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Effects of Upward Seepage on Depth of Scour Hole Downstream of Free Falling Jets Under Constant Tail Water Depth

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Abstract

Grade control structures are used to control bed erosion in steep small rivers mostly in the mountains. Scour downstream of this structure can lead to failure. Over the past years, the effect of different variables on this phenomena have been studied, however the effect of upward seepage which is common due to head difference of the banks water table or water surface level between the upstream and downstream reaches of a grade control structure has not been studied. In this paper, results of an experimental investigation on the maximum scour depth downstream of a grade control structure with and without upward seepage through bed sediments are presented. Experiments were run for the conditions of free falling jets, over sedimentary beds (median sizes = 1.5, 2.4 and 3.15 mm). Our data for the case of existing upward seepage shows that D' Agostino and Ferro (2004) expression significantly overestimates the scour depth. New finding of this study indicates that with the presence of upward seepage the scour depth decreases significantly which confirms the results of Sarker and Dey (2006) on scour downstream of horizontal jet with no horizontal apron.

Keywords

Upward seepage; Scour; Grade control structures; free falling jets; Sediment transport; Hydraulics

1. Introduction

S Grade control structures are river bed crossing structures which are constructed in series in steep mountain rivers to control river bed erosion. Scour downstream of this stru-cture is a common occurrence due to jet falling from its crest. The removal of alluvial bed just downstream of the structure can lead the failure of the structure. The local scour down-stream of a free falling jet has attracted the attention of many researchers. They have tried to fully discover the mechanism of scour phe-nomenon and have developed mathematical relations for predicting the scour hole dimen-sions. Doddiah et al. (1953) have shown that the scour depth d_s increases with time mean, T according to the following relation-ship:

$$\frac{d_s}{y_t} = k_1 + k_2 \, log\left(\frac{QT}{bz^2}\right) \quad (1)$$

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Where k_1 and k_2 are constant values; y_t is the downstream water depth above the bed level; and Q is the flow discharge over the weir; b and z are the width and height of the weir, respectively.

A literature review and data analysis was carried out by Mason and Arumugam (1985) on the scour due to free falling jet and tested some formulas of scour using their experimental model and prototype data. They obtained the best agreement between the selected equations and measurements for the model data using a representative diameter d_e (m) equal to the mean particle size d_m. They also proposed an equation, which can be rewritten according to the suggestions of Yen (1987) in the following form:

$$d_s = 3.27\frac{q^{0.6}H^{0.05}Y_t^{0.15}}{g^{0.2}d_{50}^{0.1}} \qquad (2)$$

Where, H is the height difference (m) between upstream and tail water levels. Mason and Arumugam (1985) considered the mean particle size of d_e in Equation (2) for models and a constant value of 0.25 m when using Equation (2) for predicting scour on prototypes. Borman and Julien (1991) and Shafai Bejestan and Albertson (1991) developed a semi theoretical relation based on the incipient motion and jet concept for predicting scour depth at the base of free falling jets.

D' Agostino and Ferro (2004) applied the incomplete self-similarity (ISS) theory proposed by Ferro (1997) and some available scour data downstream of free falling jets by Veronese (1937), Bormann and Julien (1991), D'Agostino (1994), and Mossa (1998) to develop a series of non-dimensional relationships describing the geometrical pattern of the scour profile including maximum scour depth, horizontal distance between weir crest and the section of maximum scour depth, horizontal distance between weir crest and the dune crest. For the maximum scour depth they proposed the following formula:

$$\frac{d_s}{z} = 0.540(\frac{b}{z})^{0.593}(\frac{y_t}{H})^{-0.126}(A_{50})^{0.544}\times (\frac{d_{90}}{d_{50}})^{-0.856}(\frac{b}{B})^{-0.751} \qquad (3)$$

Where,

$$A_{50} = \frac{Q}{bz\left[gd_{50}\left(\frac{\rho_s-\rho}{\rho}\right)\right]^{1/2}} \qquad (4)$$

