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ORIGINAL ARTICLE

Required time to Achieve steady state scour hole due to Submerged Hydraulic jet on a Removable bed

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ABSTRACT

In developed countries, in addition to use of groundwater and stored water in dam reservoirs, special attention is also given to the urban run-off. Construction of large reservoirs in downstream side of urban natural or artificial drainages and waterways is under consideration. Gradual accumulation of sediments and therefore reduction of the useful volume is the main problem associated with run-off reservoirs. Due to the large area of these reservoirs, mechanical methods for sediments removing are expensive and unjustified. The use of submerged hydraulic jets is one of the alternative options for collecting and redirecting the sediments to the flashing gates. In current research, the development of the scour hole is investigated. The experiments were carried out on a wide flume that allows the user to model the hole caused by different shape submerged nozzle in three dimensional forms. The results indicate that the width of the scour hole reaches equilibrium states later than the other geometric dimensions. Experimental results also showed that the ratio of equilibrium time and practical equilibrium time for non-cohesive sediments is varies from 1.5 to 3.7. The equilibrium time in which all geometric parameters are stabilized was approximately 220 minutes.
Keywords: *Submerged hydraulic jet, Scouring, Equilibrium time, Froude number*

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INTRODUCTION

The types of submerged hydraulic jet can be classified as Wall jet, Round jet, Radial jet and Compound jet. Key variables that examined in these types of flow are maximum velocity, velocity differences, width of the shear layer and also corrosive effect on the surrounding environment. Submerged hydraulic jet can be used to inject industrial pollutants into the rivers and seas or can be used to sediment management in run-off reservoirs and intakes. In addition, hydraulic jets are used as a mechanism for energy dissipation in downstream of the hydraulic structures.

Due to sedimentation in some hydraulic structures, they will not be able to perform their duties. For example, sedimentation in run-off reservoirs reduces their active volume or similarly, the accumulation of sediments in the intakes may cause obstruction that treatment of these cases is very difficult and expensive. Optimal sediment management is possible, using the hydraulic jets at the intakes, suction pool of pump stations and urban run-off reservoirs. In other words, sediments can be moved to the flashing gates using the submerged hydraulic jets and there is no need to drain the stored water thus the reservoirs can perform their duties well. Nozzles arrangement at the reservoir bed has an important role on jet forming and sediments conduction which should always be considered.

Previous studies on submerged hydraulic jets are reviewed in this section. S. Ushijima (1990) 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 (1995) 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 (1996) 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 [8]. 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 (2002) 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 (2006) 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 (2007) 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 froud number was the most effective parameter on the scouring pattern [31]. J. Sui (2009) 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 [53]. P. Taheri [54] 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. The present study has examined the changes of scour hole dimensions using different nozzles and varies densimetric Froude numbers.

MATERIALS AND METHODS

The experiments were performed in hydraulic laboratory of Khouzestan 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. The position of nozzle was adjusted to the removable bed surface. In the current research, two types of nozzles are used, simple and central-body nozzle (with different shapes). The central-body nozzle have a core with different diameter size (Dc) from one nozzle to another, the core position toward the nozzle outlet (Lc) was changeable (Figure 2). The core diameter for central-body nozzles was in the range of 8 to 20mm whereas nozzle outlet diameter (D) was 10mm and also the distance from the core to nozzle outlet chosen between 1 to 12mm. The main objective of placing the core in the center of simple nozzle was to increase the maximum velocity (Um) in a constant discharge or constant average velocity (Ua). 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 3). In the measurement step, longitudinal and transverse profiles of the hole were measured by a laser meter system.

RESULTS AND DISCUSSION

Due to the removable bed thickness and the tank wideness, as mentioned in (Figure 3) the scour hole was not affected by rigid sides so its shape was 3D. In other words, the scour hole length, width and depth were measurable. In the earlier studies, the scour hole length was the key term for determining the equilibrium time but in current research all effective terms have been identified. The reason for choosing the maximum width, length and depth of the hole for calculating the scour volume is related to the degree of importance of these variables whose variation ratio is discussed in detail later (Figure 4). It is clear that the maximum length, depth and width would change with time till to equilibrium condition for each of them and that means $\left(d_{\max}, W_{\max}, L_{\max} = f(time,\ flow\ and\ sediment\ properties\right)$.

