

EXPANSION RATIO EFFECTS ON SCOUR BY 3D JETS

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The influence of channel expansion ratio (ratio of channel width-to-nozzle size) on the scour geometry at various tailwater depths caused by submerged square jets is studied. Results show that the extent of influence of the expansion ratio depends on the densimetric Froude number, grain size of the bed material and tailwater conditions. Further, the effect of channel expansion ratio is reduced as the densimetric Froude number and the tailwater depth increases. An empirical equation describing the dependency of scour depth on the densimetric Froude number, tailwater depth and expansion ratio has been developed.

Key Words : *Local scour, square jets, densimetric Froude number, tailwater ratio and expansion ratio.*

Introduction

Over the last three decades, several experimental studies have been conducted to investigate the local scour process caused by submerged and unsubmerged two-dimensional (Bey et al., [1]; Deshpande et al., [2]; Balachandar et al., [3]; Johnston, [4]; Rajaratnam, [5]; and Balachandar and Kells, [6]) and three-dimensional (Faruque et al., [7]; Sarathi et al., [8]; Ade and Rajaratnam, [9]; Ali and Lim, [10]; Chiew and Lim, [11]; Rajaratnam and Berry, [12]) jets. Researchers had drawn several insights from these studies. Results indicate that the local scour process and the corresponding scour profiles depend on several variables such as the jet exit velocity, grain size of the bed material and mainly on tailwater depth and densimetric Froude number ($F_o = U_o / \sqrt{g(\Delta\rho/\rho)d_{50}}$, where, g = gravitational acceleration, U_o = jet exit velocity, ρ = mass density of water, $\Delta\rho$ = mass density difference between bed material and fluid, and d_{50} = median grain size of bed material). It was found that at a given F_o , there is critical tailwater condition beyond which a decrease or increase in tailwater causes an increase in the maximum depth of scour [10]. It is generally assumed that F_o absorbs any grain size effects.

In most laboratories, in an effort to reduce uncertainty in scour geometry measurements (by

obtaining a reasonably large scour geometry), researchers have tended to use fairly large nozzles in standard channels with width ranging from 200 mm to 600 mm. Some inconsistencies in the scour geometry have been noted for similar bed conditions. A lower value of expansion ratio causes restriction of jet expansion in lateral direction due to the presence of the side walls. Lim [13] pointed out that the scour profile is not affected by the channel sidewalls when the expansion ratio ($ER = B/b_o$) is ten or greater. He also noted that the downstream channel would affect the lateral development of the scour hole if it become too narrow and restrict the normal diffusion of the three-dimensional jet. However, Faruque et al. [7] have noted that the width of the downstream channel does have an effect on the scour process even for an expansion ratio (ER) as high as 14.5. They reported the presence of two secondary ridges on both sides of the main deposition ridge in the experiment at a low tailwater depth ($H = 2b_o$). On the other hand, Faruque et al. [7] and Sarathi et al. [8] noted that no secondary effects were observed for an ER of 41.4. Clearly, the occurrence of the secondary ridges along the wall should be an effect of the jet expansion ratio. It is necessary to understand the influence of expansion ratio on local scour process.

In this paper, an effort is made to understand and incorporate the effect of expansion ratio to further

explain scour caused by 3-D wall jets. To this end, an experimental study was carried out using two different nozzle sizes and two different bed conditions. Data from previous studies are used to expand the range of expansion ratio. Empirical equations are also proposed to explain the dependency of scour depth on the densimetric Froude number, tailwater ratio ($TWR = H/b_o$) and expansion ratio (ER).

