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Interrelationships between Characteristic Lengths of Local Scour Hole

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ABSTRACT

This paper presents the results of an experimental study on local scour of noncohesive sediments downstream of a horizontal rigid apron. The experiments were carried out in a rectangular flume with 9m length, 0.5m width and 0.6m height which includes an alluvial test reach of 1.65m length and 0.2m depth at the end of the apron. Two types of uniform sediment with median diameters of 0.73mm and 1.85mm were used in the experiments. Time variations of the maximum scour depth was measured for some experiments. It was found that the scour hole does not reach the equilibrium state even after 48 hours. However, after the first 12 hours, the rate of extension of the maximum scour depth is found to be less than 0.001 cm/min. Although the scour profile seems to be three dimensional in nature, it was found that there is a geometrical similarity between the scour holes in all of the experiments. Variations of the characteristic lengths of the scour hole such as the maximum scour depth, d_{sm}, the maximum extension of hole, L_0, and the dune height, h_d, are related to each other. Nondimensional graphs and formulas are suggested to determine the variation of these parameters in different conditions.

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1. Introduction

When jets impinge upon loose beds of granular material downstream of hydraulic structures such as weirs or sluice gates, they can lead to significant local scour and may cause stability problems of the structure. Constructing a rigid apron adjacent the structure is a typical engineering solution to protect the structure. Over the last three decades, several experimental studies have been conducted to investigate the local scour process caused by submerged and unsubmerged two-dimensional (2D) and three-dimensional (3D) jets. Results indicate that the maximum scour depth not only depends on the impinging flow velocity, characteristics of bed material, but also the apron length and apron surface roughness.

The limit of the scour pattern can be considered to be an isoline of constant shear stress with a value equivalent to the threshold bottom stress. However, estimating the threshold shear stress of a certain material presents uncertainties.

An approach to characterize the response of the sediment to jet flow, in the case of non-cohesive sediment, is to use the densimetric Froude number associated with a representative diameter. The densimetric Froude number F_0 is defined as $U_0/(gd_i\Delta\rho/\rho)^{0.5}$, where U_0 is the jet velocity at the nozzle, g the acceleration due to gravity, d_i a representative size of the bed material, and $\Delta\rho$ is the difference between the density of the bed material ρ_s and the density of the fluid ρ. From dimensional considerations, F_0 is a measure of the ratio of the tractive force acting on the bed particle to the submerged specific weight of the particle.

Due to the practical importance, local scour caused by the jets has been a topic of continued interest to the researchers and the design engineers as well. Farhoudi and Smith (1985) studied the development of scour holes downstream of a spillway due to hydraulic jump over an apron. Ali and Lim (1986) conducted experimental investigations to study the localized scour caused by two- and three-dimensional turbulent wall jets. Recently published results indicate that the scour hole develops rapidly in the early stages and progresses towards an asymptotic stage beyond which the scour profile does not change significantly with time and reaches an equilibrium state (Balachandar *et al.*, 2000; Kells *et al.*, 2001; Lim and Yu, 2002; Sarkar and Dey, 2004; Dey and Sarkar, 2006; Alihosseini *et al.*, 2008; Oliveto *et al.*, 2008, Sarathi *et al.*, 2008, Hamidifar *et al.*, 2010, 2011; Omid *et al.*, 2009).

Dey and Westrich (2003) investigated the flow characteristics of submerged jets over an apron and in an equilibrium scour hole in cohesive beds. Moghim et al. (2008) developed an empirical equation by using regression analysis to predict the maximum scour depth downstream of aprons. In a more recent study Khwairakpam and Mazumdar (2009) conducted a review on local scour around hydraulic structures.

However, nowadays many criteria are proposed to determine dimensions of the scour hole. The research reported in this paper focused on finding the interrelations between characteristic lengths of local scour hole downstream of an apron.

2. Materials and Methods

Experiments were carried out in a recirculating glass-sided flume in the central laboratory of water researches in University of Tehran. The flume was 9m long (the test reach being 3 m long), 0.5m wide and 0.6m deep. Water was continuously pumped from the downstream reservoir into the upstream head tank with a maximum capacity of 25 l/s. A calibrated rectangular sharp crested weir was used to measure the discharge.

Figure 1: Experimental setup.