In order to decrease the number of tests to determine the equilibrium time for each nozzle and flow condition, scour tests were conducted respectively for 2, 5, 15, 30, 60, 90, 150, 240 minutes. After each time the length profile of the hole and the width profile at the maximum width location were measured. As mentioned in the paragraph above, in previous researches mostly on 2D jets, usually only one of the parameters of width or depth were investigated and the way in which these parameters equilibrated was taken into account. In order to determine the equilibrium time, this study evaluates each equilibration process of the three effective geometric parameters (i.e. length, maximum width and depth of the hole) separately.

By the equilibrium time, we mean the time distance from the beginning of the formation of the scour hole till all of its geometric components are stabled. However since this time is usually very long and it can be derived using Extrapolation, it is better to provide another definition for the equilibrium time, so that its conduction in experimental conditions is fully realized. According to the previous researches, the equilibrium time refers to the time interval after which geometrical components of the scout hole reach 95% (and in some researches 97%) of their final value. Moreover previous researches about the single nozzles have proved that the final equilibrium time for the cohesive sediments is about four times the equilibrium time defined in the last paragraph. This indicates the logarithmic and very smooth distribution of the equilibrium time specifically at its ending section. So far the ratio between the final equilibrium time and the defined equilibrium time based on the 95% development of the dimensions of the hole has not been stated for the non-cohesive sediments and here we also intend to discuss this ratio. Another parameter which is not seriously investigated for the single nozzles is the effect of the Densimetric Froude number on the diagram of the equilibrium time. In addition to the effect of the Densimetric Froude, this study also discusses the effect of the nozzles having a central core on the gradient of the equilibrium time curve. The Densimetric Froude and the characteristics of the nozzles having a central core have already been discussed before.

In this part the performance of the simple and central-body nozzles are compared. For this order, the simple nozzle and a central-body nozzle (Dc=20mm, Lc=1mm) data are selected. In the following figures the development of scour hole dimensions in the flow rate equal to 2m3/h are presented for simple nozzle (Figures 5 and 6). In the following figures the development of scour hole dimensions in the flow rate equal to 2m3/s are presented for central-body nozzle (Dc=20mm, Lc=1mm) (Figure 7). The rate of changes in the bed lateral cross profile at maximum width position for simple nozzle shown in (Figure 8).

After the recent comparison, we concluded that the final dimensions of the scour hole (length, depth and width of the hole) using a nozzle having a central core shows a significant increase in comparison to a simple nozzle. Finding the exact time of equilibrium requires many tests especially in long time intervals to increase the points of the curve and ensure the uniformity of the equilibrium time curve at its ending. For that purpose, various complementary tests were conducted separately for all nozzles with different velocities or different densimetric Froude numbers (Figures 9 and 10). The results of these tests for the simple nozzle and a nozzle having a core with a 2D diameter (D_c=20mm, L_c=1mm) are presented only for two discharges in the following graphs. In order to observe the variation process more properly, the measuring times 180, 200 and 220 minutes were added to the time table.

Using the previous graphs which were presented for the time developments of the geometric characteristics of the scour hole for two different nozzles and different flow rates, we can argue about the development ratio of the aforementioned components. Almost all geometric dimensions in the time interval of 180 to 220 minutes reached constant values and increasing time makes no tangible change in these values. This statement is also true for the other nozzles and the analysis of all results show that we can most certainly accept 200 minutes as the final equilibrium time $(t=t_\infty)$. In fact after this time, all geometric parameters have reached their final values $(d=d_\infty, W=W_\infty, L=L_\infty)$ and there will not increase anymore. But as it was mentioned, in order to facilitate the experiments and considering the slow growth rate of the parameters, mostly a percentage of the final equilibrium time is used as the equilibrium time of the experiments $(t=t_*)$. We can conclude that the final equilibrium time (and consequently the experimental equilibrium time) is completely dependent on the type of the nozzle and the Densimetric Froude number (or flow rate) and it cannot be a constant value. Now if we use the previous logarithmic equations to find the equilibrium time (base on the 97% development of the scour hole dimensions), one equilibrium time is obtained for each geometric component and each flow.

