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Prediction of Scour Dimensions Downstream of Siphon Spillways

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Abstract: Scouring is one of the challenging problems in hydraulic structures operation which has many negative effects on dam safety. Siphon spillways are one of the hydraulic structures which are in face of this problem. In the present work, by using a physical model of siphon spillway, scouring at the downstream of its submerged jet was investigated. Experiments were conducted for four different discharges, four different tail water elevations, three sizes of bed material and three different bucket angles. By performing more than 125 tests, three empirical equations were developed to predict the scour depth and its length for submerged jets as well beginning point of scouring from the bucket lip at siphon spillways.

Key words: Siphon spillway · Scour dimensions · Physical model · Submerged jet · Hydraulic structures

INTRODUCTION

In dams, water flow over the spillways and through the bottom outlets has a great potential in producing the scour on the bed material at the tail water. Scour hole prediction and forecasting its geometry is one of the challenging matters among the hydraulic structure designers. Two ways are available to calculate it. One way is using the numerical methods. This means by simulating the prototype condition, try to predict the scouring at the downstream of the structure. This way is not sufficient in many of important projects and its results may not be accurate in design procedure. The second and general way is constructing a physical model and measuring scour parameters on it. The results of this procedure are more closed to the prototype data and therefore have been used in the design process widely. Many formulas have been developed to predict the scour hole at the downstream of buckets which are based on laboratory as well as prototype observations. Rajaratnam and Mazurek measured the scouring which produced from vertical jets on the non cohesive materials in low tail water depths [1]. Espinoza *et al.* have studied score in non-cohesive soil due to impact jet and found mathematical equation for depth of scour [2]. Ghodsian studied depth of scour hole downstream of flip bucket [3]. Day and Barbhuiya developed a semi-empirical model to compute the temporal variation of scour depth for short abutments [4]. Parvishi *et al.* and Alias *et al.* by performing some experiments concluded that the lip angle of 45 degree is the optimum angle which gives minimum longitudinal area of the scour hole [5, 6]. Pagliara *et al.* extended previous results to the 3D scour hole arrangement [7]. Pagliara *et al.* performed some experiments on scour hole which was produced by impacting a water jet and suggested some protector structures [8]. They also in following their researches work over the time development of scouring at plunge pools [9]. Momeni *et al.* some experiments carried out to show the mechanism of local scour due to rectangular jet at downstream of flip bucket [10]. Sui and Balachandar performed a series of experiments on scour depth which is produced by square jets. They found that the Froude Number of the jet and depth of the tail water have a meaningful effect on the scour depth [11]. Azamathula *et al.* compared experimental scour hole properties with software techniques [12]. Li and Liu studied bed scour downstream of high dams [13]. Zhao *et al.* studied the effect of the sediment particle diameter on scour hole depth downstream of submerged hydraulic structures [14].

It should be mentioned that most of these researches were focused on the scouring at the impact of jet from a bucket to the downstream and not a comprehensive study was done on submerged jets and also it is rare in

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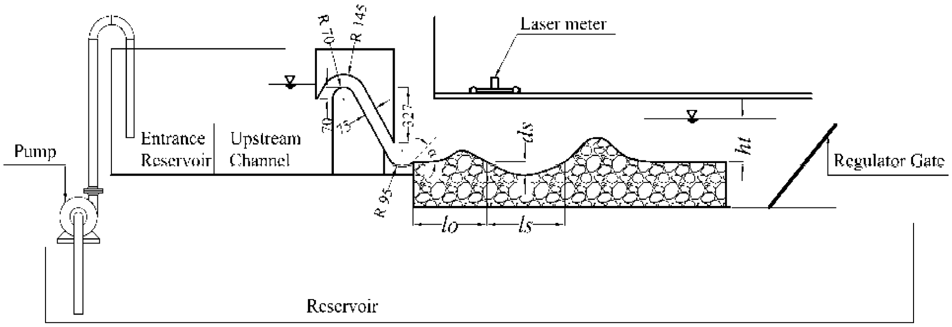

Fig. 1: Longitudinal section view of the model and its attachments

the siphon spillways. In the present experimental study, the scour hole and its geometry were measured in four discharges, four tail waters, three bed material sizes and three lip bucket angles. By using more than 125 test data, three empirical equations based on experimental data were developed to predict the scour hole geometry.

Dimensional Analysis: Regarding the affective parameters on the scour at the downstream of a bucket, one can write:

$$d_s, l_0, l_s = f(Q, \rho_w, \rho_s, h_t, \mu, d_{50}, g, a) \qquad (1)$$

Where d_s = maximum depth of scour, l_0 = distance of start point of scouring from the bucket lip, l_s = length of scouring, Q = flow discharge, ρ_w = water density, ρ_s = sediment density, h_t = tail water depth, μ = dynamic viscosity, d_{50} = mean sediment size, g = acceleration due to gravity, α = lip angle of bucket.