A submerged horizontal jet was produced by flowing water through a sluice gate opening equal to 2cm over an apron of 1m length followed by a 0.2m deep sediment bed container. The initial bed slope was adjusted to zero for each run using a carriage system riding on the

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rails over the flume. At the downstream end, a tailgate allows the regulation of the flow depth in the flume. The discharge Q, was set constant for each run and a constant tailwater depth Tw, 10 times the gate opening Y_1, was also set in order to satisfy the conditions of deeply submerged horizontal jet.

3. Results and Discussion

As soon as the water flowing from the sluice opening reached the erodible bed, the movement of bed materials from the end of the rigid apron started and the geometry of the scour hole started changing with time. The scour profiles at various times were marked on one of the glass walls of the flume. It was observed that during the initial stage the rate of scouring was very high. It then gradually tapered off as time elapsed. Ultimately the equilibrium stage was reached when no movement of grains was observed at the location of maximum scour.

For each type of bed material, experimental runs have been undertaken for different tailwater depths and for various discharges. Before starting a particular run, the initial bed surface was leveled. To avoid the disturbance of the bed before regulating the tailwater depth and discharge, the alluvial bed surface was covered with a Plexiglas plate with the same width as the flume. After the desired conditions were established, the plate was removed gently from the downstream.

Before starting the next run, the disturbed bed was leveled after dewatering and drying the bed. The whole procedure was then repeated, and a new scour profile was obtained. The scour profiles have been used to determine the characteristic lengths of the scour hole at the equilibrium state.

Time variations of the maximum scour depth was measured for some experiments. It was found that the scour hole does not reach the equilibrium state even after 48 hours. However, after the first 12 hours, the rate of extension of the maximum scour depth is found to be less than $0.05cmh^{-1}$.

From the scour profiles, the maximum scour depth d_{sm}, the location of maximum scour depth X_m, the maximum scour point L_0, the maximum dune height h_d and the location of maximum height of the dune X_d for all the test runs has been measured. To obtain relationship between the characteristic lengths of the scour hole, these parameters were plotted against the dimensionless maximum scour depth.

Figure 2 shows the variation of the maximum dune height h_d. It is observed from this figure that the variations of these two parameters follow a linear trend which can be expressed as Eq. (1):

$$\frac{h_d}{d_{50}} = 2.827\left(\frac{d_{sm}}{d_{50}}\right) - 8.84 \qquad R^2=0.96 \qquad (1)$$

In Figure 3 variations of the maximum scour point L_0 is plotted against the maximum scour depth. It is clear that the variation trend is not linear and a quadratic equation as Eq. (2) can fit the experimental data.

$$\frac{L_0}{Y_1} = -0.025\left(\frac{d_{sm}}{d_{50}}\right)^2 + 1.839\left(\frac{d_{sm}}{d_{50}}\right) - 7.863 \qquad R^2=0.95 \qquad (2)$$

In Figure 4 the variations of the location of the maximum dune height X_d, is shown. By examination of different parameter to nondimensionalize X_d, it was found that the gate opening Y_1 is more appropriate than the particle median size d_{50}. So, a new dimensionless equation is proposed as below to determine X_d when d_{sm} is known.

$$\frac{X_d}{Y_1} = -0.043\left(\frac{d_{sm}}{d_{50}}\right)^2 + 3.198\left(\frac{d_{sm}}{d_{50}}\right) - 10.51 \qquad R^2=0.88 \qquad (3)$$

Variations of X_m, against d_{sm} is plotted in Figure 5 where X_m is the location of the maximum scour depth downstream of the apron. As figure 5, the gate opening Y_1 was used to nondimensionalize this parameter as shown in Eq. (4). However, using Y_1 was not remedial to cover scattering of the data as well as figure 5.

$$\frac{X_m}{Y_1} = -0.004\left(\frac{d_{sm}}{d_{50}}\right)^2 + 0.417\left(\frac{d_{sm}}{d_{50}}\right) - 0.338 \qquad R^2=0.74 \qquad (4)$$