The important conclusion from the data analyzing is that a geometric parameter determining the equilibrium time is the width of the hole. So generally width, depth and length of the hole respectively have the most degree of importance in determining the equilibrium time. Thus the length of the hole is not always determinative to estimation of equilibrium time. We concluded that the 130 minutes interval (based on the 97% development of the hole) is the best option such that in addition to equilibrating almost all geometric parameters, its realization in experimental conditions were fully possible. The point mentioned about the single jets in most previous researches and reports is that the equilibrium time of the scour hole length is about 4 times the 95% equilibrium time for the cohesive sediments; however the experiments of this research shows that the ratio of the final equilibrium time to the 95% equilibrium time (t_∞ / t_*) for the non-cohesive sediments is between 1.5 to 3.7 and only limited to this range.


Figure 1. Experimental setup


Figure 2. Central-body nozzle

Figure 3. Scour hole after the tank draining

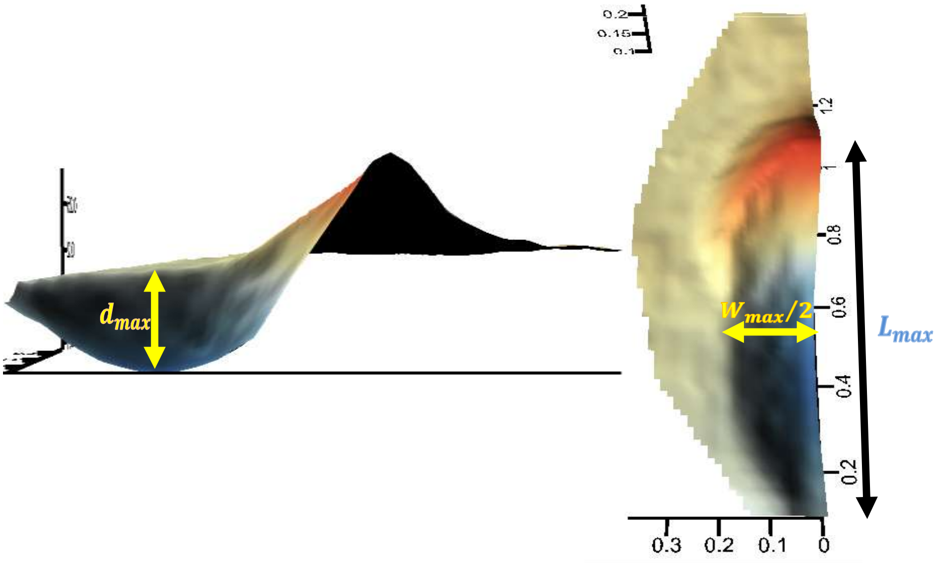

Figure 4. Main components of the plan and length of a scour hole

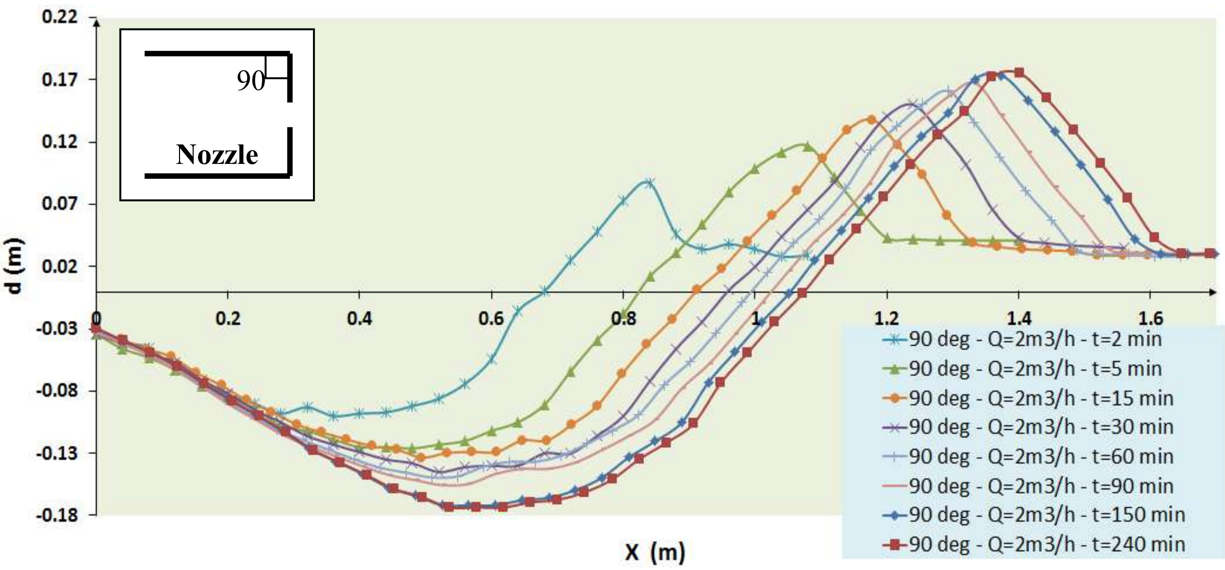

Figure 5. Changes in the bed longitudinal profile along the center line of simple nozzle

