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TRANSIENT LOCAL SCOUR BY SUBMERGED THREE-DIMENSIONAL WALL JETS: EFFECT OF TAILWATER DEPTH

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Abstract: The present study deals with the effect of submergence on the scour caused by three-dimensional jets issuing from a square cross-section nozzle onto a non-cohesive sand bed. The densimetric Froude number was maintained below ten, while the jet expansion ratio was held greater than ten. The results indicate that the densimetric Froude number, tailwater depth and grain size-to-nozzle size ratio, all have an influence on the extent of scour caused by three-dimensional jets. However, each parameter has a dominant influence at different flow conditions. The present results also indicate that the jet expansion ratio can have a significant influence, especially at very low tailwater depths.

1. Introduction

In hydraulic engineering practice, the prediction and control of scour have been considered to be very important. To better understand the scouring process, a significant number of studies have been conducted and erosion by jets is perhaps one of the most studied scour related problems. An excellent review of the different types of jet scour can be found in Breusers and Raudkivi (1991). A significant number of variables influence the scouring process and the complexity of the flow patterns do not render an easy analysis. In practice, the jets can be two- or three-dimensional, and the flow can be free or submerged depending on the tailwater conditions. Many studies have been conducted with plane wall jets that interact with non-cohesive sand beds. Other forms of jet scour caused by plunging jets, offset jets and impinging jets have also been studied.

Scour by 3-D and circular wall jets have also been studied, but to a lesser degree than that caused by plane jets. These include the study by Rajaratnam and Berry (1977), Ali and Lim (1986), Chiew and Lim (1996) and Ade and Rajaratnam (1998). Rajaratnam and Berry (1977) studied the scour produced by circular wall jets and concluded that the main geometric characteristics of the scour hole are functions of the densimetric Froude number ($F_o = U_o \big/ \sqrt{g(\Delta\rho/\rho) d_{50}}$). Here U_0 is the jet exit velocity. Ali and Lim (1986) recognized a critical tailwater condition beyond which a decrease or increase in tailwater causes an increase in the maximum depth of scour. Also, their data indicates that this critical value increases with increasing densimetric Froude number. It is possible that different types of flow patterns are associated with changing tailwater conditions causing the depth of scour to vary. Lim (1995) studied the effect of the channel width (expansion ratio) on the scour development and noted that there was no effect for an expansion ratio greater than ten. Chiew and Lim (1996) suspected that the ratio of the size of the nozzle to sand particle size should have an influence on the scour profiles. However, their tests did not indicate any such effect. Using over 350 data sets, Ade and Rajaratnam (1998) emphasize the use of F_o as the characteristic parameter to analyze scour caused by circular wall jets. However, they noted that the asymptotic dimensions of the scour hole were dependent on the tailwater conditions for $F_o > 10$. Ade and Rajaratnam (1998) also noted that the maximum depth of scour was found to be larger at deeper submergences and higher values of F_o, which is consistent with the measurements of Ali and Lim (1986). In studying erosion below culvert-like structures, Rajaratnam and Diebel (1981) found that the relative tailwater depth and relative width of the downstream channel do not affect the maximum depth of scour whereas the location of the maximum scour was affected.

This paper presents the results of clear water local scour generated by a 3-D wall jet in a non-cohesive sand bed at low tailwater depths. Existing literature indicates that the role of tailwater depth needs to be clarified, especially at lower submergences. In the present study, the jet was generated using a well designed nozzle with a square exit. The tailwater depth was varied from two to six times the nozzle exit width. The time development of scour was obtained from the start of the test until near asymptotic conditions were attained. Velocity measurements were also obtained at various locations in the flow field using a laser Doppler anemometer.