By applying the Buckingham π-theorem the following non-dimensional general relation can be developed as:

$$\frac{d_s}{h_t},\frac{l_0}{h_t},\frac{l_s}{h_t}=f(\frac{d_{50}}{h_t},\frac{Q}{h_t^2\sqrt{g(G_s-1)h_t}},\alpha) \qquad (2)$$

Where $G_s = \rho_s/\rho_w$ is the specific gravity of sediment particles.

Experimental Setup: To reach the goals of this study, a physical model was constructed at the Water Research Institute (WRI) of Iran and used in the present research. The length of flume was so designed that the entry water had no disturbance and be uniform. The width of flume was also considered so that the scour hole is distinguished and viewable. The height of flume as well as two previous dimensions, regulated with maximum tail water which was used in the present work by considering a suitable free board. Constructed model includes: the entrance reservoir, upstream canal for damping the flow energy and generating uniform flow, siphon spillway, the regulator gate at tail water. Figure 1 shows longitudinal section view of the experimental model.

To make possible photography and see the scour pattern from side of flume, one side was constructed with Plexiglas. A regulator gate was used and installed at the downstream of the flume for the purpose of control of tail water depth. The water in the model was circulated by an electro pump. The designed siphon spillway in the present work was also made from Plexiglas and installed at the middle of the flume. The cross section of the siphon spillway was rectangular with dimensions of 7.5cm × 30cm.

Experimental tests were conducted on a hydraulic model of the siphon spillway. A rectangular flume 1m wide, 19m long and 0.8m high at the place of scouring and in place of siphon installation 1.6m high was used. The flume was supported by two upstream and downstream canals to reduce water surface fluctuation before and after siphon spillway.

Based on Mason, d_{50} was selected as the average diameter of the materials in this research [15]. The bed materials which were used in the present work were non cohesive materials and had a d_{50} equals to1.4mm, 3.7mm and 8.1mm (Figure 2). In this figure, three used materials are distinguished by A, B and C. Materials were full filled downstream of the bucket in length of 3 meters and thickness of 30 centimeters.

In the experimental procedure, three different bucket angles were investigated: 30°, 45° and 60°. Four different flow discharges equal to Q = 0.039, 0.042, 0.045 and 0.050 m^3/s were studied. The canal bed was carefully leveled at the beginning of each experiment.

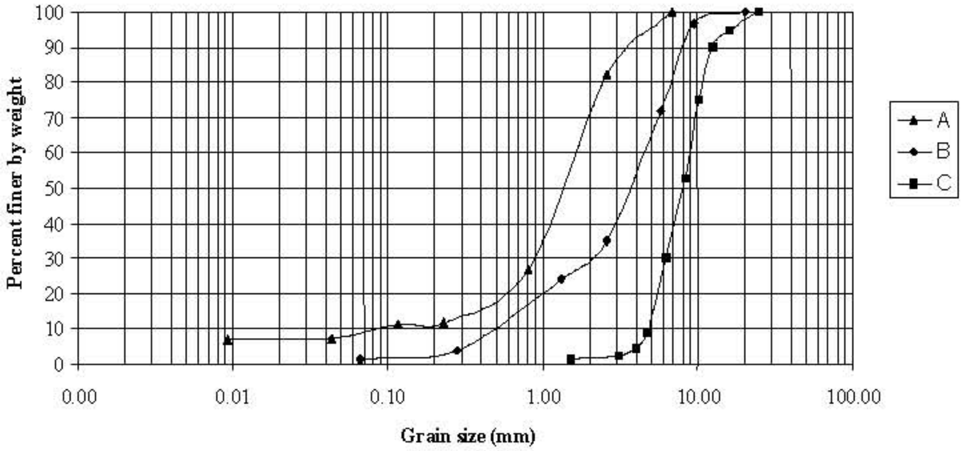

Fig. 2: Grain sizing curves of the bed material downstream of the spillway

Fig. 3: A sample of scour development at the downstream of bucket

Tests were carried out for four different values of tail water equal to: 15, 20, 25 and 30cm. The canal bed profile was measured after two hours from the beginning of each test and in static condition by using a laser meter with accuracy of 1mm. This instrument allows reading scoured surface without direct contact with the place of measurement. Data were recorded over a net of wire which was generated over the model to fix the points of measurements. The dimensions of mesh were 10×10 centimeters. This means in each test 279 points were recorded. A rectangular spillway was used to measure passed discharge at the downstream of the model (end of the canal). The water surface was measured by a liminimeter with accuracy of 0.1mm.