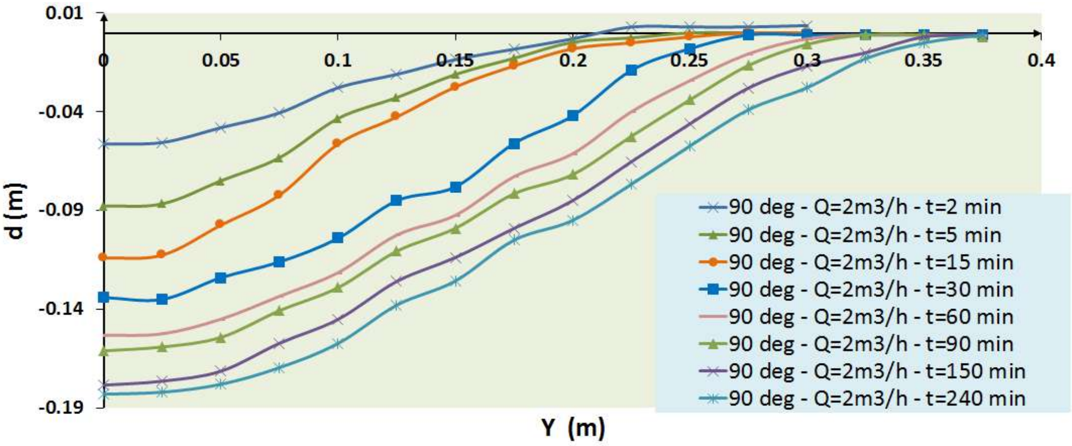

Figure 6. Changes in the bed lateral cross profile at maximum width position for simple nozzle

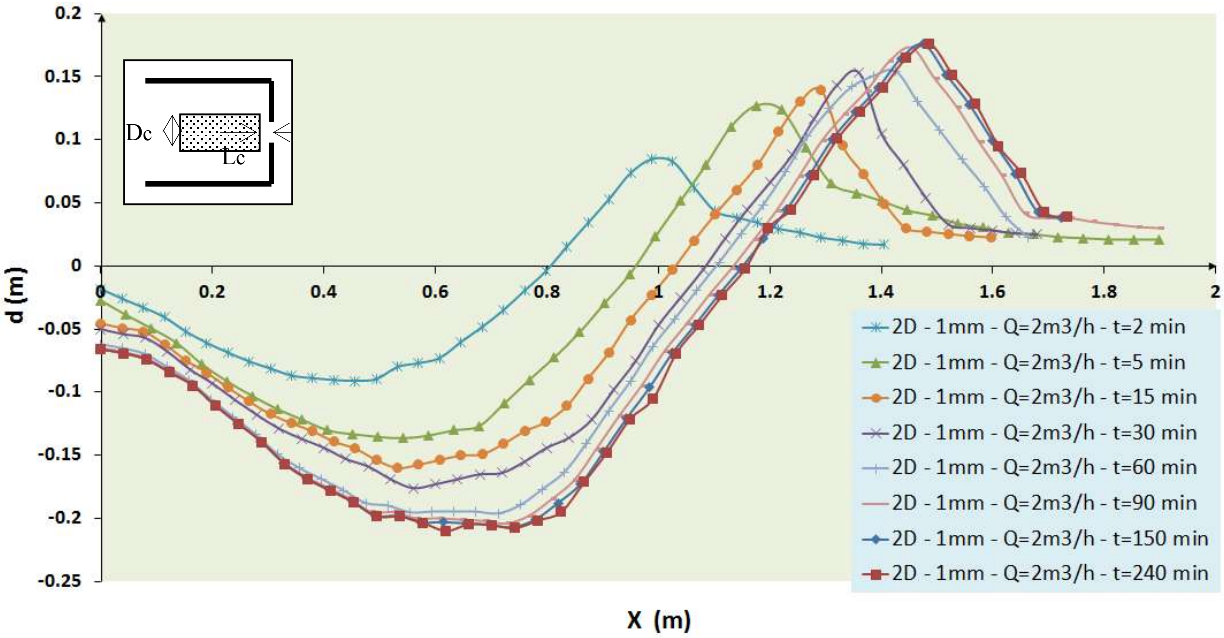

Figure 7. Changes in the bed longitudinal profile along the center line of central-body nozzle