2. Experimental set-up and procedure

Experiments were conducted in an open channel flume which was 8.0 m long, 1.1 m wide (B) and 0.92 m high. Two different nozzles with square exits (width b_o = 76 and 26.6 mm) were used to generate the jets. For the larger b_o, the nozzle provided an area contraction of 16:1, while for the smaller b_o, the area contraction was 131:1. The corresponding jet expansion ratios (B/b_o) were 14.5 and 41.4. These values of the expansion ratio are greater than the recommended value of 10 (Lim, 1995). Additional details are available in Faruque (2004) and avoided here for brevity. A bed made up of sand particles (d_{50} = 2.46 mm) was leveled to the invert of the nozzle outlet. The gradation characteristics indicate that the sand is uniform. The bed was 325 mm deep and 3 m long, the surface was leveled to provide zero-slope and saturated prior to the start of the test. Three different tailwater depths, corresponding to $2b_o$, $4b_o$ and $6b_o$ were chosen for the study (Table 1). The change in nozzle size enables conducting tests with a larger d_{50}/b_o ratio. The tests with the smaller nozzle (Tests D to I) were either conducted to match the exit Froude number or the densimetric Froude number of the larger nozzle. In the case of Test C (lower tailwater ratio), beyond a test period of one hour, additional deposition in a manner not noticed in tests A and B occurred and it appeared that secondary effects (such as the proximity of the side walls to the ridge periphery) may have an influence on the flow characteristics. This test was discontinued beyond three hours. However, as shown in Table 1, tests D and E were conducted with the smaller nozzle for the lower tailwater ratio ($H/b_o = 2$) until asymptotic conditions were attained. Test J was conducted to enable comparison with one particular test of Ali and Lim (1986) carried out using a square cross-section nozzle at a tailwater ratio of 1.57.

Table 1: Summary of test conditions

Test #	Nozzle width (b_o - mm)	Velocity (U_o – m/s)	Tailwater ratio (H/b_o)	d_{50}/b_o	F_r	F_o	Test duration
A	76	1.31	6	0.032	1.5	6.6	1 to 72 hrs.
B	76	1.31	4	0.032	1.5	6.6	1 to 72 hrs.
C	76	1.31	2	0.032	1.5	6.6	1 to 3 hrs.
D	26.6	1.31	2	0.092	2.6	6.6	1 to 6 hrs.
E	26.6	0.78	2	0.092	1.5	3.9	1 to 6 hrs.
F	26.6	1.31	4	0.092	2.6	6.6	1 to 6 hrs.
G	26.6	0.78	4	0.092	1.5	3.9	1 to 6 hrs.
H	26.6	1.31	6	0.092	2.6	6.6	1 to 6 hrs.
I	26.6	0.78	6	0.092	1.5	3.9	1 to 6 hrs.
J	76	0.87	1.57	0.032	1.0	4.4	0.3 to 3 hrs.

3. Results:

3.1. *Stages of the scour process*

The following general description based on visual observation applies to the scour process for tests A and B conducted with the larger nozzle. Any dissimilarity at the various tailwater depths are addressed as the discussion progresses. As the jet exits the nozzle and interacts with the sand bed, the scour progresses rather quickly in the longitudinal direction. The jet expands in the lateral direction and the scour also progresses in this direction, albeit slower than that in the longitudinal direction. During the early stages of scour, a certain amount of material goes into suspension that is convected with the main flow and deposited as a downstream ridge. Figure 1 provides a schematic of the scour hole and the ridge that is formed downstream of the scour hole. With progress in time, the depth of scour increases while retaining the same general shape of the hole, which is more-or-less elliptical in shape. As scour progresses, the upper portion of the scour slope ($x < x_m$ in Figure 1) attains an equilibrium stage, while the lower portion is still developing. Turbulent bursts can be seen to occur in the lower portion of the scour hole contributing to the transport of the sand particles. The scour caused by the turbulent bursts is quite different from the large scouring action of the jet reported earlier. The turbulent bursts are not strong enough to cause a large scale suspension of the particles and only cause a rolling motion of the sand particles. These bursts occur quite frequently with the frequency of occurrence appearing to decrease slightly as time progresses. The bursts persisted throughout the test period. Visual observations also indicated the absence of any large scale recirculating zone in the vicinity of the bed. With increasing time, flow continuity considerations indicate that the erosion capacity in the zone of maximum scour depth should be small (due to flow deceleration). However, beyond x_m, one has to note that the flow has to negotiate a ridge of significant size and particles could be seen to be slowly rolling down the ridge past the crest. The particles would clearly require a significant amount of energy to convect past the ridge. This energy will have to be drawn from the mean motion of the jet which gets decreased as the jet expands and interacts with the bed. With progress in time, the dimensions of the scour hole do not change significantly and a quasi-equilibrium stage is reached.

