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ORIGINAL ARTICLE

Unsteady sediments transport rate for non-cohesive material due to submerged hydraulic jet

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ABSTRACT
Sediment management in intakes and run-off reservoirs reduces the maintenance cost and increase the service life of them. Use of submerged hydraulic jets near the bottom of these structures is one of the efficient methods for sediments suspension and transportation. In the present article, the dynamic scour hole has been considered. In a physical model with densimetric Froude number varies from 30 to 50, the change of geometric parameters of scour hole against the time was observed. The results indicate that the rate of scour hole length changes is greater than the rate of changes for width and depth and on the other hand the rate of changes of depth was less than the others. Base on these rates, the formula for unsteady sediment transport for scour hole due to submerged hydraulic jets is provided. The maximum amount of unsteady sediment transport occurred for maximum densimetric Froude number and also in the early moments of the experiments, thus the rate of sediment transport decreases with decreasing the dens metric Froude number and elapsed time.
Keywords: *Submerged jet, Densimetric Froude number, Scour hole, reservoir sedimentation*

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INTRODUCTION

The hydraulic jet is submerged or non-submerged turbulent flow that can be used for various purposes. Using of hydraulic jet for sediments washing and discharging the pollutants into rivers is common. Use of submerged hydraulic jets near the reservoir bottom is one of the efficient methods for sediments suspension and transportation. Turbulent hydraulic jets are capable to transport the sediments toward the flashing gates in run-off reservoirs. Flow rate, nozzle shape, concentration difference between jet and ambient fluid, and environment geometry are the most important variables that may be considered. In the present study the effect of flow rate on sediment transport rate are physically investigated. In the following paragraph, some pervious researches in this area are mentioned. In some of these studies the hydraulic behavior of jets investigated and in the other research in addition of hydraulic patterns, jets erosion power considered also.

Previous studies on submerged hydraulic jets are reviewed in this section. S. Ushijima [1] proposed a 2D numerical method to estimate sea bed sediments erosion caused by release of cooling water from power plants. He compared and evaluated their model results with the experimental model (Scale 1:100) and the development of the scour hole was the key parameter that he examined [1]. A. Johnston (1994) focused on the behavior of circular jet in shallow water and tried to simulate this behavior through both ways numerically and experimentally [3]. N. Rajaratnam [5] studied cross-mix flow as turbulent wall jet moving into the ambient fluid therefore in his own investigation to simulate the wall jet behavior; the circular nozzles were placed close together on the bottom of flume [5]. Y. Chiew [8] examined the erosion of non-cohesive sediments due to circular hydraulic jet in shallow and deep water. He concluded that the densimetric froude number and the vertical distance from nozzle center-line to bed are the most important parameters for determining the dimensions of the hole in static condition . O. Aderibigbe (1998) studied the effect of sediment size on non-cohesive sediments scouring and concluded that it is better to use D95 instead of D50 for estimating the densimetric Froude number [12]. P. Roberts (2001) measured the circular jet velocity gradient in static ambient fluid and with different salt concentration for jet fluid; he concluded that the mixing length in center line of the jet is greater that what was mentioned in previous researches [14]. A. Law [19] examined circular jets with 50 different forms of nozzle in three dimensional experimentally and concluded that the behavior of the jet was independent of nozzle Reynolds number [19]. M. Faruque [29] investigated the effect of submergence on wall jet behavior and concluded that densimetric Froude number, submergence, nozzle width and sediments size are the most important items in scouring [29]. O. Sequeiros [31] studied the scouring due to single and multiple jets on bed with finite thickness thus his study was in two dimensional (scouring plan), he found that the densimetric Froude number was the most effective parameter on the scouring pattern . J. Sui [34] focused on square jet on the removable bed in a flume with movable sides and found that with approaching the rigid walls to each other the length of scour hole decreases and vice versa [34]. M. Soleimani (2012) studied the behavior of single and multiple nozzles in submergence condition and different shapes of nozzle. In addition of hydraulic behavior of the jet, he focused on the rate of scouring also. Soleimani found that the shape of nozzle is an important factor in energy dissipation and scouring rate [51]. P. Taheri [52] studied numerically the behavior of the circular jets by Comsol multiphysics, then compared the results with experimental data and found that the turbulent intensity at nozzle outlet can play an important role in calibration of model and also the accuracy of numerical model decreases with increasing flow rate, increasing distance from the jet or decreasing internal angle of nozzle [52]. The present study has examined the changes of scour hole dimensions using single nozzle and varies densimetric Froude numbers. The unsteady rate of sediments transport estimated based on hole volume changes till equilibrium time, it is clear that after this time the rate of sediments transport is reduced to zero.