All tests were conducted in submerged jet and black-water conditions, although as stated by Pagliara *et al.* for black-water flows, scour depths are practically the same for both submerged and un-submerged jets [16]. A total of about 125 tests have been carried out with different bucket lip angles, tail water depths, material sizes and flow discharges.

Experimental Results: In data analyzing, both observations and measurements were considered. The main parameter in scour development is energy of water jet. This means in presence of tail water at the downstream of the bucket, due to impact of jet by water surface, the core of jet will dissipate and its energy will reduce along the its moving and reaching to bed materials. By impacting the jet with bed materials of the tail water, a hole will produce and with passing time it will develop till reaches an almost equilibrium depth and size (Figure 3).

Regarding to affective parameters on scour hole (discharge, tail water depth, average of bed material size and the takeoff angle of bucket), experiments were performed to assess the influence of each one on scouring at siphon spillways. Results showed that the discharge has a meaningful effect on scour profile (Figure 5 which correlated to condition: d_{50} = 8.1mm, h_t = 25cm and a = 60°). As can be seen from this figure, by increasing the discharge, length and depth of the scour hole were increased. It should be mentioned that this result was yielded also by other researchers [5, 10].

It was observed and measured that tail water depth has a great effect on scouring at the downstream of siphon spillway. When tail water was increased, the depth of scouring was decreased. It is due to damping energy which is caused by grater flow depth at downstream. As tail water increases, the kinetic energy of the incoming jet will more be dissipated before it reaches to bed surface. Figure 6 shows the longitudinal profile of bed surface downstream of the bucket. As it can be seen from this figure, the scour depth is very low when the tail water is equal to 25 cm.

In another sets of experiments, the effect of bed material sizes were investigated. To do so, three different sizes of sediment were used. Results showed that by increasing the bed material sizes, the scour hole was