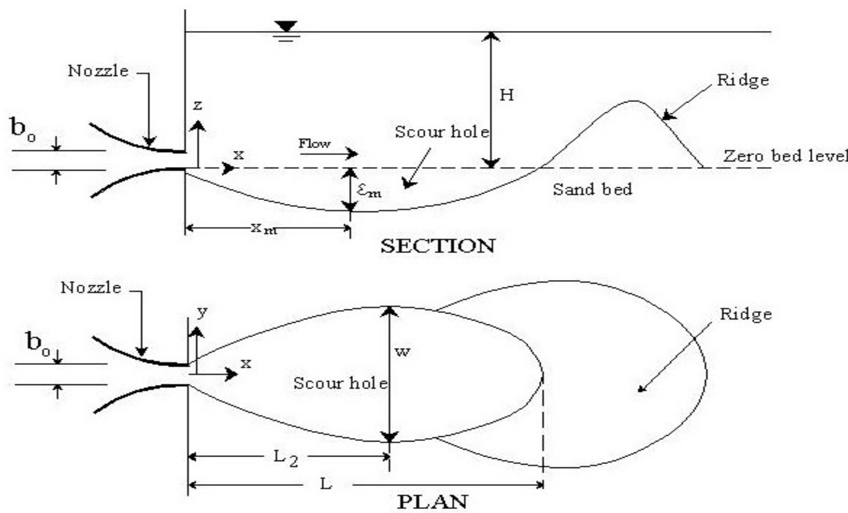

Figure 1. Definition of scour parameters

It should be remarked that around the periphery of the scour hole and close to the start of the ridge, the deposition pattern was slightly different at the lowest tailwater depth (Test C) compared to that at the higher tailwater depths. One could notice that after about an hour of testing, there was the formation of a secondary ridge on either side of the main ridge. The secondary ridge was elongated in the longitudinal direction and Figure 2a provides a pictorial representation of the scoured hole at t = 3 hours. A similar phenomenon was not noticed with the smaller nozzle (Figure 2b) for the same jet exit velocity (Test D) and tailwater ratio. However, with the smaller nozzle, at the tailwater depth of $2b_o$, the main ridge appeared to be flatter (without a sharp crest) with a plateau forming on the top surface of the ridge (Figure 2b). A similar flattening of the ridge was noticed by Lim (1995) at tailwater ratio of 0.47. At a lower F_o (i.e., lower velocity), the jet initially tends to move laterally to one side of the flume. With increasing time, the jet tends to become symmetrical about the nozzle axis and the scour hole changes in response to this jet movement. Further progress of the scour hole tends to be symmetrical. There was no initial preferential movement of the jet (to one side or the other) that was noticed during the various tests that were conducted. The lateral movement of the jet was absent at the higher jet exit velocities.