MATERIALS AND METHODS

The experiments were performed in hydraulic laboratory of Khuzestan Power and Water (KWP) authority, for this purpose a tank with 6m in length and 1.5m in width was made (Figure 1). A Galvanized steel plate was used to build the floor of the tank and the walls were made of glass, the weight of all parts was tolerated by a steel frame. Median size of sediments that covering the tank bottom was 1mm (D50=1mm, D95=2mm) by the way the thickness of removable bed was 0.25m. The tank was filled with water up to 0.75m and the amount of submergence was kept constant by a morning glory spillway in all experiments. A drain pipe system was used to complete drainage the scour hole (Figure 2).

Figure 1. Experimental setup and accessories

Figure 2. Drainage system

The position of nozzle was adjusted to the removable bed surface. Nozzle Inner diameter was 5cm, also the diameter of nozzle outlet was 1cm. Nozzle supply pipe connected to a pump system consist of two centrifugal pumps. Each pump was capable to provide the flow rate and pressure of 100lit/min and 35m respectively. The flow rate measured by a Rotameter and the scour hole dimensions estimated by a laser meter system. Four discharges and accordingly four densimetric Froude number based on D95 in the range of 30 to 50 were used in the experiments. The flow rate was in the range of 1.6 to 3m3/h (cubic meter per hour). For each experiment, the sediments surface graded and then the tank was filled with water, in the next step the pumps were turned on and the jet was formed, after the user desired time, the pumps were turned off and the tank drained slowly then the scour hole appeared for the measuring phase (Figure 4). In the measurement step, longitudinal and transverse profiles of the hole were measured by a laser meter system.

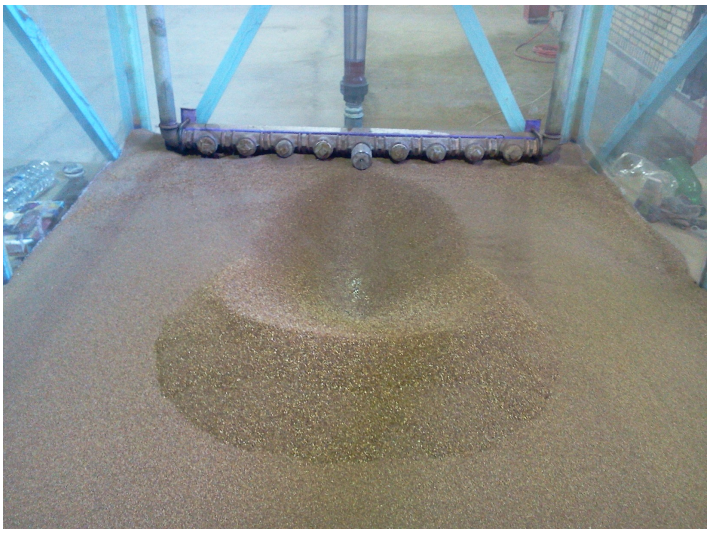

Figure 4. Scour hole after the tank draining

RESULTS AND DISCUSSION

Calculation of scour hole volume is the first step to estimation of sediments transport rate. A laser system associated with Surfer software was used to determine the negative volume (eroded sediments) of scour hole. This procedure is relatively time consuming, but nevertheless the method was used for thirty scour hole with different size. Introducing the baseline surface to the software, the positive and negative volume values and their difference are then calculated using the trapezoidal and Simpson methods. It is clear that the volume of the washed up sediments equals the volume below the baseline surface. After estimating the volume for each individual surface, the values of maximum length, depth and also height of the sediment stack peak is derived using this software. All these components transferred to the Minitab software after making them dimensionless. After introducing the initial equation and providing an initial conjecture for the constants, this software performs nonlinear fitting and optimizing the initial raw constant values. In the next equation, the optimized constants by the Minitab software are presented. Then the eroded sediments volume was expressed as a function of maximum length, width and depth of scour hole, it is clear that these values can changes over time (Figure 5).