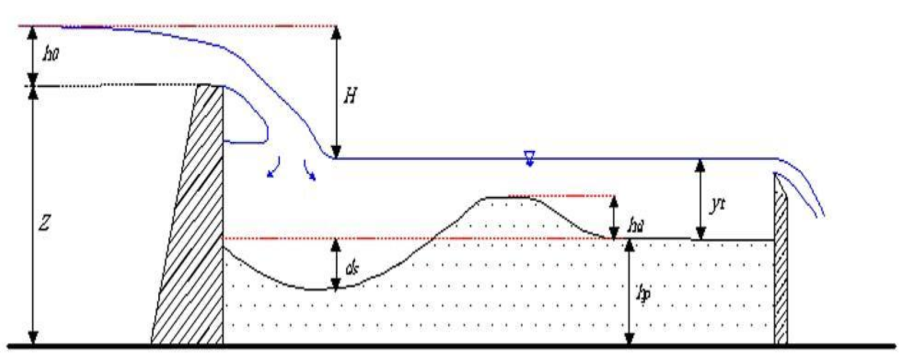

Fig. 1. Sketch of the scour of an alluvial bed downstream of a grade control structure

The correlation coefficient (R^2) of the equation is equal to 0.974. They argued that the dependency of s/z to h_0/z is highly significant (R^2=0.961). Therefore, the following simplified predictive equation was proposed by applying the data:

$$\frac{d_s}{z} = 0.975\left(\frac{h_o}{z}\right)^{0.863} \quad (5)$$

Where h_o is the head above the weir crest. In this equation R^2 was equal to 0.961. Guven and Gunal (2008) used neural networks to predict scouring downstream of grade controls. They concluded that the performance of this method was superior to other regression- based equations. Scurtock et al. (2011) based on laboratory data studied equilibrium scour downstream of three dimensional free falling jets. They compared their results with the well known relationships found in the literature and found that their expressions predicted the scour dimensions more accurately.

The effect of upward seepage which can exist on alluvial bed river because of the difference between ground water table within the banks and river water surface has been subject of recent researchers to investigate its effect on incipient motion (Cheng and Chiew 1998 a,b; Cheng and Chiew 1999; Dey and Zanke 2004; Dey and Cheng 2005), and on scour downstream of horizontal apron due to submerged jet. Experimental study of Cheng and Chiew (1998 a) showed that the upward seepage from the bed can increase the stream wise velocity in the upper layer of the velocity distribution. Cheng and Chiew (1998b) presented the modified logarithmic law for the velocity distribution subjected to upward seepage. Also, Cheng and Chiew (1999) conducted experiments and found that the threshold shear velocity decreases with an increase in the upward seepage velocity. Dey and Zanke (2004) developed a mathematical model for the incipient motion of sediment under upward seepage. They validated their model by the experimental data of Cheng and Chiew (1998b). Dey and Cheng (2005) derived the expression for Reynolds stress distribution in non-uniform unsteady flow through open channels under upward seepage and concluded that the Reynolds stress distribution is considerably influenced by the upward seepage velocity.

Sarker and Dey (2007) experimentally studied the effect of upward seepage on the scour downstream of a horizontal apron due to submerged jets and found that the characteristic scour dimensions, such as maximum equilibrium scour depth, horizontal distance of maximum scour depth from the sluice gate, horizontal extension of scour hole from the sluice gate, dune height and horizontal distance of dune crest from the sluice increase with increase in seepage velocity. Dey and Sarkar (2007) reported another study on the effect of upward seepage on scour downstream of horizontal submerged jet downstream of a slide gate with no horizontal apron and showed that the scour dimension decrease as the upward seepage velocity increases. They concluded that the difference between these two studies is in different flow patterns. Their conclusion was that the flow patterns can significantly affect the scour dimensions.

As has been mentioned over the past years, different studies have been conducted to investigate the effect of variables on scour hole dimensions downstream of grade control structure. However, the effect of upward seepage which is usually developed due to water surface difference between upstream and downstream of the structures or due to difference between banks water table and river water surface, has not been studied. Since the flow pattern in free falling jet is different from the case of submerged jet, it was decided to experimentally study the effect of upward seepage on scour depth downstream of the free falling jet.