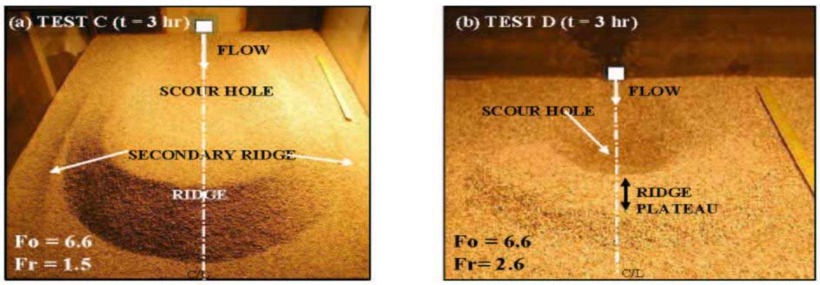

Figure 2. Photographs of scour at various flow condition

3.2. *Scour profiles*

Figure 3a shows the time development of scour profiles along the nozzle axis (side view). Figure 3b shows the plan view of the perimeter of the scour hole. In these figures with increasing time, the profiles gradually tend to an asymptotic state, i.e., there is no significant change in the profile after t = 48 hours. From Figure 3a, one can note that the maximum depth of scour (ε_m, see Figure 1 for definitions) and the location of the maximum depth from the nozzle exit (x_m) increase with increasing time. For a given test, Figure 3a also shows that the difference between two consecutive profiles at a fixed distance from the nozzle increases with increasing x. This indicates that the scour profiles attain a near-equilibrium state at earlier times for locations closer to the nozzle.

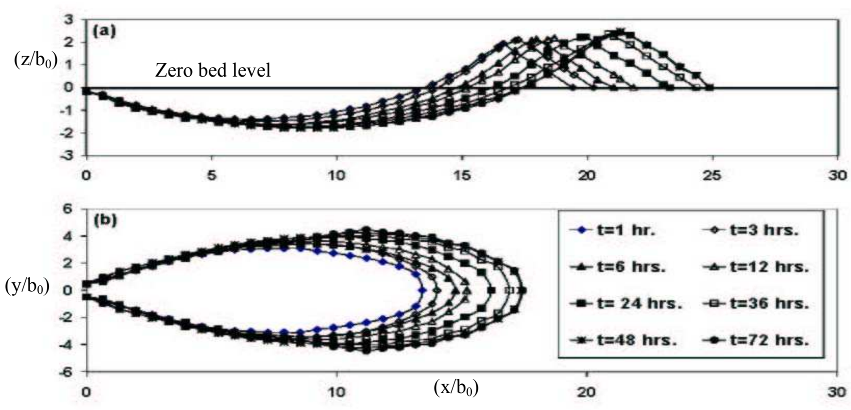

Figure 3.Time development of scour profiles for Test A: a) centre line profile b) plan view of scour hole

The time dependency of the scour profiles are very similar for the other tests conducted in the present study. However, with the smaller nozzle, the asymptotic state is reached much earlier (t ~ 6 hours). Longitudinal mean velocity measurements were conducted at three different sections (x/b_o = 1.3, 5.3 and 13) at various instants from the start of the test. The velocity measurements were carried out along the plane containing the nozzle axis. The velocity profiles indicate that they are uniform close to the nozzle exit and are similar over the entire test duration. At the second and third sections, negative values of velocity occur at farther distances from the bed indicating the presence of a reverse flow closer to the free surface. The measurements also indicated that as scour progresses, the velocity measurements do not change significantly at the later two sections. A similar behavior was noticed for all the tests carried out in the present study. The velocity profiles were consistent with the development of the scour profiles in that the profiles are well collapsed for small values of x/b_o

Figures 4a-c compare the time variation of scour profiles along the nozzle axis for b_o = 76 mm at the three tailwater depths. For $x/b_o < 10$, the profiles are similar for the tests with the two larger tailwater depths at all instants of time. At all t and $x/b_o > 10$, the scour hole is consistently larger (albeit only slightly) for $H/b_o = 6$ compared with $H/b_o = 4$. However, one should note that in these profiles, the absolute value of ε_m is very similar for both Tests A and B up to t = 12 hours, beyond which ε_m is larger for $H/b_o = 4$ (see inset in Figure 4a). For t > 12 hours, though the difference in ε_m is only 3 ~ 5 mm, the data trend indicates that the maximum depth of scour tends to be consistently larger at a lower submergence. It should be remarked that for circular wall jet scour, Ade and Rajaratnam (1998) found the maximum depth of scour to be larger at deeper submergences.