Experimental setup and measurements

Clear-water experiments with various tailwater depths (H) ranging from $2b_o$ to $12b_o$ (b_o = nozzle thickness, Figure 1) were carried out in two recirculating open channel flumes (15 m long, 0.6 m wide, 0.9 m deep and 8 m long, 1.1 m wide, 0.92 m deep, respectively) at the University of Windsor. Details of the experimental facilities are available elsewhere ([1]; [7]) and avoided here for brevity. 20 different experiments were done at various tailwater ratios ranging from 2 to 12, two values of densimetric Froude numbers (6.6 and 10.0) and two types of sand particles with median grain size (d_{50}) of 0.71 mm and 2.30 mm were used. The geometric standard deviations (σ_g) of both sands were ≈ 1.20 and can be considered to be uniform. Two different square nozzles ($b_o = 19.0$ and 26.6 mm) were used in the study. The corresponding expansion ratios (ER) were 31.6 and 41.4, respectively. These values were deliberately chosen to provide data in a range that would be encountered in a typical hydraulic engineering laboratory. Flow straighteners were used at the entrance to the nozzle to reduce the turbulence level and condition the flow. A digital point gauge with a resolution of ± 0.01 mm was mounted on a traversing system to obtain the scour profiles.

Visual observations

Figure 1 shows the schematic of the scour hole and ridge that is formed downstream of the nozzle. A general description is first provided and the specific effects of ER are addressed later. As the jet exits the nozzle, it expands and interacts with the sand bed. The initial progression of scour hole and ridge is similar to those observed by other researchers ([9]; [7]; [8]) and a detailed description is avoided here for brevity. In addition, frequent near-bed turbulent bursts were observed all over the scour hole identified by the sporadic movement of sand. As the scour progress, the frequency of turbulent bursts

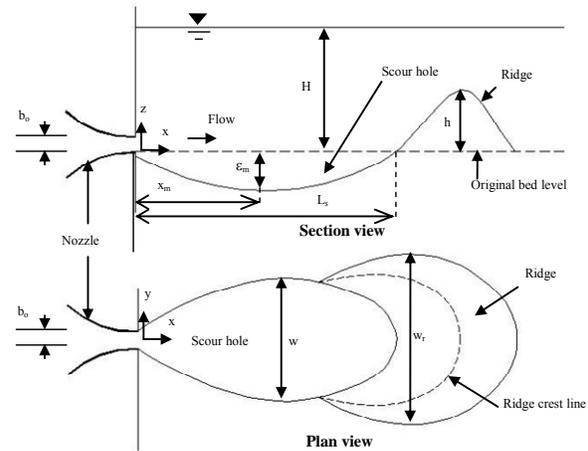


Figure 1: Definition of scour parameters

reduced. More active turbulent bursts were observed in the region upstream of the maximum scour depth. One could notice turbulent bursts for tests with both sand beds (fine and coarse sand). Due to the necessity to expend higher energy to move the coarser sand particles, it was observed that turbulent bursts played a greater role in sediment transportation of the finer sand.

Furthermore, streamwise secondary ridges were observed on either side of the main ridge at $F_o = 10$ with the coarse sand bed ($d_{50} = 2.30$ mm) for $ER = 31.6$. For $TWR \leq 4$, two secondary ridges on both sides of the main deposition ridge gradually formed during scouring process. At $TWR = 2$, the presence of the secondary ridges was first identified at about 6 hours from the start of the test. At asymptotic conditions, the length and maximum height of the secondary ridges was about $12b_o$ and $0.5b_o$, respectively. At $TWR = 3$, the secondary ridges appear later (at about 9 hours). At $TWR = 3$ and 4, the length of secondary ridge was $17b_o$, while the maximum height of the secondary ridges was $1b_o$. With increasing tailwater depth, the geometry of the secondary ridge at asymptotic conditions appeared to initially increase and stabilize. When TWR was greater than 4, no secondary ridges were observed irrespective of the tailwater depth. Interestingly, for the finer bed material ($d_{50} = 0.71$ mm), no secondary ridges were observed at any tailwater depth. Further, for a low densimetric Froude number ($F_o = 6.6$), secondary ridge was not noticed for the coarse sand. However, Faruque et al. [7] noted the formation of secondary ridges for a coarse sand ($d_{50} = 2.46$ mm) and $F_o = 6.6$ with an expansion ratio of 14.5. From the above observations, one can conclude that the development of secondary ridge that was previously noted to be an effect of the jet expansion ratio also depends on densimetric Froude number, tailwater

ratio and grain size.