Fig. 4: Bed profile after water relaxation

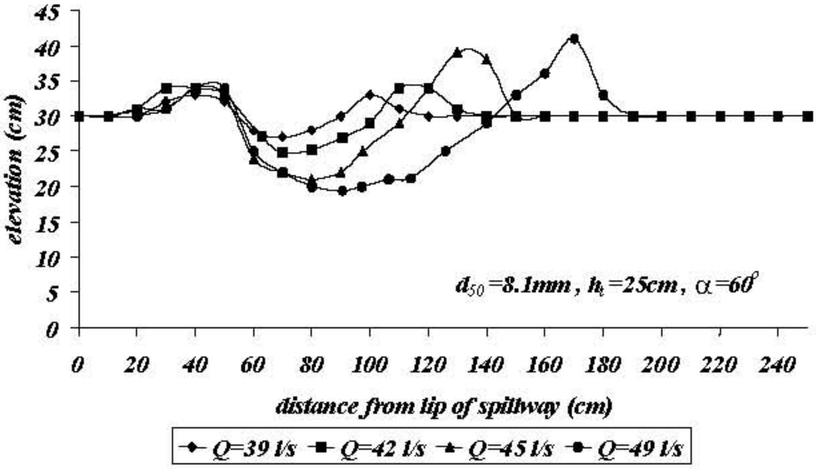

Fig. 5: Scour profile with changing discharge

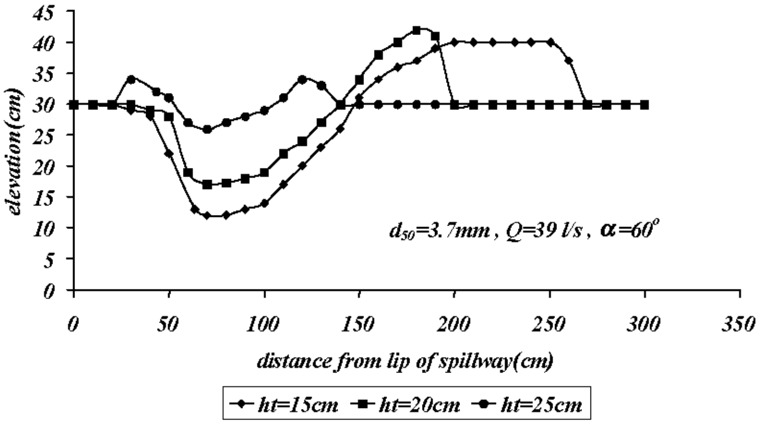

Fig. 6: Effect of tail water depth on scouring profile

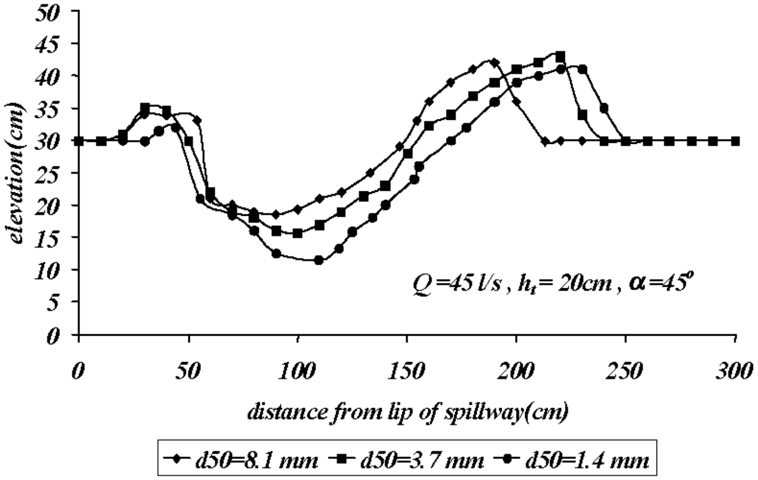

Fig. 7: Effect of bed material sizes on scouring profile

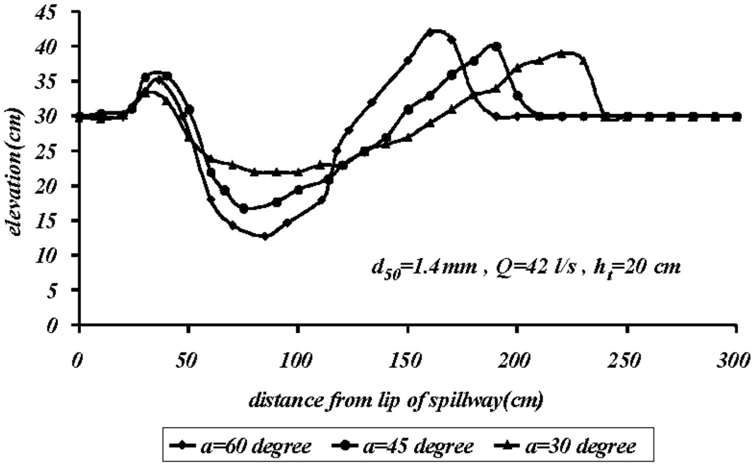

Fig. 8: Effect of lip angle on scour hole

decreased. Results which plotted in Figure 7, show the scour dimensions increase as the bed material sizes decrease from 8.1 mm to 1.4 mm.

Series of tests also were conducted to investigate the effect of lip angle of bucket. The angle of takeoff was changed in these experiments of 30°, 45° and 60°.

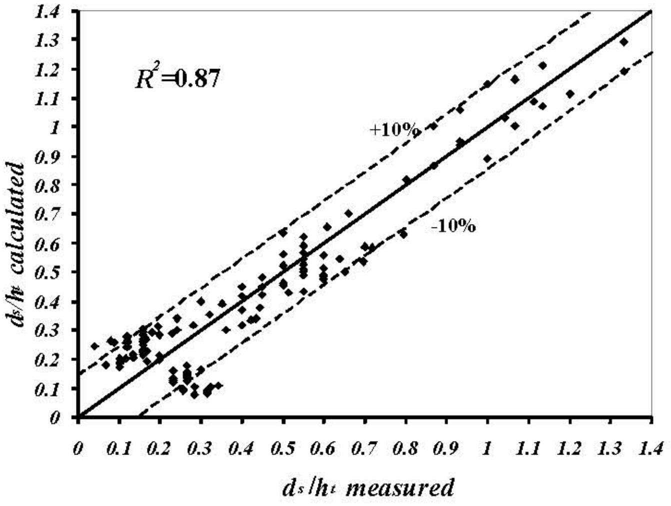

Fig. 9: Plotted measured and calculated data for relative scour depth

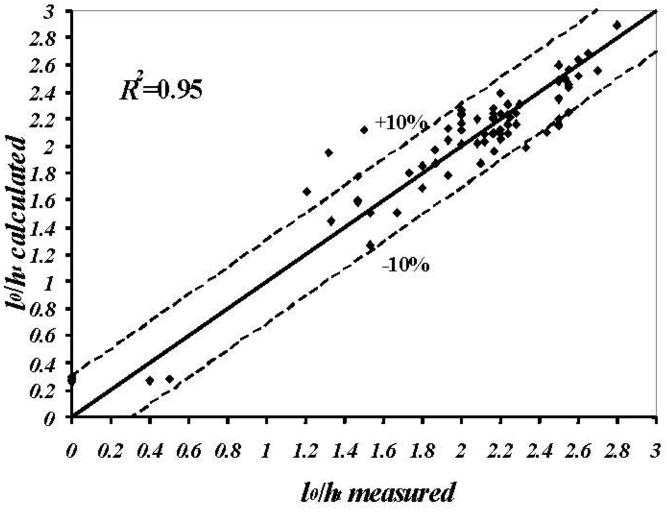

Fig. 10: Plotted measured and calculated data for relative beginning point of scour hole

