PREDICTION OF SCOUR DEPTH DOWNSTREAM OF GABION STEPPED SPILLWAY

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1. Abstract

Use of rocks and gabions in hydraulic works especially in the area of river engineering have been increased during recent decades. Gabion stepped spillway is a type of hydraulic structures which is designed for river bed protection. Most of the flow kinetic energy is dissipated when flow cascade from one step to another. Therefore in most cases, the stilling basin does not considered at the downstream end of spillway, because of this a scour hole may developed. The main objective of this study is to conduct a series of experimental tests to investigate the mechanism of scour hole development. A total of 19 tests were conducted. The results of this study reveals that the scour hole dimensions in simple stepped spillway is larger than the pooled stepped spillway. Three equations have been presented for prediction of maximum scour hole depth.

2. Introduction

Rocks in its natural form is the most abundant and economical material in hydraulic engineering practice. Rocks have been used in dam construction, river engineering works, river intakes etc. The size of rock in these practice depends on the hydraulic conditions such on flow velocity, shear stress, hydrostatic and hydrodynamic pressures. When these conditions are high, the required size of stone will be large and impractical. In such case, the alternative is to tie the stones together by some means. Gabions are hexagonal mesh boxes filled with small sizes of stone. The advantage of gabion are a) their stability b)low cost c) flexibility d)porosity (Chinnarasri, et al. 2003). The Gabions retains the advantages of rock fill in its flexibility and permeability so that water pressure are minimized. The wire mesh container can act intension. Nowadays, the gabion is used for hydraulic engineering works such as revetments, channel linings, weirs, groins and energy dissipation structures (Stephenson, 1979). One application of gabion is for constructing the stepped spillways. In this structure, the energy is dissipated. as water flows downstream. Flow through the rock mixes with the flow over the crest, resulting in energy dissipation by Jet impingement as well as due to friction loss through the rock fill. In addition, the energy is dissipated as flow cascade from one step to another. Three types of flow occur in gabion stepped spillway: a) "napped flow" when flow cascade from one step to another, b) "skimming flow", when the water fully flow through the steps and c) "pooled flow" when a step is provided at the end of each step. Many empirical equations have been developed to distinguish three types of flow. Table 1 shows some of these formulas. In these equations y_c is the critical depth, approximately equal to the flow depth at the crest. h and l are the height and length of each step.

Table 1 : Formula for distinguish of three types of flow

Type of flow	Formula	Author (s)
Nape flow	$\frac{y_c}{\hbar} = 0.092(\frac{\hbar}{\ell})^{-1.276}$	Chanson (1994)
	$\frac{y_c}{\hbar} = 0.89 - 0.4(\frac{\hbar}{\ell})$	Chanson (2001)
	$\frac{y_c}{\hbar} = 0.80 - (0.55)(\frac{\hbar}{\ell})$	Chinnarasri (2003)
Skimming flow	$\frac{y_c}{\hbar} = 0.862(\hbar / \ell)^{-0.165}$	Yasuda and Ohtsu (1999)
Pooled flow	$\frac{y_c}{\hbar} = [0.55 - 0.16Ln(\frac{\hbar}{\ell})]^6$	Aigner (2004)

Many researches have investigated the energy dissipation in stepped spillway including gabion stepped spillway. Kazemi- Nasaban (1996) and Peyras et al.(1992) have presented the following equations for the case of nape flow:

$$\frac{1}{1-\frac{\Delta E}{H}} = a(\frac{q^2}{gH^2})^b \tag{1}$$

in whish ΔE is the amount of energy dissipation, H is the height of spillway, q is the unit discharge, a and b are coefficients which depend on the slope of spillway as shown in Tables 2 :

Table 2 : Values of a & b in Eq. (1)

Slope (H:V)	a	b
1:1	0.238	-0.526
2:1	0.169	-0.654
3:1	0.208	-0.647
3.5:1	1.736	-0.279

For the case of pooled spillway, Aigner (2004) developed the following formula:

$$\frac{\Delta E}{H_{\max}} = \frac{\frac{H}{y_c}}{\frac{H}{y_c}+1.5} \tag{2}$$

in which $H_{\max}$ is the total upstream energy.

Even though the cascading and impingement dissipate a lot of the energy, the scour at the downstream end of the spillway remains to some extent a problem, especially when a stilling basin has not been provided at the downstream. The extent of such scour hole may result the instability of the spillway or even its failure. Predicting the scour hole depth can help the engineers to design the spillway more safe. Review of literature reveals that no such study, by the knowledge of the authors, have been conducted. Therefore, it is the purpose of this study to conduct an experimental tests and to develop a relationship for predicting the maximum scour hole depth, downstream of the gabion stepped spillways.