Results

Figure 2 shows the scour profiles at an asymptotic state along the centerline of the nozzle for the fine sand ($d_{50} = 0.71$ mm) at $F_o = 10$. Figure 2a shows the scour centerline profile for $TWR = 2$. One can note a difference between the two profiles (albeit slightly upto the location of maximum scour depth). The size of the scour hole is larger and the ridge is longer at the higher expansion ratio. The ridge is flatter due to low tailwater conditions as observed in previous low tailwater studies [8]. Figures 2b and 2c show the scour centerline for $TWR = 4$ and 6, respectively. One can note a slightly bigger scour hole up to the location of maximum scour depth ($x/b_o < 20$) for the higher expansion ratio, while the condition is reversed for the remaining portion of the scour hole. One can also note that at the downstream end of the ridge, the profiles tend to merge. Figure 2d shows the scour centerline profile for a much higher TWR ratio ($= 12$). Based on previously published results, one can recall that at $TWR > 12$, tailwater effects are absent. The scour hole profiles merge up to the location of maximum scour depth and then the scour hole becomes larger for the lower expansion ratio. Clearly, the effect of expansion ratio is prevalent at all values of TWR, though not dominant.

Figure 3 shows the plan view of the perimeter of the scour hole and ridge at asymptotic conditions for the conditions described in Figure 2. In Figure 3a, the scour hole and ridge are wider and the length of scour hole is longer at the higher expansion ratio. Figures 3b to 3d show that the scour hole is wider but shorter in length for the higher expansion ratio. The trend of the profiles in Figure 3a is different from that noted at the higher tailwater depths. When the flow is commenced, it exits the nozzle and is free to expand in the lateral direction. The flow is confined in the vertical direction due to presence of sand bed.

The presence of free surface also restrains the jet in the vertical direction. With increasing time and increasing scour hole size, the jet is less confined in vertical direction. However, as an asymptotic condition is reached, the capability of the jet to expand in the lateral direction is not diminished. Consequently, the scour hole increases in size laterally at the higher expansion ratio as the jet has more space to expand laterally. At the lowest TWR, the length of the scour hole is also comparatively longer, indicating that TWR effect can be dominant at the low values of TWR. One can also note from

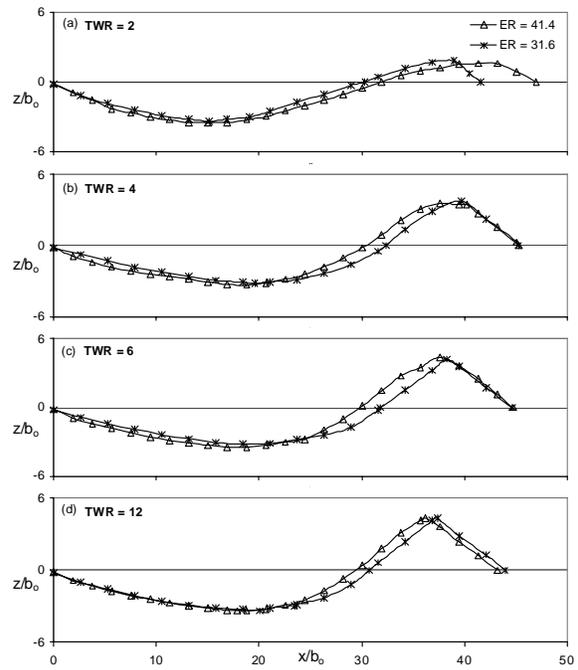


Figure 2: Scour centerline profile at asymptotic conditions for $F_o = 10$ and fine sand ($d_{50} = 0.71$ mm).