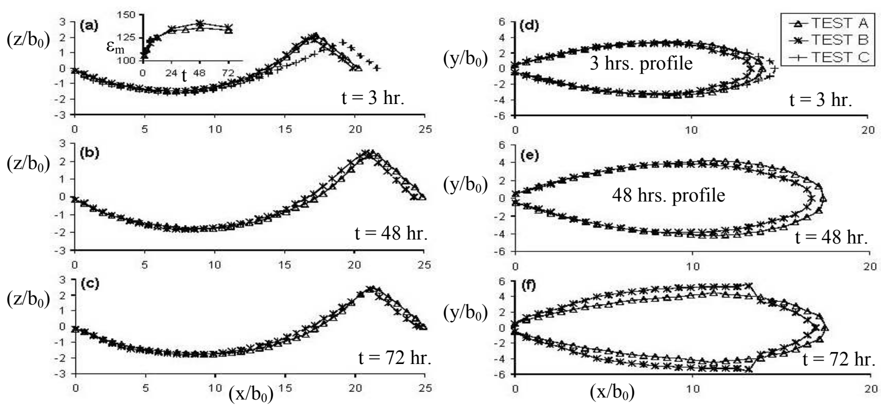

Figure 4.Comparison at various instants of time, a-c) scour profile along nozzle centre line. d-f) plan view of the perimeter of the scour hole

Figure 4a indicates that at $H/b_o = 2$ and t = 3 hours, the scour hole is larger compared to the other two tests, while the ridge height is smaller and the peak is farther away from the nozzle exit. The plan view of the perimeter of the scour hole indicates that the affected zone is consistently larger at $H/b_o = 6$ compared to $H/b_o = 4$ (Figure 4d-f). However, as asymptotic conditions are reached (Figure 4f), one can note that the hole perimeter expands laterally at $H/b_o = 4$. The 72-hour test was chosen for repetition and ensured that this behavior was repeatable. LDA measurements also confirmed that there was no change in flow conditions at the exit of nozzle. Furthermore, for the same tailwater ratio, this lateral increase in scour hole size was not noticed for the test with the smaller nozzle at or near asymptotic conditions. One can suspect that this is a consequence of secondary flow effects that occur at low tailwater depths, lower expansion ratios and as the ridge grows in size. On comparing Figure 4f with Figure 2a, one can note that at $H/b_o = 4$ and t = 72 hours, the scour hole is affected by secondary flow effects, while only the ridge is affected by secondary effects at the lowest tailwater depth (t = 3 hours). One should note that the extent of the scoured region is influenced both by the tailwater depth and the time from the start of the test.

Figure 5 shows the variation of the maximum depth of the scour hole with increasing time. The depth of scour is normalized by b_o while (U_o/b_o) is chosen as the time scale. The data of Ali and Lim (1986) obtained with a 51 mm x 51 mm square cross-section nozzle is also shown for comparison. Their data set was obtained at a densimetric Froude number of 4.4, H/b_o was 1.57, and the ratio d_{50}/b_o was 0.016. To enable direct comparison with this data set, an additional test (Test J) was conducted as part of the present study using the larger nozzle at the same value of F_o and H/b_o. However, it should be remarked that the value of d_{50}/b_o in this test is 100% greater than that of Ali and Lim (1986).