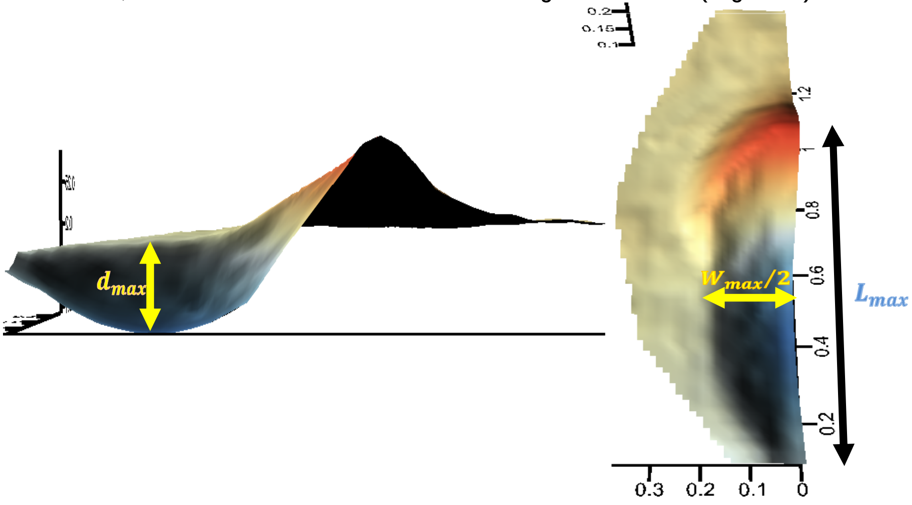

Figure 5. Main components of the plan and length of a scour hole

$$\frac{\forall_s}{d_{\max}^3} = 0.198\left(\frac{W_{\max}}{d_{\max}}\right)^{2.429} + 0.022\left(\frac{L_{\max}}{d_{\max}}\right)^{2.284} \tag{1}$$

Where $\forall_s$ is the negative volume of scour hole (below the initial level of sediments), $W_{\max}$, $d_{\max}$ and $L_{\max}$ are the maximum width, depth and length of scour hole respectively.

However it must be noted here that while deriving the above equation, preserving the simplicity of the equation and quick readability of the variables are the priority. Moreover one of the key reasons of choosing two independent variables is to fit a shell-shaped area from the experimental data so that the user can obtain the volume of the hole only from the shape and without referring to the equation (Figure 6).

If in the above equation is drawn in the variation bound of the variables, which was discussed before, this figure is formed. The whole problem space is placed on a shell-shaped area. This shell-shaped area is the front proposed as the optimized front by the statistical analysis software. According to the next figure, the fluctuation of the volume of the scour hole is more a function of the width of the hole than its length. As it can be seen in the indices of the above equation, the effect of the width of the hole is more significant than its length. This statement is proved in the figure below as the gradient of the shell-shaped area along the width of the hole is more than along its length. The counters on the figure also enable the user to obtain the volume using the maximum depth, width and length of the hole without referring to the equation.

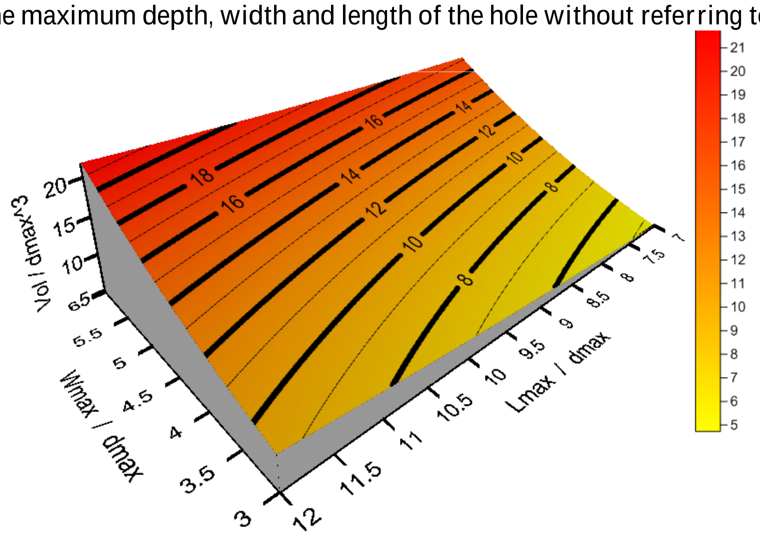

Figure 6. Scour hole volume changes with changing other geometrical parameters

It is better to also derive the time variations of the volume of the hole. The results indicate that the rate of length changes for scour hole is greater than the rate of changes for width and depth and on the other hand the rate of change of depth was less than the others. Unsteady sediments transport rate is defined as follow:

(2)

$$for\ \ t < t_*$$

$$\frac{\forall_s}{d_{\max}^3} = f\left(Fr_d, \frac{t}{t_*}\right) \rightarrow \frac{\forall_s}{d_{\max}^3} = C_1 \left(Fr_d\right)^{C_2} + C_3 \left(\frac{t}{t_*}\right)^{C_4}$$

$$q_s = \frac{d\forall_s}{dt} = \frac{d}{dt}\left(C_1 \left(Fr_d\right)^{C_2} d_{\max}^3 + C_3 \left(\frac{t}{t_*}\right)^{C_4} d_{\max}^3\right)$$

$$\frac{q_s}{\frac{d}{dt}\left(C_1 \left(Fr_d\right)^{C_2} d_{\max}^3 + C_3 \left(\frac{t}{t_*}\right)^{C_4} d_{\max}^3\right)} = 1 \quad that \quad d_{\max} = f(Fr_d, \frac{t}{t_*})$$

Where q_s is defined as the rate of sediments transport, t_* is the equilibrium time (based on 97% of final equilibrium condition), this period was estimated approximately 130 minutes. t is the time from experiments beginning point. Fr_d Is densimetric Froude number according to D95. C_1, C_2, C_3 And C_4 are constants that must be determined based on experimental results. Other parameters were already defined. It is obvious that after achieving equilibrium condition the rate of sediment transport approaching to zero.