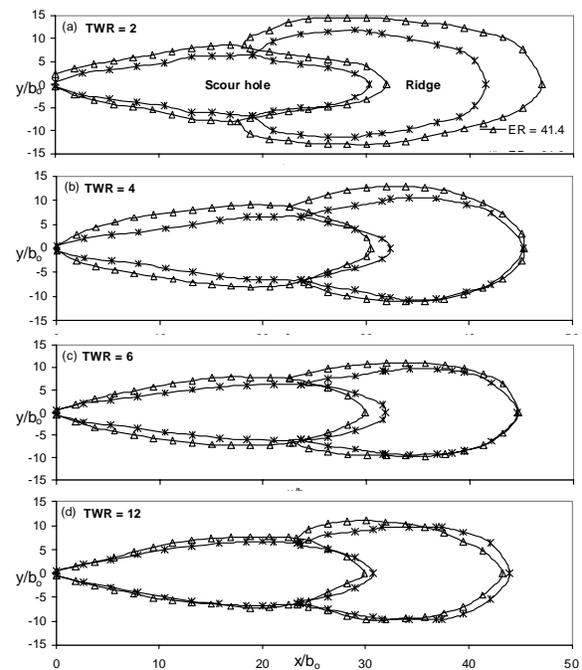


Figure 3: Plan view of the perimeter of the scour hole and ridge at asymptotic conditions for $F_o = 10$ and fine sand ($d_{50} = 0.71$ mm).

Figures 2 and 3 that the effect of expansion ratio on scour profile reduces with increasing tailwater ratio.

Figure 4 shows the asymptotic scour profiles along the centerline of the nozzle for the experiments for the coarse sand ($d_{50} = 2.30$ mm) at $F_o = 10$. For $TWR = 2$ (Figure 4a), the profiles in the hole region merge reasonably well. Nevertheless, the trend of the

profiles is not the same as in Figure 2a. With increasing TWR, the trends in the two profiles are similar to that noticed in Figure 2. One can also note in the Figure 4 that the length of scour hole and the distance of the end of the ridge from nozzle exit are always higher for the smaller ER. The perimeter of the scour hole and ridge at asymptotic conditions show a trend similar to that noticed for the fine sand and are not presented here for brevity. The results are consistent with the earlier figures (Figure 2 and 3) indicating that the difference is due to the difference of expansion ratio.

Figure 5 shows the variation of the different scour parameters with tailwater ratio for both fine (Figures 5a to 5c) and coarse sand (Figures 5d to 5f). As shown in Figure 5a, one can note that the maximum scour width increases with increasing TWR and attains a maximum value at TWR = 4 for the tests with ER = 41.4. Further increase of TWR results in a reduction of maximum scour width. Clearly, at a lower expansion ratio, the magnitude of the width is smaller at all values of TWR. As the bed material and densimetric Froude number remains constant, one can note that this variation is exclusively a result of expansion ratio. Figure 5b shows the variation of maximum ridge width with TWR. One can note the maximum ridge width reduces with increasing TWR and attains a constant value for $TWR \geq 6$. Again, the effect of ER is clearly visible in the graph. Figure 5c shows the variation of the maximum length of scour hole with TWR. One can note that the maximum length of scour hole increases with increasing TWR and attain a maximum value at TWR = 4 for the tests with ER = 31.6. Further increase of TWR, results in a reduction of maximum length of scour hole. For the tests with ER = 41.4, the maximum length of scour hole decreases with increase in TWR and attains a constant value for $TWR \geq 6$. One can also note that the maximum length of scour hole is shorter for higher ER for $TWR > 3$. The difference in the trend at lower TWR can be due to dominant effect of lower TWR. With the exception of the maximum length of scour hole at TWR = 2, Figures 5a to 5c clearly show that the maximum scour and ridge width is higher for higher ER which results in a shorter scour hole length. Figure 5d shows the variation of maximum scour width with TWR for the coarse sand. With the exception of lowest TWR (=2), the trend is similar to that of the fine sand (Figure 5a). However, one can note that the maximum width of scour is smaller (albeit slightly) for the higher expansion ratio for $3 \leq TWR \leq 4$ and with increasing TWR, the trend reversed. One can also note from Figures 5a and 5d that the effect of ER reduces with increasing sand