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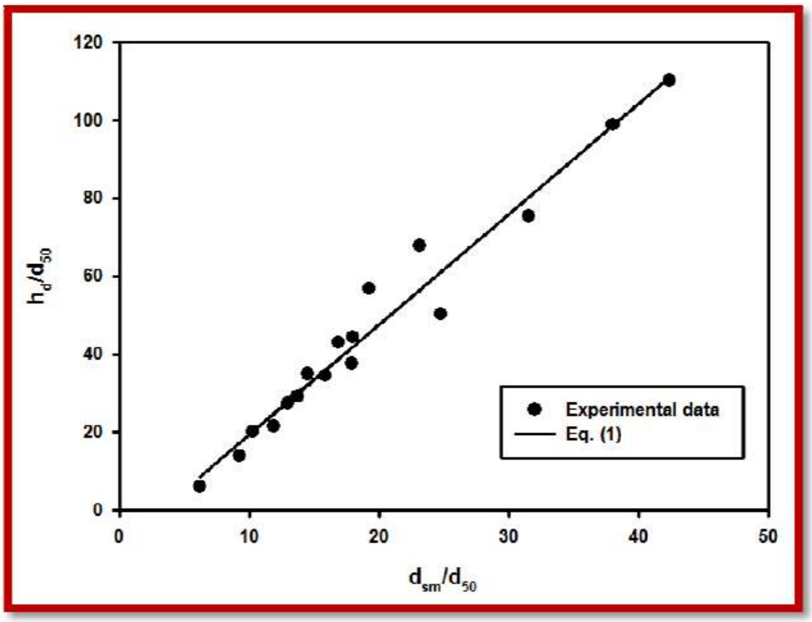

Figure 2: The relation between maximum scour depth and maximum dune height.

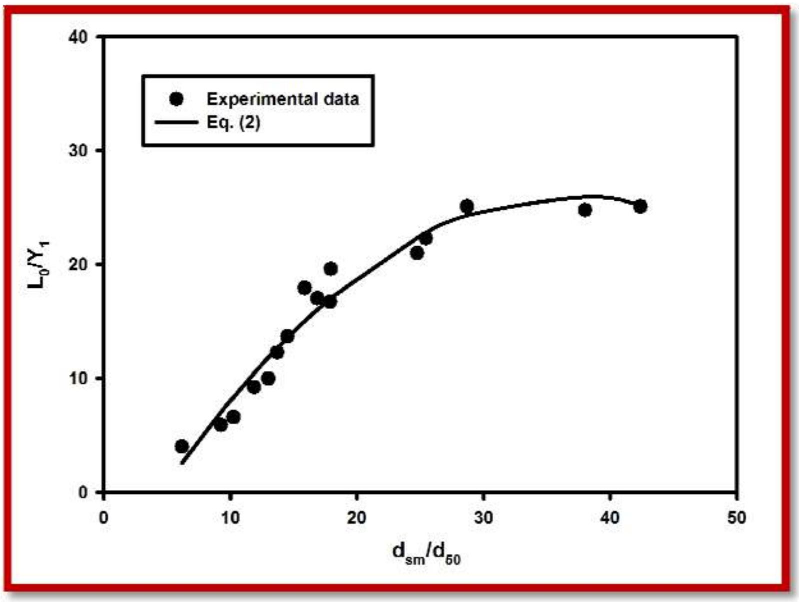

Figure 3: Variations of maximum length of the scour hole against maximum scour depth.

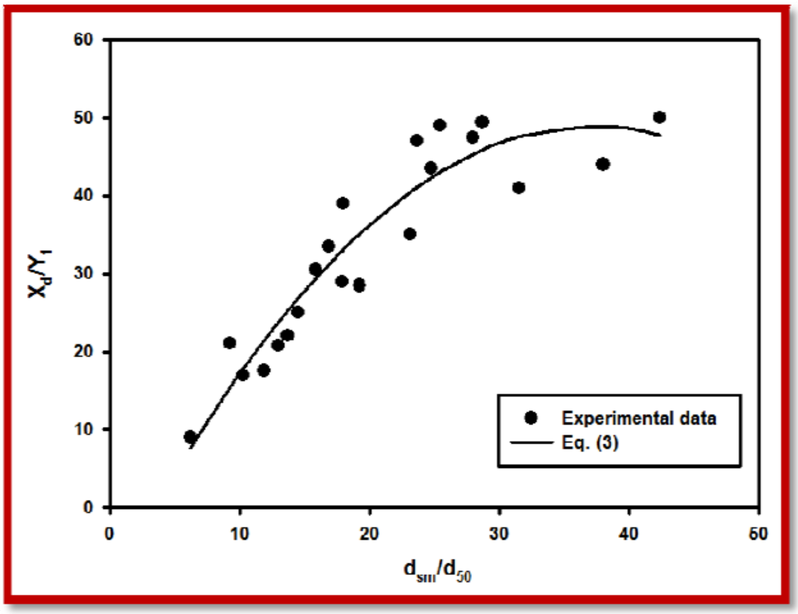

Figure 4: Relation between the location of the dune maximum heigth against d_{sm}.

