Predicting the scour depth downstream single step broad crested weirs

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Abstract: The main purpose of broad crested weir used in open channels is to raise and control upstream (U/S) water level. The most important problems for downstream of hydraulic structures are the local scour formed at the downstream of hydraulic structures. Scour control process considered as the main objective to ensure safety and economical design of hydraulic structures to prevent any serious failure in the future. In this study, four models of Single-Step-Broad-Crested weirs with different angles were tested under different flow intensity for duration of 6 hours. Acoustic Doppler Velocimeter (ADV) was used to investigate the velocity field. The results showed that, the model C reduces local scour hole volume was about 87.6%, 55.58% and 44.8% and the maximum depth of scour reduced 73.43%, 32.56% and 24.22% as compared with model D at each discharge.

Keywords: Broad crested weir, Scour reduction, Local scour, Weir.

1. Introduction

The weirs are of different kinds such as ogee crest weir, sharp crested and broad crested weir. A broad crested weir is generally considered for most hydraulic structures for flow measurement and to control the water surface level in open channels. The streamline flows over broad crested weir are parallel to the crest, critical depth occur along the crest and the pressure distribution is hydrostatic [1].

The weir is an obstruction constructed across a river or stream in order to increase and control water head at the upstream of the weir or for water flow measurement. There are different zones in the flow over a weir and the energy loss of the flow over a weir [2]. To dissipate energy and to prevent erosion and scouring in D/S ends, step at D/S ends of weirs is constructed or lining by rubbles and riprap [3].

Guan et al. [4] studied the flow patterns and turbulence structures in a scour hole downstream of a submerged weir. The study presented the distributions of flow patterns, bed shear stresses, and turbulence structures in the approach flow and the scour hole downstream of a submerged weir. [5] Studied experimentally to predict the scour geometry downstream the weir. The scour was decreased by using a row of semicircular baffle blocks. The results show that the time required for settling the operation of scour was 6 hours. [6] studied the characteristics of square and round edge (R) for broad crested weirs under free and submerged flow conditions. Furthermore, they found that the flow...
separation is essentially eliminated. The authors [7] are investigated experimentally the effect of upstream face slope of trapezoidal broad crested weir on discharge coefficient and water surface profile. They concluded that decreasing the upstream face slope prevent development of separation zone and the discharge coefficient increased up to 10% when the upstream face slope decreased to 21\(^0\). The experimental results of [8] showed that the single step broad crested weir increased the energy dissipation percent up to 46% and was better and gets higher values in comparison with traditional broad crested weirs. [9] They examined the effect of the approach angle on discharge efficiency of broad crested weir. The results indicated that the discharge coefficient is not only a function of crest length but also the approach angle. They also proposed empirical relation contained approach angle. [10] Stepped and unstepped weirs were investigated in a laboratory study for steep slope channels in order to find their efficiency for dissipating flow energy. It was found that the maximum energy dissipation ratio in stepped weirs was approximately 10% higher than in unstepped weirs. The influence of the upstream slope face on a trapezoidal broad-crested weir was investigated using Open FOAM Two turbulence models (standard k-\(\varepsilon\) model and the SST k-\(\omega\) ) were used in the numerical simulations. The simulation results were compared with experimental results the results showed that study that the Inter Foam solver of Open FOAM can provide a good prediction of the free-surface profile and discharge coefficient [11]. [12] studied experimentally the effect of channel bed slope on energy dissipation of flow for single step broad crested weir. He found that the maximum energy dissipation ratio was 12.71\% for \(S = 0, P/P1 = 3\). The impact of upstream and downstream slope coefficients S1 and S2 on overflow discharge coefficient in rectangular short crest weir numerically simulated with volume of fluid (VOF) and Renormalization Group k-\(\varepsilon\) turbulence model. The simulated results were compared with experimental data and showed that the difference of discharge coefficient will decreased with upstream slopes, and increased with downstream slope as total energy heads increases [13]. The investigation of [14] for single step broad crested weir, showed that the ratio of the length of D/S step to the length of the weir (\(L2/L1 = 0.5\)) gives a higher E\% in similarity with other weir models.

In order to reduce the risk of undermining weir foundation, various form of bed protection is used, which weaken the process of local scour and shift it to a safe distance from the foundation. One of them is the single step broad crested weir.

Scour process considered as the main objective to ensure safety and economical design of hydraulic structures to prevent any serious failure in the future.