2. Materials and Methods

Experiments were performed on a flume 0.88 m wide, 0.80 m deep and 8.5 m long. Schematic view of the experimental arrang-ement is shown in Figure 2. Sedi-mentary bed in the sediment recess was 0.26 m deep and 2 m long. An arrangement was made to apply upward seepages from the bottom of the sediment recess through the sediment bed (see Fig .2). A broad crested weir was considered as grade control structure as shown in Figure 2.

Seepage flow rate was measured and controlled by a valve and rectangular sharp weir. The valve remained closed in tests without seepage. The advantage of using this arrangement was that it provided a uniform distribution of the upward seepage flow. As was evident, the twelve bed piezometeric pressures didn't change significantly and also increasing the level of water seepage was smooth and uniform. Three uniformly graded sediments $(\sigma = \sqrt{\frac{d_{84}}{d_{16}}} \leq 1.3)$ and median diameters of d_{50} = 1.5, 2.4, 3.15 millimeters were used in the experiments (see Table 1).The flume side walls were made of glass to have visual access to the flow and sediment movement. Weir surface and flume sidewalls were covered by Plexiglas. Tail water depth, y_t was controlled by an adjustable tailgate at the downstream end of the flume. Water was fed to the flume from a constant tank. In order to minimize un-desirable water drops from the weir without adequate tail water depth, the flume was first filled with water at a slow rate. Once the water level reached the desired depth, the experi-ments were started by adjusting the inflow to the required rate. Water surface profile was measured by point gauge with a precision of $\pm$ 0.1 mm.

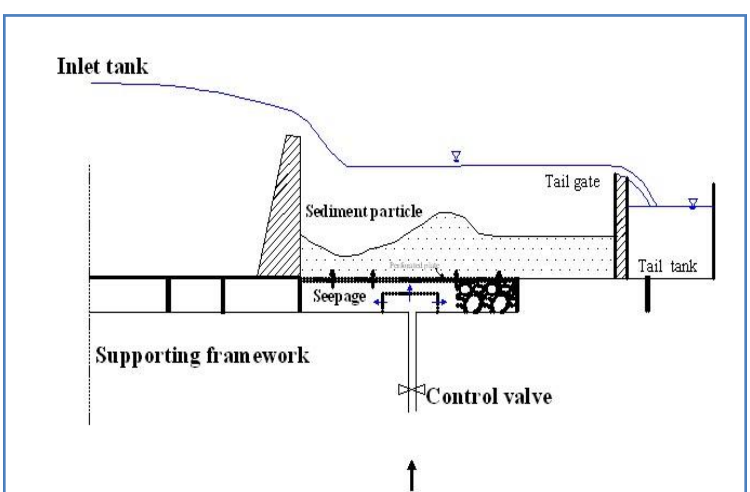

Fig.2. schematic experimental set up to investigate the upward seepage effects on scour hole.

The scour profiles were traced at regular time intervals. The time period to obtain equilibrium scour holes was about 6 hr, when the scour profiles observed to be unchanged over a period of time.

2.1. Non-dimensional Equation

To develop a general non-dimensional expression, the same method of D' Agostino and Ferro (2004) was applied. The scour hole dimensions can be expressed by the following functional relationship:

$$\Phi = f(z, y_t, q, \rho_s, \rho, \mu, g, d_{50}, H, H_s) \qquad (6)$$

In which, Φ = stands for any scour hole dimensions (e.g. d_s =scour depth), z is the height of weir above the bed level; y_t is the tail water depth, q is the flow discharge per unit width of the weir, ρ_s is the mass density of sediments; ρ is the mass density of water; d_{50} is the sediment diameter for which 50% of particles are finer; H is the hydraulic head (difference between upstream and downstream water surface); H_s is the upward seepage pressure.