3. Theoretical consideration

Consider a scour hole downstream of stepped spillway, for an equilibrium scour hole , the particles on the bed are at incipient motion. Forces exerted on the particles are the drag and lift forces and the submerged weight of particles. From the stability analysis of a particle at threshold condition, one can obtain [Shafai- Bajestan et al . (1995)]:

$$\frac{d_s}{D_{50}} = f(SN, \frac{y_1}{D_{50}}) \qquad (3)$$

In which d_s is the maximum scoure hole depth , D_{50} is the median particles, and SN is the stability number defined are :

$$SN = \frac{V_1}{\sqrt{g(G_s - 1)D_{50}}} \qquad (4)$$

y_1 and V_1 are the flow depth and flow velocity just downstream of the spillway, G_s is the particle specific gravity and g is the acceleration of gravity .

4. Experimental set_ up

Eq.3 is a general relation for predicting the scour hole depth. To determine the coefficients of this equation, a series of experimental tests have to be conducted . The experimental tests were conducted in a flume 50 cm wide , 8 meter length and 1.5 m height in the hydraulic laboratory of Shahid_Chamran university. Figure 1 shows the plan and section view of the flume. Three types of gabion stepped spillway, Fig.2, were tested under different flow conditions. Two different sizes of bed material, A and B, were placed inside the gabion mesh and three types of bed materials, C,D, and E were placed downstream of the spillway. Figure 3 shows the size distribution of these materials.

After placing the desired gabion spillway and bed material, the required flow discharge was established by simultaneous opening of the inflow valve and the downstream gate.

In all tests, the flow type was the nape or pooled flow. Upon the establishment of the desired flow and tail water depth, the flow characteristics and the scour depth was measured during the test. It should be noted that the scour hole initiated just downstream end of gabion apron and its dimension increasing with time. When no removal of bed material from the scour hole is observed, usually 60 minutes from the start, pump was shut down and at the same time the downstream gate gradually was closed to prevent sediment particles entering the scour hole. At the end of each test, the scour hole dimensions were recorded. The results are shown in Table 3. Figure 4 shows the scour hole geometry for three types of spillways when the discharge (Q) was 20 l/s.

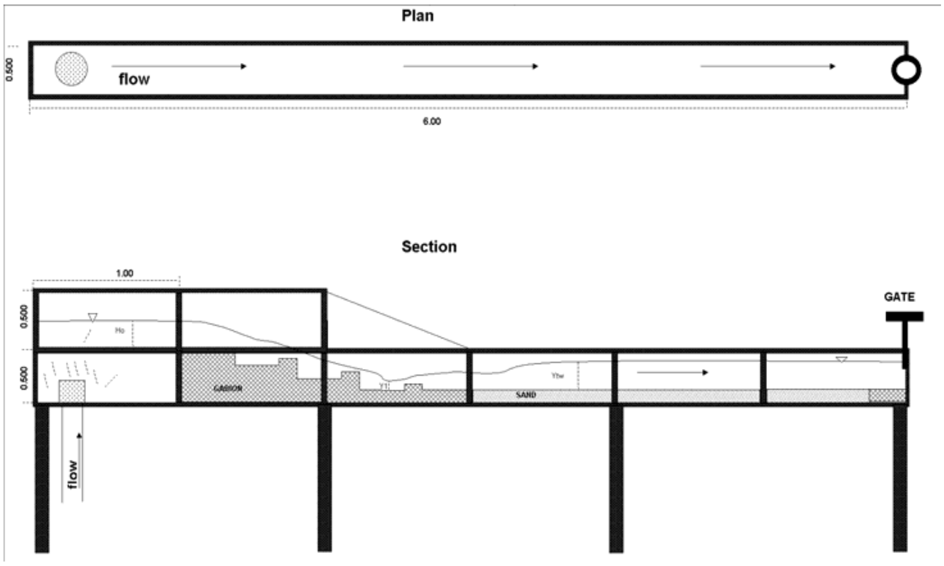

Fig. (1) Plan and section view of the experimental flume.

