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Investigation on local scour downstream of adverse stilling basins

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Submerged jet

Abstract This paper is focused on local scour downstream of adverse stilling basins where a submerged wall jet issued from a sluice gate. Experiments were conducted in a wide range of Froude numbers, grain sizes, tailwater depths, and stilling basin slopes. The results showed that the scour profiles at any bed slope follow shape similarity. However, the longitude evolution of scour profiles and the volume of eroded materials were increasing in accordance with slope of basin. A polynomial equation was derived to define the non-dimensional profiles under different slopes. The time evolution of scour hole dimensions and the equilibrium state were defined. It was found that under a specific condition of sediment grain size, approaching Froude number, the length and slope of adverse basin, the scour depth at the downstream of adverse basin, initially increases with tailwater depth, and after reaching its maximum value decreases to a constant value. It was also observed that the maximum depth of scour hole was decreased as the length and slope of stilling basin increased, whereas the longitudinal dimensions of the hole were increased. It was found that the maximum depth of scour hole occurs at the vicinity of side walls with slight decrease in the centerline. Finally, a power equation was expressed to fully define the dimensions of scour hole, time scale and geometry of sluice gate.

1. Introduction

Local scour at the vicinity of hydraulic structures is considered as an important phenomenon which may endanger the stability of such structures. Hydraulic jump at the downstream of stilling basin with high velocities causes high local shear stress which generally exceeds the threshold shear stresses of bed materials. If the depth of scour hole is large enough, the stability of upstream stilling basins may be endangered. Therefore, preventing precautions has to be considered in designing of stilling basins to ensure their stability under scour evolution. The prediction of maximum depth of local scour at downstream of hydraulic structures is as a common problem in river

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Nomenclature

a_{0-3}	coefficients (–)
C_u	uniformly coefficient (–)
d_o	a dimension related to the linear dimensions of the sluice gate ($d_o = 2w$), (L)
D_{10}	10% finer sediment size (L)
$D_{15.9}$	15.9% finer sediment sizes (L)
D_{50}	median sediment size (L)
D_{60}	60% finer sediment size (L)
$D_{84.1}$	84.1% finer sediment size (L)
Fr_1	approaching Froude number (–)
F_o	densimetric Froude number $\left(F_o = \frac{q}{\sqrt{g(s_s-1)D_{50}^3}}\right)$ (–)
g	acceleration due to the gravity (L T^{-2})
k	factor in scour development relationship (–)
L	length of stilling basin (L)
q	flow discharge per unit width of the rectangular basin (L^2 T^{-1})
S_o	slope of stilling basin (–)
t	time from beginning of scour development (T)
T_0	time taken for the maximum scour depth to equal d_o (T)
$V_s(t)$	volume of scour hole per unit width at time t (L^2)
w	gate opening (L)
x_m	horizontal distance of maximum scour depth from the stilling basin at time t (L)
x_{me}	horizontal distance of maximum equilibrium scour depth from the stilling basin (L)
x_s	length of scour hole at time t (L)
x_{se}	length of scour hole at equilibrium stage (L)
y_1	flow depth at the *vena contracta* (L)
y_{me}	maximum equilibrium local scour depth (L)
y_m	maximum scour depth at time t (L)
y_t	tailwater depth (L)
α	exponent in scour development relationship (–)
θ	angle of the basin slope (–)
ε	factor (–)
ϕ	angle of repose (–)
v	fluid kinematic viscosity (L^2 T^{-1})
ρ	mass density of fluid (M L^{-3})
ρ_s	mass density of sediments (M L^{-3})
σ_g	geometric standard deviation (–)

engineering. The scour phenomena at the downstream of grade control structures have absorbed wide attentions by various researchers. Laursen [1] was probably, the first who reported the similarity of scour profiles developed by a horizontal jet, without any theoretical implication. Breusers [2] investigated the time variation of scour hole due to the flow over and under an estuary closure structure in absence of hydraulic jump. He suggested a power-law equation to estimate the scour depth at any time. Farhoudi and Smith [3] applied the findings of Breusers [2] to determine the time scale of scour hole downstream of an Ogee spillway. Hassan and Narayanan [4] studied the flow characteristics and the similarity of scour profiles downstream of an apron due to a submerged jet issuing from a sluice gate. Farhoudi and Smith [5] reported the scour process downstream of hydraulic jump featuring the characteristic parameters of scour hole. They demonstrated that the development of local scour hole downstream of an apron in the passage of time shows a certain geometrical similarity where a non-dimensional scour profile could be defined by an unified equation. Dargahi [6] presented an experimental study to examine the similarity of scour profiles and the scour geometry. No experimental evidence was found in support of the similarity assumption for temporal development of the scouring process. Power-law type equations were introduced to predict the geometry of scour hole, mainly in terms of affecting variables such as, flow depth over the spillway crest and sediment size. Dey and Sarkar [7] carried out an experimental investigation under different parameters affecting the depth of scour hole downstream a submerged horizontal jets. Certain geometrical similarity in scour profiles at different times was exhibited and expressed by a combination of two polynomials. Dey and Sarkar [8] investigated the effect of upward seepage on the scour hole at the downstream of an apron due to submerged jets. They reported that the maximum scour depth increases linearly with increase in upward seepage velocity. Oliveto et al. [9] in their work did not report any similarity for scour hole profiles at the downstream of spillway with positive-step stilling basin. Helal [10] studied experimentally the effect of single line of floor water jets on the scour hole dimensions and observed significant reduction in maximum depth of scour hole and its location from the floor by using this suggested system. Abdelhaleem [11] studied experimentally the influence of semi-circular baffle blocks on local scour downstream of a Fayoum type weir. He has reported the significant influence of baffle blocks on the scour hole dimensions. At the presence of baffle blocks, both upstream and downstream slopes of the scour hole increases but the downstream slope is steeper than the upstream.

It is understood that any alterations in channel geometry, would change the characteristics of hydraulic jump and therefore its influences on vicinity of such structures. Hydraulic jump on an adverse slope is an interesting phenomenon which affects the sequent depths, energy loss and length of stilling basins. The weight of water on adverse stilling basins, decreases the sequent depths, the length and the energy loss of the hydraulic jump. Consequently, this phenomenon can shorten the stilling basin and the height of side walls hence, optimization of construction costs. However, a hydraulic jump on an adverse slope is an unstable phenomenon which causes some complexities in controlling the jump which is the core of many reports published by several researchers in the past decades [12–15]. This phenomenon may increases the geometrical characteristics of scour hole. Therefore, the results of these two reciprocal effects have to be studied to achieve some novel recommendations for designers.

In this paper, the scour phenomenon at the downstream of adverse stilling basins issuing from a submerged sluice gate was investigated. The purpose of this research is to understand the effect of adverse rigid apron on the similarity of scour profiles. Also, experimental data were used to present some empirical equations for estimating the scour characteristics at semi-equilibrium stage and the time scale of scour hole.