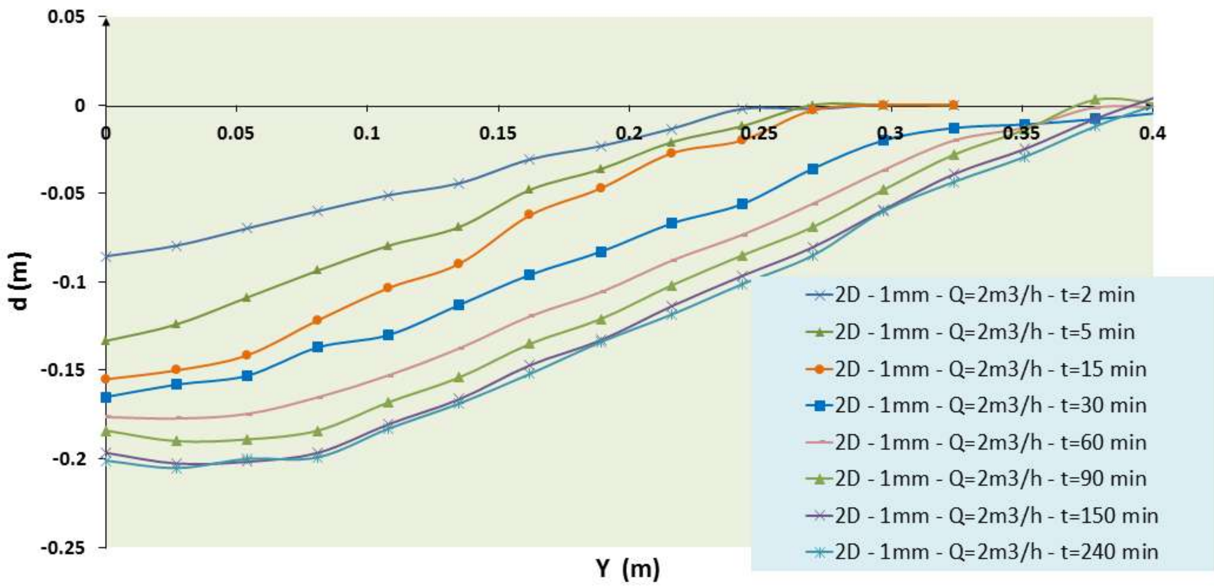

Figure 8. Changes in the bed lateral cross profile at maximum width position for simple nozzle