2. Theoretical Analysis

The first step to develop an empirical relationship is to select the main parameters that have an influence on the local scour. These parameters can be functionally expressed as follows:

\[ f_1 (D_s, H_W, d_{50}, h, \sigma_g, q, \nu, g) = 0 \]  \hspace{1cm} (1)

In which:
\(D_s\) = Maximum scour depth, cm
\(H_W\) = U/S water head above the crest, cm
\[ D_{50} = \text{Median size of sand, mm} \]
\[ h = \frac{D}{S} \text{ water head, cm} \]
\[ q = \text{Discharge over the weir per unit width, cm}^2/s/cm \]
\[ \nu = \text{Kinematics viscosity of water, cm}^2/s \]
\[ g = \text{Acceleration due to gravity, cm/s}^2. \]

Using Buckingham Π theorem, the variables in Eq. (1) may be expressed in nondimensional form as:
\[ \frac{D_{50}}{H_w} = f_5\left(F^*, \frac{H_w}{h}, \frac{D_{50}}{H_w}, R_e\right) \]

In which:
\[ F^* = \text{Densimetric particle Froude number} \]
\[ R_e = \text{Reynolds number} \]

Because the flow over the weirs is absolutely turbulent, which means Reynolds Number \( (R_e) \) is very high, hence the effect of this number will be very little, therefore, \( R_e \) may be neglected and \( D_{50} \) is fixed in this study then equation (2) can be rewritten as:
\[ \frac{D_{50}}{H_w} = f_5\left(F^*, \frac{H_w}{h}\right) \] (3)

A particle dens metric Froude number \( F^* = \frac{U}{\sqrt{(S-1)g D}} \) (where \( U=\text{mean velocity} \), \( S=\text{ratio of sediment and fluid densities} \), \( g=\text{acceleration due to gravity} \) and \( D=\text{characteristic diameter of bed particle} \) is here proposed as an alternative criterion to predict hydraulic conditions for the initiation of motion.

3. **Experimental Setup**

Experimental study was conducted in an open channel with 12 m long, 0.5m width and 0.5 m depth.

The test section at the flume bed is 2 m long, 0.5 m wide and depth is deeply model was prepared at a distance 3 m from the channel entrance to eliminate water surface fluctuation as shown in Figure(1) with glass sides and steel bottom. The test section was filled with sand of median particle size \( D_{50}=1.8 \text{ mm} \) and standard deviation, \( \sigma_g = 3.65 \) with the specific gravity of 2.65.
Four models of Single Step Broad Crested Weirs [Model (A), Model (B), Model (C), and Model (D)] respectively with different positive angles ($0^\circ$, $5^\circ$, $10^\circ$, and $15^\circ$) were tested as shown in Figure (2). Three discharges were measured (15, 20 and 25 l/s) for duration of 6 hours.

4. Results and Discussions

Analysis of results included three main aspects, water surface profiles, total scour volume (maximum scour depth) and factors effecting on maximum scour depth over traditional single step broad crested weir and single sloped step broad crested weirs with different positive angles along the crest and face.

4.1. Water surface profile

Water surface profiles were plotted and analyzed to examine their shape and there variation with horizontal distances upstream and downstream the crest.

The experimental results of measurements of water surface profiles along the center line of the channel show a descending trend from the point of measurement with a drop near the downstream face of all types of weirs. Water surface profiles over traditional single step broad crested weir and single sloped step broad crested weirs with different positive angles for all test runs of models (A, B, C and
D) were plotted for all discharges as shown in figures (3, 4, 5 and 6). This figure shows the relation between Y and X, where, Y is the depth of flow reckoned above the bed of the channel (Hw) in (cm) and X is the horizontal distance (D) measured from the upstream end of the crest to the downstream toe of spillway in (cm). Also, it can be seen that water surface profiles were becomes horizontal when X/P≤ -2.63 where (X) is the U/S distance from water surface profiles were becomes horizontal and (P) weir height. These water surface profiles were used to determine the average velocities and U/S water heads over the weir when water surface profiles were essentially horizontal. Skimming flow occur when water flows over all models, the trend of these water surface profiles for all discharges were mostly similar, smooth and follow the shape of the weirs.

It can be seen that from all figures below, the effect of horseshoe vortex is very strong for model D, but the effect of horseshoe vortex is reduced for model C due to large energy dissipation.
4.2. Total scour volume (Maximum scour depth)

The total scour volume and maximum scour depth were measured and compared with each of four models as shown in Table (1). It is clear that maximum scour depth is lowest for model C and the volume of local scour is little than the other models at each discharge.
Table (1): Properties of local scour.

| Model | Angle (β°) | Q (l/s) | Maximum scour depth (D_s cm) | Scour Volume (V_s cm³) |
|-------|------------|---------|-----------------------------|------------------------|
| A     | 0          | 15      | 11                          | 27993                  |
|       | 0          | 20      | 12.8                        | 42537                  |
|       | 0          | 25      | 12.4                        | 48583                  |
| B     | 5          | 15      | 9.5                         | 19597                  |
|       | 5          | 20      | 12.8                        | 32405                  |
|       | 5          | 25      | 12.4                        | 52680                  |
| C     | 10         | 15      | 3.8                         | 7974                   |
|       | 10         | 20      | 11.6                        | 31338                  |
|       | 10         | 25      | 12.2                        | 43784                  |
| D     | 15         | 15      | 14.3                        | 64326                  |
|       | 15         | 20      | 17.2                        | 70556                  |
|       | 15         | 25      | 16.1                        | 79316                  |

Experimental measurements in Table (2) shows that maximum scour depth is reduced 73.4%, 32.6% and 24.2% for model C comparing with models D at each discharge. In addition, the scour volume for model C is reduced about 87.6%, 55.6% and 44.8% comparing with model D at each discharge are shown in Table (2). Local scour depth and volume of local scour is reduced because the effect of horse shoe vortex.