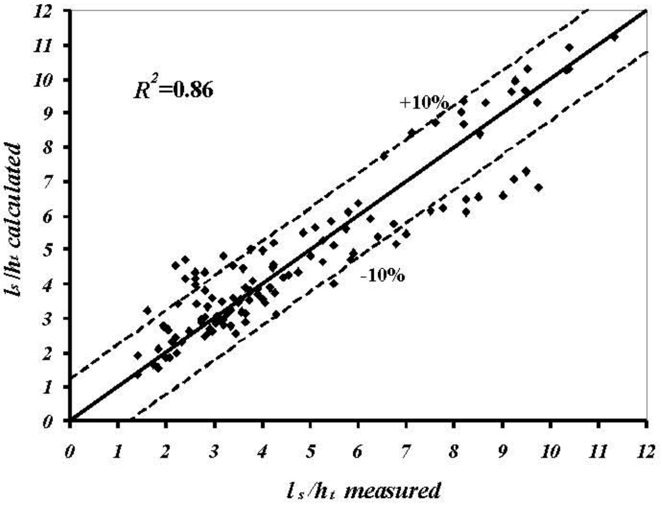

Fig. 11: Plotted measured and calculated data for relative length of scour hole

Figure 8 presents bed profiles due to these changes. As it is clear from this figure, the scour dimensions are different for $\alpha = 60°$ compare to the scour dimensions for $\alpha = 30°$ such as by increasing the lip angle of bucket to vertical position, the length of scour hole was decreased and the depth of scour hole was increased. This is because as α decreases, the jet impinges the water surface further downstream of the bucket and therefore most of the jet energy dissipates through the air before jet impingement.

Finally, by using more than 125 tests, three practical equations were developed to predict the scour hole dimensions downstream of a siphon spillway. Equations focused on maximum scour depth, the beginning point of scouring from the bucket lip and the length of scouring. Good agreement was resulted on each equation (Figures 9, 10, 11). Correlation factor (R^2) of each equation is presented in the related figure.

$$\frac{d_s}{h_t} = 0.748\left(\frac{d_{50}}{h_t}\right)^{-0.0686}\left(\frac{Q}{h_t^2\sqrt{g(G_s-1)h_t}}\right)^{1.14}\alpha^{0.367} \quad (3)$$

$$\frac{l_0}{h_t} = -0.421\left(\frac{d_{50}}{h_t}\right) + 3.73\left(\frac{Q}{h_t^2\sqrt{g(G_s-1)h_t}}\right) + 4.25\alpha - 1.967 \quad (4)$$

$$\frac{l_s}{h_t} = -20.815\left(\frac{d_{50}}{h_t}\right) + 7.809\left(\frac{Q}{h_t^2\sqrt{g(G_s-1)h_t}}\right) - 3.627\alpha + 3.395 \quad (5)$$

As shown in Figures 9, 10 and 11, the correlation factor of each one denotes very significant agreement between measured and calculated data. Therefore, equations 3, 4 and 5 predict very well the scour hole dimensions at downstream of siphon spillways.

CONCLUSIONS

In the present experimental work, by using a physical model of siphon spillway, the scouring at downstream of its bucket was studied. Four affective parameters (discharge of the siphon, tail water depth, bed material size and lip angle of bucket) on hole scour size were considered and changed in various positions. Experiments showed that by increasing the discharge, the scour hole was extended in length and depth. Increasing on tail water depth had an inverse effect on scour geometry. This means cause to reduce the length and depth of scour hole. In another sets of experiments, effect of bed material sizes were investigated. To do so, three average sizes were used and results showed that by increasing the bed material sizes, the scour hole was decreased. The angle of takeoff was changed in these experiments (30°, 45° and 60°). The measured data indicated that by increasing the lip angle of the bucket to vertical position, the length of scour hole was decreased and the depth of scour hole was increased. Regarding more than 125 experimental data, three practical equations were developed to predict the three important geometrical parameters (depth of scouring, length of scouring and the beginning point of scouring from the bucket lip). All three equations had good agreement with measured data.

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