In following equation the volume of eroded sediments expressed in terms of Fr_d and t.

$$\frac{\forall_s}{d_{\max}^3} = 0.198\left(\frac{W_{\max}}{d_{\max}}\right)^{2.429} + 0.022\left(\frac{L_{\max}}{d_{\max}}\right)^{2.284} = C_1 \left(Fr_d\right)^{C_2} + C_3 \left(\frac{t}{t_*}\right)^{C_4}$$

After calculating the constants can be written as follow:

(3)

$$\forall_s = \left(-1.987\left(Fr_d\right)^{-0.02608} + 1.946\left(\frac{t}{t_*}\right)^{0.00557}\right)^3 \left(0.0413\left(Fr_d\right)^{1.410} + 2\left(\frac{t}{t_*}\right)^{0.175}\right)$$

Also the following equation can be written for $d_{\max}$:

(4)

$$d_{\max} = -1.987\left(Fr_d\right)^{-0.02608} + 1.946\left(\frac{t}{t_*}\right)^{0.00557}$$

After substituting equation 4 and 3 in equation 2 we have:

$$q_s=\frac{0.35\,A^3}{t_*\left(\frac{t}{t_*}\right)^{0.825}}+\frac{0.0325\,A^2\left(2\left(\frac{t}{t_*}\right)^{0.175}+0.0413\,Fr_d^{1.41}\right)}{t_*\left(\frac{t}{t_*}\right)^{0.9944}} \tag{5}$$

$$\textit{Where} \qquad A=1.946\left(\frac{t}{t_*}\right)^{0.0056}-1.987\,Fr_d^{0.0261}$$

The above equation expressed the unsteady rate of sediments transport before equilibrium condition for submerged single nozzle in the range of $30\le Fr_d\le 50$ and $0.015\le\frac{t}{t_*}\le 1$. The following figure represents the equation 5 in the mentioned period.

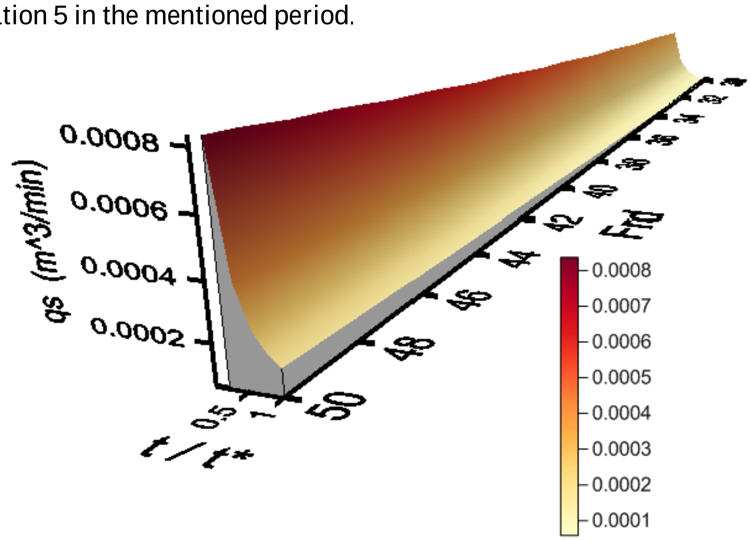

Figure 7. Unsteady sediment transport rate based on densimetric Froude number

As can be seen in figure 7 the rate of sediments transport increases with increasing the froude number. The maximum rate was $q_s=13.73\times10^{-3}\,m^3/\mathrm{min}$ and occurred in $Fr_d=50$ and $\frac{t}{t_*}=0.015$.

CONCLUSION

In current research, the rate of erosion due to submerged hydraulic jet in unsteady condition was studied experimentally. Median size of sediments that covering the tank bottom was 1mm (D50=1mm, D95=2mm) by the way the thickness of removable bed was 0.25m. The tank was filled with water up to 0.75m and the amount of submergence was kept constant. Single nozzle was used in these experiments and placed according to the sediments initial surface. Results indicate that the erosion rate depends on the relative time and densimetric Froude number. The relative time range was from 0.015 to 1 and also the range of densimetric Froude number was from 30 to 50. The rate of sediments transport at the beginning point of experiments increases with increasing the Froude number so that the maximum rate was occurred in $Fr_d=50$ and $\frac{t}{t_*}=0.015$.

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