By choosing three variables (H, q and ρ) as independent variables and combining with the remaining variables the following non-dimensional parameters are developed:

$$\Pi_0 = \phi / H$$

$$\Pi_1 = y_t / H$$

$$\Pi_2 = z / H$$

$$\Pi_3 = gH^2 / q$$

$$\Pi_4 = \rho q H^2 / \mu$$

$$\Pi_5 = (\rho_s - \rho) / \rho$$

$$\Pi_6 = d_{50} / H$$

$$\Pi_7 = H_s / H$$

By combining Π_2, Π_3, Π_5 and Π_6 a new dimensionless parameter similar to densimetric Froude number in the form of $q / z[g(G_s - 1)d_{50}]^{0.5}$ can be developed. Π_4 is a non dimensional parameter similar to Reynolds number which represents the effect of fluid viscosity. Since scour study is associated with high turbulence, the effect of Reynolds number or shear viscosity can be neglect. In this study, tail water depth has been kept constant, so Π_1 is neglected. Therefore, final general non-dimensional relation is as follow:

$$\frac{d_s}{H} = f\left(\frac{H_s}{H}, \frac{q}{z[g(G_s - 1)d_{50}]^{0.5}}\right) \qquad (7)$$

3. Results and Discussion

In this study two series of experimental tests (a total of 48 tests) were conducted. In the first series (9 tests), no upward seepage was applied and the second series (39 tests) of tests are conducted under different upward seepage heads (H_s).

3.1. Scour depth relation without upward seepage

To develop an expression for predicting scour depth downstream of grade control structure without upward seepage, the ratio of non dimensional scour depth (d_s/H) was plotted versus densimetric Froude number ($q / z[g(G_s - 1)d_{50}]^{0.5}$) using some data as shown in Figure 3.

By applying regression method for the dimensionless group, the following equation is developed:

$$\frac{d_s}{H} = 2.72\left[\frac{q}{z\sqrt{g(G_s - 1)d_{50}}}\right]^{0.72} \qquad (8)$$

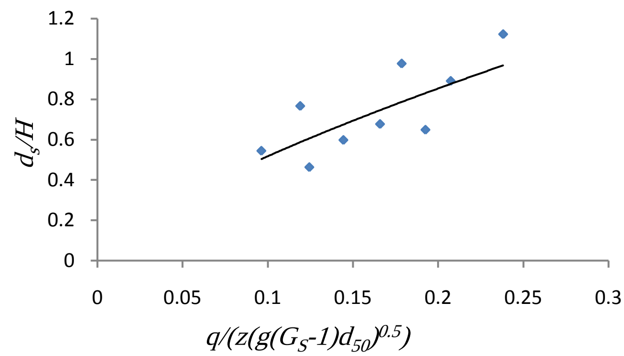

Fig.3. Variation of scour depth versus densimetric Froude number

Performance of Equation (8) was compared to Mason and Arumugam (1985), Equation (2) and D' Agostino and Ferro (2004), Equation (3). Results are presented in Table 1 and Figure 4a. Table 1 also reports the results of the multiple–regression analysis in the possible pair of groups considering d_s/H as a dependent variable. The degree of accuracy was 12:

$$RMSE=\left(\frac{1}{n}\sum_{i=1}^{n}(L_{observed}-L_{Computed})^2\right)^{1/2} \qquad (9)$$

That provides an overall rate on the relationship accuracy using Equation 9 and correlation factor (R^2) for the variable scour depth d_s as a comparison parameter. The results of this analysis are shown in Table 1.

Measured data are also compared with the results obtained from Equation (2), (3) and (8) as shown in Figure 4. As it can be seen, Equation (2) overestimates the scour depth. The results of Equation (8) developed in this study are very close to the results obtained from Equation (3) presented by D' Agostino and Ferro (2004).

3.2. Scour depth relation with upward seepage

To develop an expression for predicting scour depth downstream of grade control structure when the upward seepage is applied, the ratio of non dimensional scour depth (d_s/H) was correlated to densimetric Froude number ($q/z[g(G_s-1)d_{50}]^{0.5}$) and seepage head ratio using SPSS software. By applying non linear regression method for the above mentioned dimensionless groups, the following best fit equation was developed:

$$\frac{d_s}{H}=1.46\left(\frac{H}{H_s}\right)^{0.23}\left[\frac{q}{z\sqrt{g(G_s-1)d_{50}}}\right]^{0.33} \qquad (10)$$