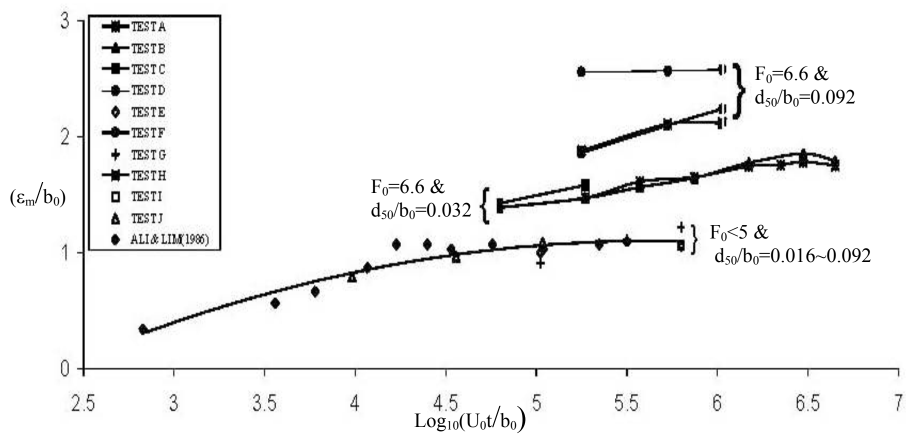

Figure 5.Variation of maximum scour depth with time

One can note from Figure 5 that the present set of data (Test J) and that of Ali and Lim (1986) are very similar. Furthermore, the present data at the lower value of F_o are very close to that of Ali and Lim (1986) indicating that tailwater depth and d_{50}/b_o have no significant effect on the maximum depth of scour. Previous studies at large tailwater depths have indicated that d_{50}/b_o has no systematic influence on the maximum depth of scour (Chiew and Lim, 1996). However, it is interesting to note that at $F_o = 6.6$ and $d_{50}/b_o = 0.032$, the data (Tests A, B and C) are fairly collapsed together and almost independent of tailwater depth, except for a slightly larger value of ε_m/b_o at the smallest tailwater depth. Comparing the results at F_o = 6.6 for d_{50}/b_o = 0.032 with d_{50}/b_o = 0.092, the effect of tailwater depth is seen to be significant, especially at the lowest tailwater depth. This leads one to conclude that F_o, d_{50}/b_o and tailwater ratio have an influence on the maximum depth of scour, with each parameter having a dominant role that depends on the test conditions.

4. Conclusion

The present study deals with scour caused by three-dimensional jets issuing from a square nozzle onto a sand bed. The tailwater condition ranges from two to six times the nozzle width. The results indicates that the densimetric Froude number, tailwater depth and grain size-to-nozzle size ratio, all have an influence on the extent of scour caused by three-dimensional jets. However, each parameter has a dominant influence at different flow conditions. For $F_o < 5$, tailwater depth and grain size-to-nozzle width ratio have no effect on the maximum depth and maximum width of scour. At higher densimetric Froude numbers, the effect of tailwater depth appears to be important at larger values of d_{50}/b_o. Previous observations have indicated that for $F_o > 10$, the effect of the tailwater depth was significant. However, the present results indicate that the cut off value for F_o could be lower depending on the value of d_{50}/b_o.

Earlier studies have also indicated that the effect of the jet expansion ratio on the scour profile is not significant for expansion ratios greater than ten. However, the present results indicate that this factor can have a significant influence, especially at very low tailwater depths. Present results also indicate that in the lower range of submergences, the maximum depth of scour is not necessarily deeper at higher tailwater depths. It should however be noted that the volume of scour is greater at higher tailwater depths even in the lower range of submergences encountered in the present study.

References:

Ade, F., and Rajaratnam, N. (1998). "Generalized study of erosion by circular horizontal turbulent jets." *J. of Hydr. Research*, 36(4), 613-635.

Ali, K. H. M., and Lim, S. Y. (1986). "Local scour caused by submerged wall jets." *Proc. of the Instn. of Civil Engrs.*, Part 2, 81, 607-645.

Breusers, H. N. C., and Raudkivi, A. J. (1991). *Scouring, hydr. structure design manual.* A. A. Balkema, Rotterdam. The Netherlands.

Chiew, Y. M., and Lim, S. Y. (1996). "Local scour by a deeply submerged horizontal circular jet." *J. of Hydr. Engineering*, 122(9), 529-532.

Faruque, M. A. A. (2004). "Transient local scour by submerged three dimensional wall jets: Effect of tailwater depth." M. A. Sc., thesis, University of Windsor, Canada.

Lim, S. Y. (1995). "Scour below unsubmerged full-flowing culvert outlets." *Proc. of the Institution of Civil Engineers, Water Maritime and Energy*, 112(2), 136-149.

Rajaratnam, N., and Diebel, M. (1981). "Erosion below culvert-like structure." *Proc., 5th Canadian Hydrotechnical Conf.,* May26–27, CSCE, 469-484.

Rajaratnam, N., and Berry, B. (1977). "Erosion by circular turbulent wall jets." *J. of Hydr. Research*, 15(3), 277-289.