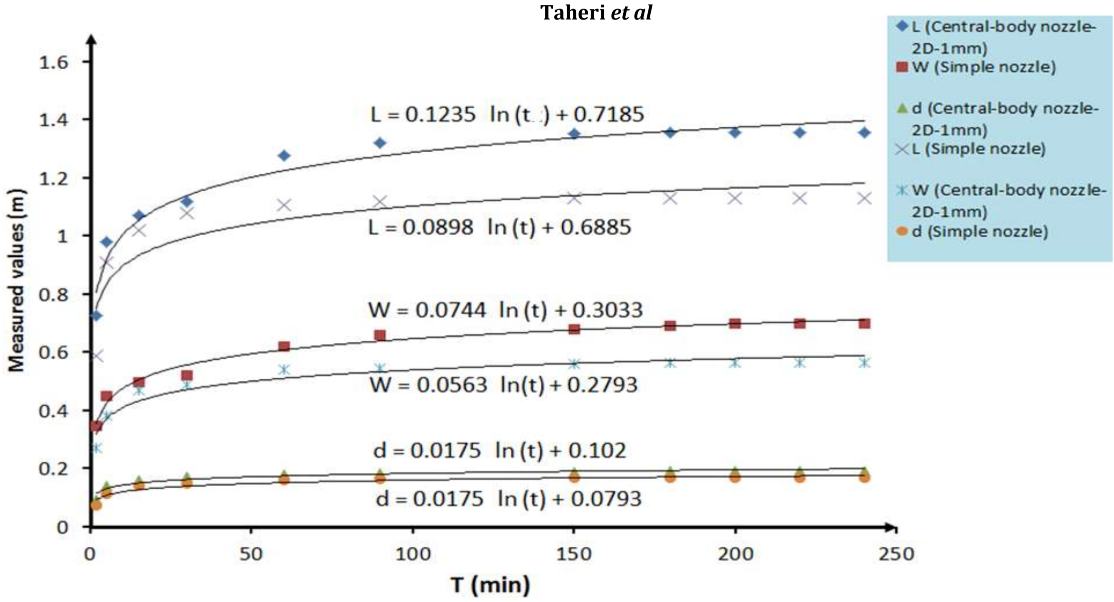

Figure 9. Scour hole geometric development for Q=1.6 m3/hr

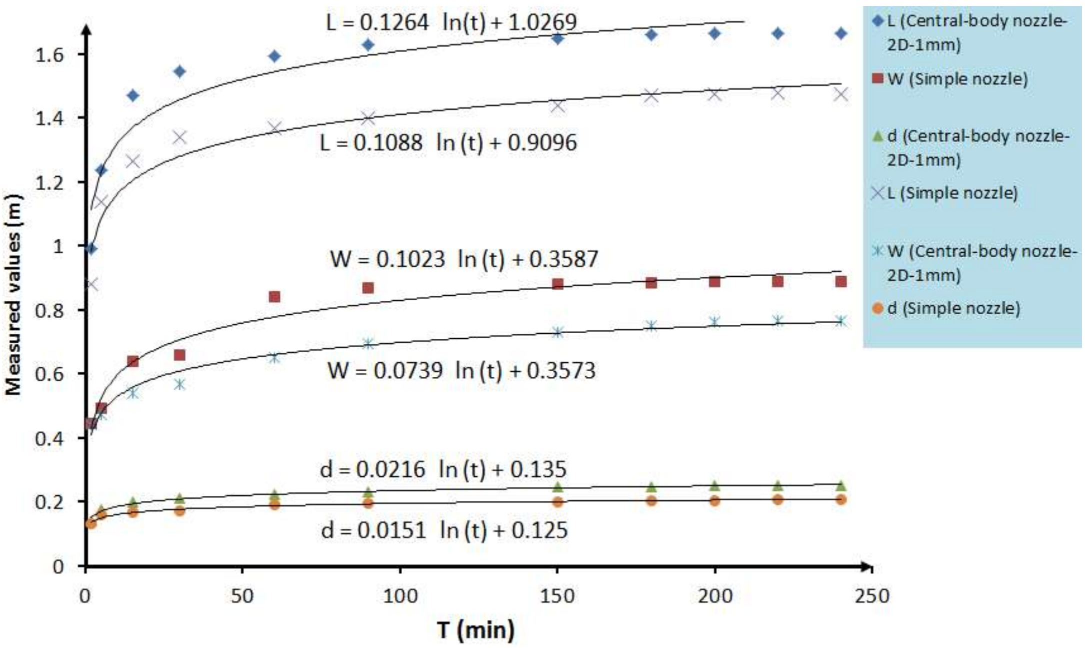

Figure 10. Scour hole geometric development for Q=2.25 m3/hr

CONCLUSION

We concluded that the final dimensions of the scour hole (length, depth and width of the hole) using nozzles with central core shows a significant increase in comparison to simple nozzles. Almost all geometric dimensions in the time interval of 180 to 220 minutes reached constant values and increasing time makes no tangible change in these values. This statement is also true for the other nozzles and the analysis of all results show that we can most certainly accept 200 minutes as the final equilibrium time $(t=t_\infty)$. Final equilibrium time (and consequently the experimental equilibrium time) is completely dependent on the type of the nozzle and the Densimetric Froude number (or flow rate) and it cannot be a constant value. Generally width, depth and length of the hole respectively have the most degree of importance in determining the equilibrium time. Thus the length of the hole is not always determinative to estimation of equilibrium time. We concluded that the 130 minutes interval (based on the 97% development of the hole) is the best option such that in addition to equilibrating almost all geometric parameters, its realization in experimental conditions were fully possible.

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