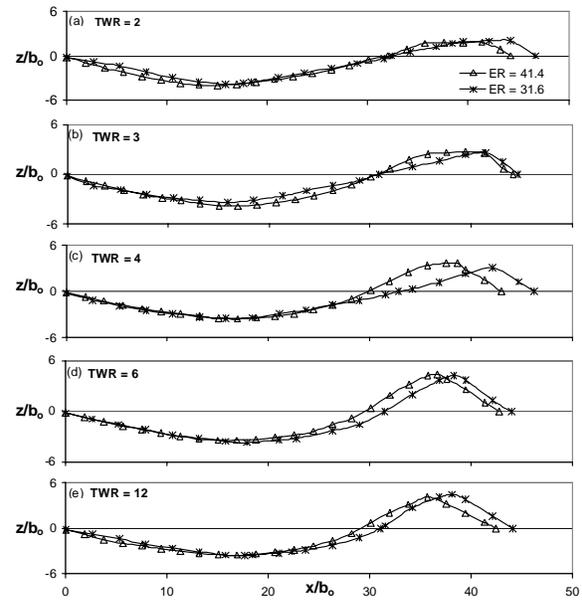


Figure 4: Scour centerline profile at asymptotic conditions for $F_o = 10$ and coarse sand ($d_{s0} = 2.30$ mm)

grain size. Figure 5e shows the variation of maximum ridge width with respect to TWR for coarse sand. The trend is similar to that for fine sand (Figure 5b). However, one can note that the maximum width of ridge is smaller (albeit slightly) for higher expansion ratio for $3 \leq TWR \leq 6$ and with increasing TWR, the trend reversed. One can also note from Figures 5b and 5e that the effect of ER reduces with increasing sand grain size. Figure 5f shows the variation of maximum length of scour with respect to TWR for coarse sand. With the exception of lowest TWR (= 2), the trend is similar to that for fine sand (Figure 5c). One can note from Figure 5 that the variation of the different scour parameters depends on TWR, ER and sand grain size but effect of ER reduces with increasing TWR and increasing sand grain size.

Figure 6 shows the asymptotic scour profiles at $F_o = 6.6$ for TWR = 4. One can note a significant difference between the two profiles (Figure 6a) with a lower expansion ratio yielding a larger scour hole. The maximum height of ridge is also higher for lower expansion ratio case. The location of maximum scour depth and maximum ridge height is closer to nozzle for the higher expansion ratio. Figure 6b shows the plan view of the perimeter of scour hole and ridge at asymptotic condition. The scour hole is wider and the length of scour hole is shorter for higher expansion ratio. The observation of the variation of the size of scour hole at the lower densimetric Froude number ($F_o = 6.6$) with respect to expansion ratio is similar to that observed for the higher densimetric Froude number ($F_o = 10$).

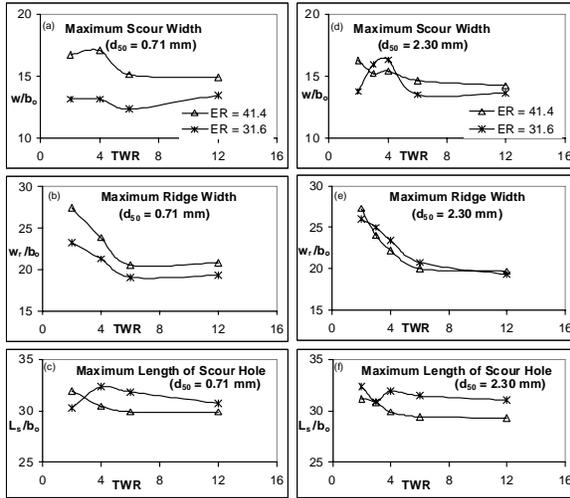


Figure 5: Variation of different scour parameters with respect to tailwater ratio (TWR) for $F_o = 10$, fine sand ($d_{50} = 0.71$ mm) and coarse sand ($d_{50} = 2.30$ mm).