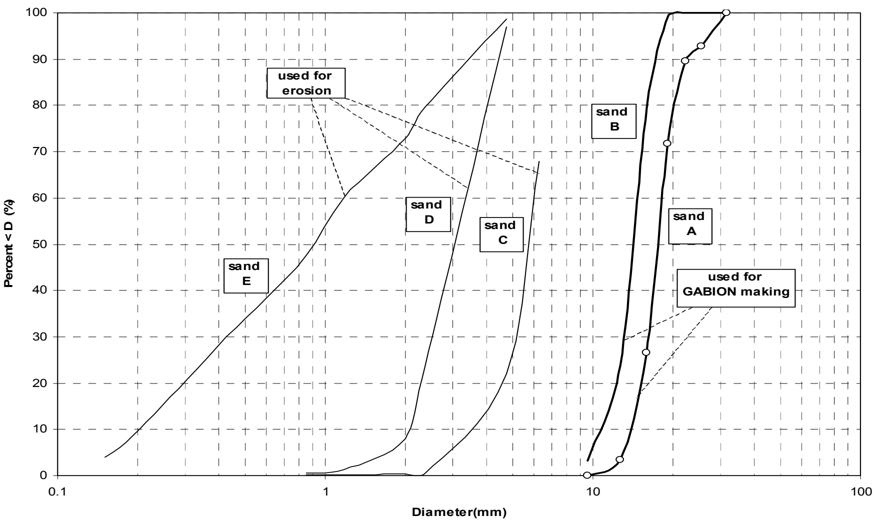

Fig. (2) Three types of stepped spillway tested in this study

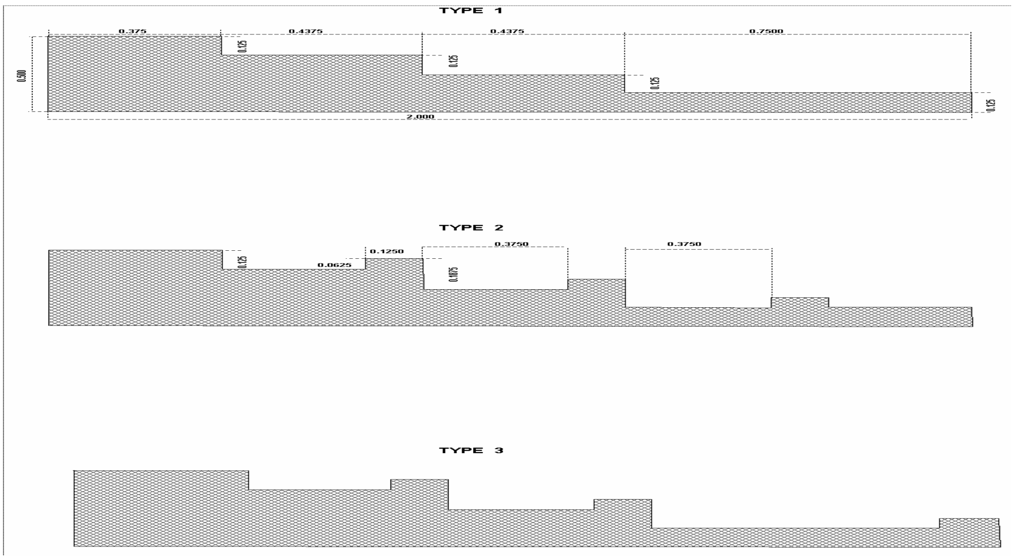

Fig 3 Size distribution of rock and bed - material

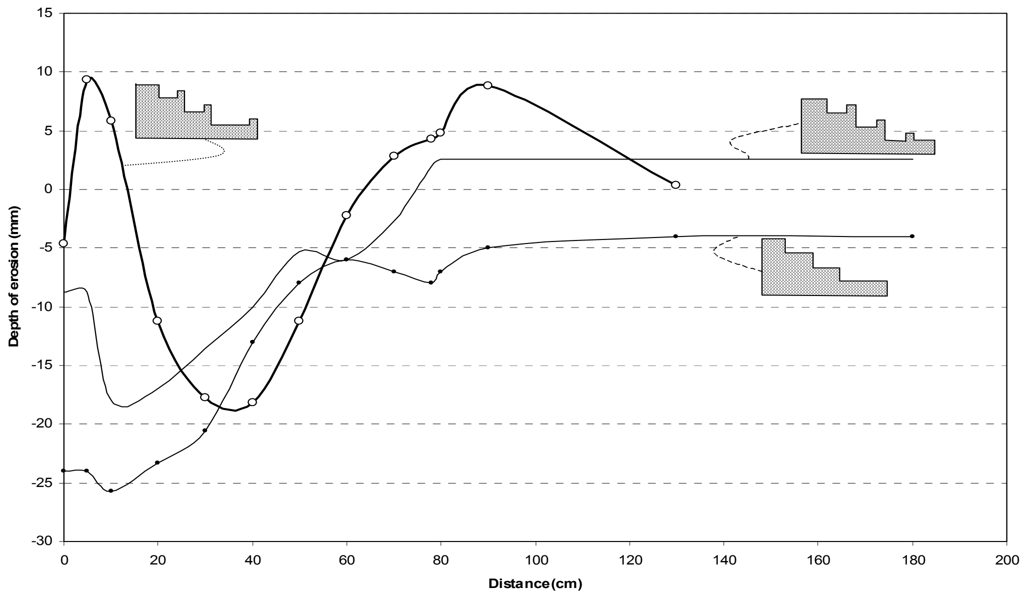

Fig. (3) Scour hole geometry for Q=20 lit/sec

5. Results and Discussions

To predict the scour hole dimensions downstream of gabion stepped spillway, experimental program was conducted. Three types of spillways with slope of 1V:3.5 H, were tested under different flow conditions and two bed material sizes. The results obtained from these tests reveals that the scour hole dimensions in type I spillway, or simple spillway, is generally larger than the other two types of spillway. This is because the energy dissipation in pooled stepped spillway is more than the simple stepped spillway. By analyzing data obtained from this study, three equations were developed by regressional method. These equations are as follow:

Table 3 : Summary of the results

Type spillway	Q (lit/sec)	Y_1 (cm)	Y_{tw} (cm)	D_{50} (mm)	F_{r1}	L_s (cm)	D_s (mm)
Type(1) Simple stepped spillway	19.91	20	20	3.0	-	-	-
	19.91	15	15	3.0	-	-	-
	19.91	13.5	11.5	3.0	0.289	10	5
	19.81	13.5	9.5	3.0	0.255	15	17.9
	41.35	19.0	24	3.0	-	35	3.6
	41.35	15.0	17	3.0	0.454	10	20.0
	57.95	16.5	21.75	3.0	0.57	40	20.4
	20	12.5	11.5	0.90	0.289	10	18
	41.35	15.0	17.0	0.90	0.454	30	21
	58.4	16.25	21.5	0.90	0.57	60	36
Type(2) Pooled stepped spillway. End sill in the middle of downstream apron	19.13	7	10.5	3	0.66	10	5.5
	41.35	11.5	17	3	0.67	10	27
	57.95	16	21	3	0.578	50	22.6
	19.91	8.5	11.5	0.9	0.513	10	25.7
	41.35	7.5	17	0.9	1.286	20	59.7
	57.95	10	21	0.9	1.17	30	44.0
Type(3) Pooled stepped spillway and sill in the end of downstream apron	19.91	15	11.7	0.9	0.219	40	18.2
	41.35	14.5	17	0.9	0.476	70	28
	58.4	14.0	21.5	0.9	2.46	60	34.5

A) For simple gabion stepped spillway:

$$\frac{ds}{D_{50}} = 0.125 \left(\frac{Y_1}{D_{50}}\right)^{1.39} (SN)^{0.95} \qquad (5)$$

$r^2 = 0.97$

B) For pooled stepped spillway (end sill at the middle of downstream apron):

$$\frac{ds}{D_{50}} = 0.43 \left(\frac{Y_1}{D_{50}}\right)^{0.98} (SN)^{0.92} \tag{6}$$

$r^2 = 0.84$

C) For pooled stepped spillway (end sill at the downstream end of apron)

$$\frac{ds}{D_{50}} = \left(\frac{Y_1}{D_{50}}\right)^{0.94} (SN)^{0.61} \tag{7}$$

$r^2 = 0.99$

6. Design procedure

The following procedure is presented to estimate maximum scour hole depth :

1) by knowing the unit discharge, and the maximum height of spillway, determine the energy loss through stepped spillway by applying the proper type of Eq.(1). For example for the case of $\hbar / \ell = 3.5$ one can find the coefficients a and b from Table(2) and thus Eq(1) will be as follow:

$$\frac{1}{1-\Delta E / H} = 1.736 \left(\frac{q^2}{gH^3}\right)^{-0.28} \tag{8}$$

2) determine the amount of energy downstream of the spillway:

$$E_1 = \frac{3}{2} y_c - \Delta E \tag{9}$$

in which $y_c = \left(q^2 / g\right)^{1/3}$

3) by solving the energy and continuity equations determine Y_1 and V_1:

$$E_1 = \frac{V_1^2}{2g} + Y_1 \tag{10}$$

$$q = V_1 Y_1 \tag{11}$$

4) determine the stability number (Eq. 4).

5) determine the scour depth applying the proper equation (Eq. 5 through Eq.7)

7. Conclusion

In this study three types of gabion stepped spillways under different flow conditions and bed materials were tested. Based on stability analysis of a particle at the point of incipient motion, a general formula was developed. By the help of regression analysis technique and use of the experimental data, three equations were developed. From these equations, one can predict the maximum scour hole depth. It was found that the scour hole downstream of simple gabion stepped spillway is more than the pooled stepped spillway.

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