Table (2) Scour volume and maximum local scour depth reduction

| Model | Angle (β°) | Q (l/s) | Volume Reduction (%) | Maximum Scour Depth Reduction (%) |
|-------|------------|---------|----------------------|-----------------------------------|
| A     | 0          | 15      | 56.5                 | 23.1                              |
|       | 0          | 20      | 39.7                 | 25.6                              |
|       | 0          | 25      | 38.8                 | 23.0                              |
| B     | 5          | 15      | 69.5                 | 33.6                              |
|       | 5          | 20      | 54.1                 | 25.6                              |
|       | 5          | 25      | 33.6                 | 23.0                              |
| C     | 10         | 15      | 87.6                 | 73.4                              |
|       | 10         | 20      | 55.6                 | 32.6                              |
|       | 10         | 25      | 44.8                 | 24.2                              |
The minimum distance of scour from weir for each discharge has occurred at model D lead to

![Figure 7: Formation of local scour and distances for model (A).](image1)

![Figure 8: Formation of local scour and distances for model (B).](image2)

Exposure for failure in the future as illustrated in Figure 7, 8, 9 and 10.
As shown in Figure 11, 12, 13, 14, 15 and 16, the maximum scour depth was found downstream the weir model D because the drop of water near from the toe of the weir. This case increases the risk of failure of the weir.
Figure (12): Formation of local scour and distances for model (C).

Figure (13): Formation of local scour and distances for model (D).
5.3. Factors Effecting on Maximum Scour Depth
5.3.1 Effect of Densimetric particle Froude number \((F^*)\) on the Maximum Scour Depth to upstream water depth ratio \((D_s/H_w)\).

Variation of \((D_s/H_w)\) with \((F^*)\) for all weirs model are shown in figure (17). From this figure one may observe that for all shapes of single step broad crested weir an increase in \((F^*)\) value causes an increase in \((D_s/H_w)\) and for all value of \((F^*)\) less than 0.57, the model C give less value of \((D_s/H_w)\) than the other models as shown in figure (17), where increase in \((F^*)\) from (0.44 to 0.57) causes an increase in \((D_s/H_w)\) from (0.27 to 0.28) for model A with \(\beta=0^\circ\), from (0.25 to 0.28) for model B with \(\beta=5^\circ\), from (0.165 to 0.28) for model C with \(\beta=10^\circ\) and from (0.35 to 0.379) for model D with \(\beta=15^\circ\).

This could be attributed to the reason that; as the head above crest of all model of the weirs increases the overflowing process becomes easier and adhere to the face of weirs and develop skimming flow over all models, trying to speed the jet and consequently increase the flow rate passing over it and increasing the energy dissipation. As well as the figure show that weir model (C) give higher energy dissipation at little value of \((F^* \leq 0.57)\) than the other models.

![Figure (17): Relation between \((D_s/H_w)\) and Densimetric particle Froude number \((F^*)\) for all model of Single Step Broad Crested Weir with d/s positive angle.](image-url)

5.3.2 Effect of upstream to downstream water depth ratio \((H_u/h)\) on the Maximum Scour Depth to upstream water depth ratio \((D_s/H_u)\).

Variation of \((D_s/H_u)\) with \((H_u/h)\) for all weirs model are shown in figure (18). From this figure one may observe that for models (A, B and D) of single step broad crested weir an increase in ratio \(H_u/h \leq 2.03\) for model A, \(H_u/h \leq 1.74\) for model B and \(H_u/h \leq 1.39\) for model D) value causes an decreases in \((D_s/H_u)\); when the ratio \((H_u/h)\) increases greater than the above value, the ratio \((D_s/H_u)\) increases. This attributed to increase in upstream water head, except if model C gives lower value of ratio \((D_s/H_u)\) then increases gradually with increases in the ratio \((H_u/h)\).
Conclusions

This research experimentally examined the application of a new shape of Single Sloped Step Broad Crested Weirs with different angles to reduce local scour on downstream of the weir. For model C, the maximum depth of scour reduced 73.4%, 32.56% and 24.2% as compared with model D at each discharge. The reduction in scour whole volume was about 87.6%, 55.6% and 44.8% when compared with models D at each discharge. The present experimental study does not need to countermeasure the scour depth by lining with rubbles and riprap to protect from failure because the distance of scour from weir was significant to prevent that, the new idea only to change the slope of downstream (D/S) of the weir.

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