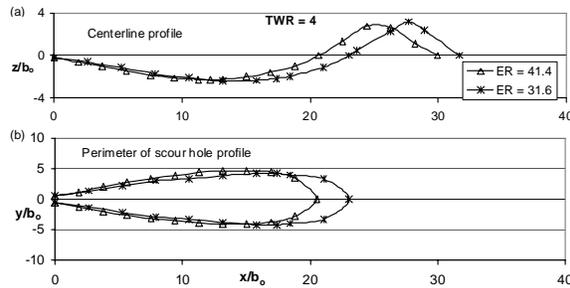


Figure 6: Scour profile at asymptotic conditions for $F_o = 6.6$ and coarse sand ($d_{50} = 2.30$ mm).

From the discussion of Figures 2 to 6, one can conclude that expansion ratio effects are important. For the same sand, profiles are different for different expansion ratios. The extent of the difference between the profiles is dependent on the tailwater ratio. To incorporate the effect of densimetric Froude number (F_o), tailwater ratio (TWR) and expansion ratio (ER) in the description of scour process, the use of various scaling variables were attempted. Dimensionless scaling variables of the form $[F_o/(TWR \times ER)]$ was found to be effective. Figure 7 shows the maximum depth of scour as a function of this scaling variable. It was noted that maximum depth of scour varies linearly with the dimensionless variable and an equation of the form

$$\frac{\epsilon_m}{H} = A \left(\frac{F_o}{TWR \times ER} \right)$$

parameter that depends on the expansion ratio. The various graphs in Figure 7 also show the results from other previous studies. The previous studies have used nozzles of various designs, size and shape. One can note from Figure 7 that the parameter 'A' and the maximum scour depth (ϵ_m/H) increases with increasing ER.

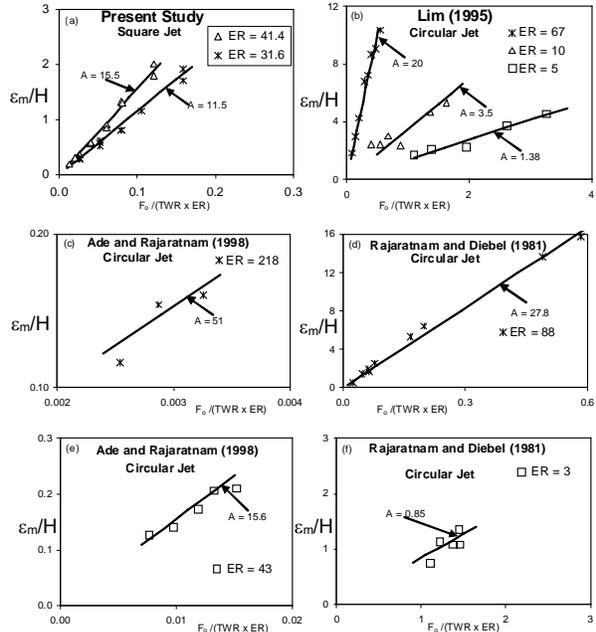


Figure 7: Effect of dimensionless scaling variables on scour depth

In an effort to further understand the role of expansion ratio (ER), the same set of data including the test results of Rajaratnam and Berry [12], Rajaratnam and Diebel [14], Lim [13], Faruque et al. [7] and Ade and Rajaratnam [9] are replotted in Figure 8 using $[F_o/(TWR)] \times (ER)^{0.10}$ as the dimensionless scale. All data sets collapsed reasonably well onto a single line. Equation 1 is proposed for predicting the equilibrium maximum scour depth.