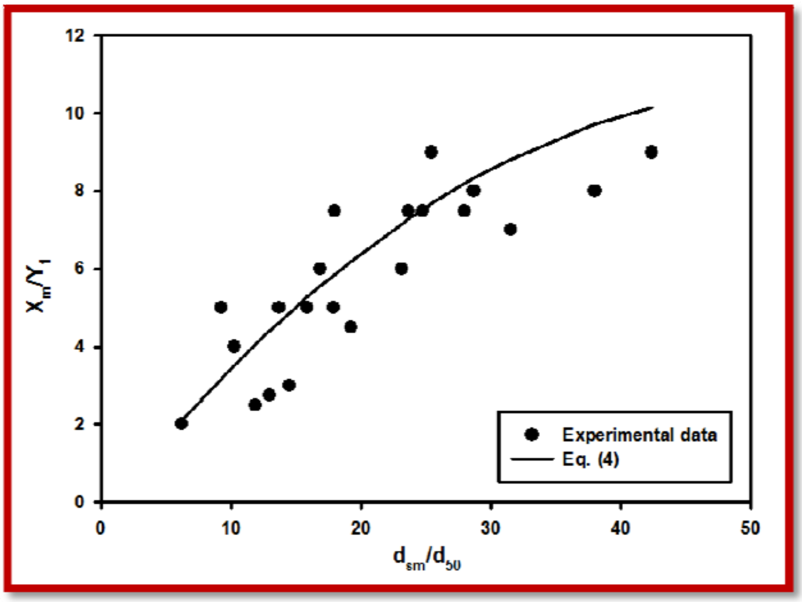

Figure 5: Variation of the location of maximum scour depth against $d_{sm.}$

A comparison between the results of the present and previous studies is shown in Figure (6). A dimensionless parameter, r, is defined as Eq. (5) to find the relative error between the results. It is seen from Figure (6) that as the dimensionless parameter dsm/Y1 increases, the relative error decreases and the results of the different studies come close to each other.

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However there is considerable scatter in data for small values of the dimensionless scour depth.

$$r = \left| \frac{\left(d_{sm}/Y_1\right)_{present\ study} - \left(d_{sm}/Y_1\right)_{previous study}}{\left(d_{sm}/Y_1\right)_{present\ study}} \right| \tag{5}$$

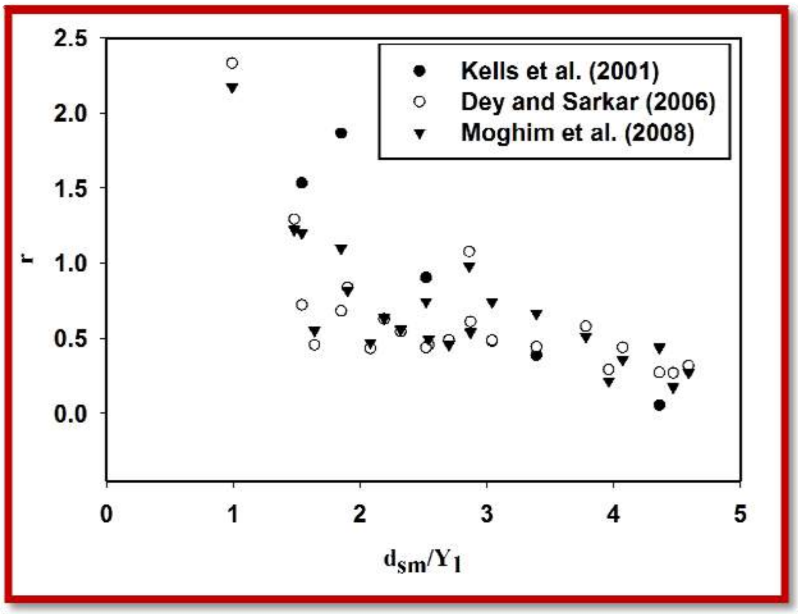

Figure 6: comparison of the results of the present and previous studies.

4. Conclusion

The interrelationships between different parameters of local scour hole downstream of a rigid apron is studied experimentally. The experiments were conducted in the wide range of tailwater depths and different flow discharges. Results showed that there are good correlations between scour hole parameters. So, some experimental equations were presented by using regression analysis. It was found that the maximum dune height, the maximum extension of the scour hole, the maximum extension of the dune, the distance between end of the apron and both the maximum scour depth and the maximum dune height will increase if the maximum scour depth increases. These proposed criteria can help hydraulic structure enginners to design structures more safely.

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