Table 1. Statistical parameters used in this study and other studies in the absence of upward pressure

Equation No.	2	3	8
Min Error	0.0518	0.0127	0.0044
Max Error	0.1492	0.0474	0.0391
Mean Square	0.0119	0.0009	0.0007
RMSE	0.1089	0.0293	0.0269
R^2	0.6536	0.8447	0.8072

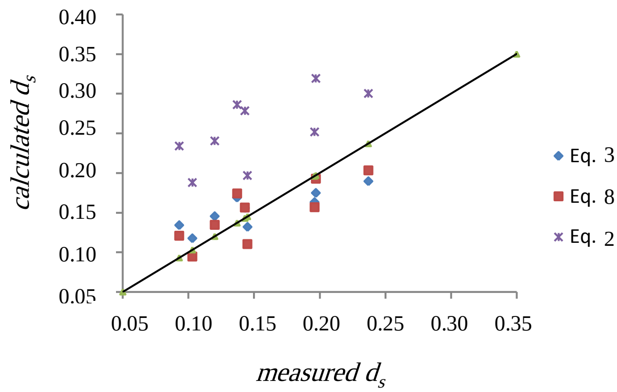

Fig. 4. Comparison of the experimental data with three equations

The RMSE and R^2 of this equation are equal to 0.028 and 0.83, respectively. Analysis and comparison of the experimental data has produced the relationship for predicting maximum scour depth of Equation (10).

Comparing the scour depth obtained from Equation (10) in the presence of upward seepage to the Equation (3) results without upward seepage it was found that Equation (3) significantly overestimates scour depth. This means that the upward seepage can decrease the scour depth. The main reason for such finding is that Equation (3) does not consider the effect of upward seepage. It also was found that scour depth decreased by applying the upward seepage. The reduction can reach as much as 25%. One explanation for such a result is that although the upward seepage can reduce the threshold conditions, it also produces an upward velocity component which can interfere with the downward jet flow velocity and reduce the kinetic energy of the incoming jet. The combination of these two cases will result in decrease of scour depth similar to the findings of Dey and Sarkar (2007) for the scour depth downstream of a horizontal jet with no apron. For the case of submerged jet with apron, the upward seepage velocity is already weak enough to interfere with the vertical component of flow velocity. In this case, the horizontal component is strong enough to wash away the sediment and transport horizontally which the final results will be a deeper scour depth. For the case of free falling jet, however, the upward seepage velocity can reduce the strength of downward flow velocity components and a less deep scour will be resulted.

4. Conclusions

In this study the effect of upward seepage downstream of grade control structures, which is a common occurrence due to head difference between upstream and downstream water surfaces, was studied experimentally. Two series of tests with and without upward seepage were conducted. By applying data from both series of tests, two relations were presented which can be applied to predict the scour depth of falling jet with and without upward seepage. Comparison of these data with the well known relations presented by other investigators shows that our data is in good agreement with D' Agostino and Ferro (2004) equation for the case of no upward seepage. Our data for the case of upward seepage presence show that D' Agostino and Ferro (2004) expression significantly over-estimates the scour depth. The new finding of this study is that with the present of upward seepage the scour depth at the base of free falling jet decreases significantly. The reason for such a reduction is that in vertical jet, the jet velocity near the bed is decreased due to the upward seepage velocity vector and therefore, the lift force which is responsible for picking up the particle is reduced that eventually causes the reduction of scour dimensions by as much as 25%.

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Notation

The following symbols are used in this paper*:*

b = weir width;
dm = median bed particle size;
ds = scour depth
d50 =bed grain size for which 50% of sampled particles are finer;
g = acceleration due to gravity;
H = difference in height of water level upstream of the weir and the tail water level;
H_s= Upward pressure
y_t = tail water depth or water depth above the un-eroded bed level;
*h*0 = total head above the weir crest;
*k*1, *k*2 = numerical constants;
Q = water discharge;
q = water discharge per unit width of the weir;
R = correlation coefficient;
ρ = mass density of water;
ρ*s*= mass density of sediments; and
μ= fluid viscosity.

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