$$\frac{\epsilon_m}{H} = 3 \times 10^{-5} \times \left(\frac{F_o(ER)^{0.10}}{TWR} \right)^3 - 3.3 \times 10^{-3} \times \left(\frac{F_o(ER)^{0.10}}{TWR} \right)^2 + 28.5 \times 10^{-2} \times \left(\frac{F_o(ER)^{0.10}}{TWR} \right) \quad (1)$$

The solid line in the Figure 8 indicates the fit to the data from the present and previous studies. The effects of tailwater depth, nozzle size, flume width, the prevailing densimetric Froude number are absorbed by the proper choice of the scaling variables. Given the wide variety of experimental

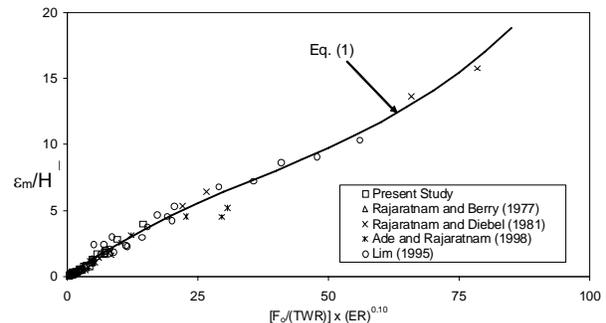


Figure 8: Scaling variables on scour depth

conditions encountered in the various tests (for both circular and square nozzles TWR ranges from 0.47 to 24.4, median grain size ranges from 0.24 mm to 7.20 mm, ER ranges from 3 to 218 and densimetric Froude number ranges from 1.9 to 90), the collapse of the data is fair.

Conclusions

The present study addresses scour caused by 3D square jets interacting with non-cohesive sand beds to further understand the effects of channel width, tailwater conditions and jet exit velocity. The tailwater ratio was varied from two to 12 times the nozzle width, while the channel width was 31.6 and 41.4 times the nozzle width. Three different jet exit velocities were adopted and two different bed materials were used. Data from several previous studies was used to compare with the present results and evaluate the proposed equation for maximum depth of scour. The following are the main conclusions that can be drawn from the study aided by both visual observation and data analysis:

1. The development of secondary ridge that was previously noted to be an effect of the jet expansion ratio (Faruque et al, 2006), was also found to depend on densimetric Froude number, taiwater ratio and grain size.
2. It is evident from the present study that for the same sand bed, scour profiles are different for different expansion ratios.
 - a. For the fine sand and for $TWR > 3$, scour hole was wider but shorter in length at the higher expansion ratio. For the coarse sand, a similar trend was observed for $TWR > 4$.
 - b. For the fine sand and for lower TWR (< 3), the scour hole was wider and longer, for tests with the higher expansion ratio.
 - c. For the coarse sand and for $3 \leq TWR \leq 4$, scour hole is strongly dependent on the tailwater ratio, especially at the lower expansion ratio.
 - d. For the very low tailwater depth ($TWR < 4$), the scour characteristics are strongly influenced by TWR.
 - e. The extent of difference for different scour parameter due to expansion ratio reduces with increasing TWR irrespective of the sand grain size.
 - f. The differences in the maximum scour hole and ridge width between the two expansion ratios reduce with increasing sand grain size.
3. The effect of expansion ratio reduces as densimetric Froude number increases.
4. Contrary to previously published results, the present study indicates that there are differences between the profiles for $TWR \geq 12$. This is due to the differences in the expansion ratio.
5. In an effort to provide useful, but a simplified scour prediction equation at asymptotic conditions, a relationship for the maximum scour depths has been proposed in terms of densimetric Froude number, tailwater ratio and expansion ratio. It has been found that the predictions based on the present study are appropriate for a wide range of test conditions.

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