_*^{0.594} \qquad (6)$$

b) $$\frac{d_I}{h\cos\theta} = \frac{0.433}{(\sin\theta)^{0.044}} F_*^{0.624} (\tan\phi)^{0.0808} \qquad (7)$$

c) $$\frac{d_I}{h\cos\theta} = \frac{0.437}{(\sin\theta)^{0.083}} F_*^{0.689} (\tan\phi)^{0.1109} \qquad (8)$$

Dynamic pressure fluctuations**:** After collecting data by pressure transducer device, this data has been analyzed by spss software and show obtained results have normal curve distribution After that, values P 1%, P 99% that P*%-number that *% of data are smaller than it-are determined. Then for each point p99% is selected as P max-maximum pressure- and value P 1% as P min-minimum pressure. According to Amador (Amador and Marti, 2009) , critical point in stepped spillway is points placed on vertical face of stepped and especially on sub-upper part near edge of each step, in relation to reduce pressure on steps and generating cavitation phenomenon. Figure 4 presents dynamic pressure fluctuations in condition of installing deflector and opening aerator, on vertical face of steps in model no.1 and deflector type1. Results present that: a)by examining pressure fluctuations, vertical face of step can be divided into two external part-near to edge of step-and internal part-under external part and above next step)in external part, average pressure and minimum pressure and maximum pressure increase as discharge increases')in internal part, maximum, average and minimum pressures increase as discharge increases. d)by enlarging dimensions of deflector, pressures on vertical face of step increase. Reason is that, by increasing deflector dimensions, volume of air entering flow increases, flow depth increases and velocity of flow decreases. Finally, pressure from flow on step increases. e) Entrance of air increases pressure fluctuations on steps.

Coefficient of cavitation (cavitation index): by using values of minimum pressure computed in previous section, cavitation index of flow passing stepped spillway is computed from following equation:

$$\sigma_i = \frac{\left(h_{pi} - h_v + h_a\right)}{\left(\frac{V^2}{2g}\right)} \qquad (9)$$

Where: σ_i :cavitation index, h_{pi} :height equals pressure on surface, h_v :height equals vapor pressure h_a :height equals atmosphere pressure V : average velocity of cross-section.

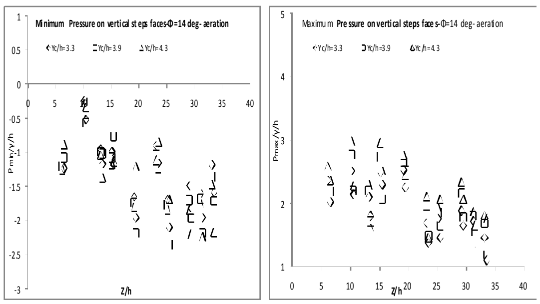

Fig. 4: Dynamic pressure fluctuations in condition of installing deflector and open aerator, on vertical face of steps in model no.1 and deflector type 1 ($\phi = 14\text{deg}$)

Results in condition of closing aerator stated that: a) Cavitation index decreases, as flow discharge increases because of decrease in pressure enforced on step surface. b) Cavitation index decreases, with increase in distance from crest of spillway, because of increase in flow velocity and decrease in pressure. c) Cavitation index in internal part of horizontal face and in external part of vertical face is less than other parts. d) Totally, cavitation index in vertical face of steps is less than horizontal face and it means that possibility of occurring cavitation, in external zone on vertical face is more than other parts. Figure5 present cavitation index–in condition of installing deflector and opening aerator-in different models and on vertical and horizontal face of steps. Results of experiments in condition of entering air into flow passing from spillway present that: a) cavitation index decreases as distance from crest of spillway increases because of increase in velocity and reduce in pressure. b) Cavitation index in horizontal internal part and vertical external part is less than other parts. c) By installing deflector and opening aerator – entrance of air- generally, cavitation index has been increased in step surface that means risk of creating cavitation on steps decreases. d) Increasing in deflector dimensions has a positive effect on increasing cavitation index in stepped spillways.

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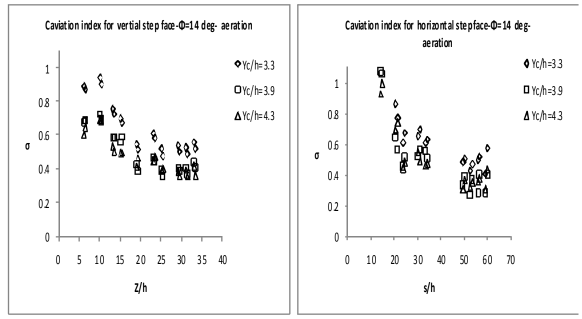

Fig. 5: Cavitation index, in condition of installing deflector and opening aerator, in model No.1 and on vertical and horizontal face of steps; s: distance from crest on pseudo bottom and z: vertical distance

5. Conclusion

By examining results obtained of experiments on model no.1 with slope of 40 degree, according to critical cavitation index $\sigma = 0.2$ and scale factor $\lambda_l = 20$, the ultimate water discharge in unit width is about $q = 36.5\ m^3/s/m$ .installing deflector and entrance of air into flow, reduces risk of cavitation, and cavitation index for a certain water discharge increases relative to not installing deflector condition and ultimate water discharge in unit width can be increased about $q = 50.6\ m^3/s/m$ that presents increasing 38.6%. But in model no.2 with slope of 51 degree, according to critical cavitation index of $\sigma = 0.2$, ultimate water discharge in unit width is about $q = 30.9\ m^3/s/m$ .By installing deflector and air entrance to flow, water discharge in unit width can be increased about $q = 40.1\ m^3/s/m$ that presents increasing 29.3%(figure 5).

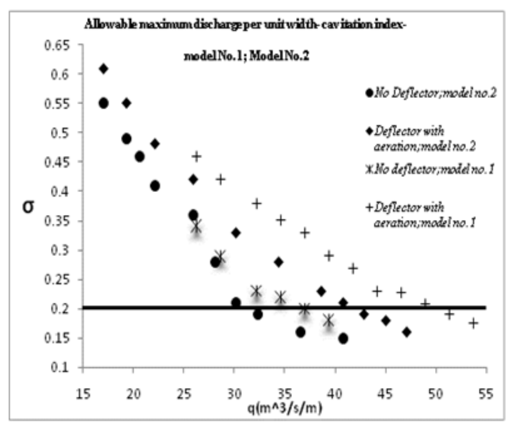

Fig. 5: Allowable maximum discharge per unit width respect to cavitation index in model No.1 and No.2

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