Scour Caused by Three-Dimensional Submerged Square Wall Jet: Sand Deposition in Scour Hole and Ridge

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Abstract—Laboratory tests were carried out to assess the local scour by three-dimensional wall jets from a square cross-section nozzle. To this end, three different tailwater depths were used and the jet expansion ratio was held greater than ten. Velocity measurements were conducted using a one component laser Doppler anemometer. The jet exit Reynolds number was maintained to $1\times10^5$ and this value can be considered to be high enough for fully turbulent conditions to prevail. It was observed in the present study that the coarser particles are deposited towards the downstream end of the scour. In fact the coarsest particles are located on down slope of the ridge. The velocity measurements were carried out along the plane containing the nozzle axis. It was found that the velocity stays uniform close to the nozzle exit and is similar over the entire test duration. At the sections farther away from the nozzle, negative values of velocity occur at farther distances from the bed indicating the presence of a reverse flow closer to the free surface. One can also note that the volume of scour increases with increase of time. However, for 72 hours test of Test B ($H/b_s = 4$), there is a significant increase in scour volume when compared with $t = 48$ hours. This is due to the expansion of the scour hole perimeter laterally at $H/b_s = 4$ and at 72 hours. The volume of scour is seen to be increasing with increasing tailwater depth.

Keywords—Scour, Tailwater Depth, Wall Jets, Nozzle, Sand, Expansion Ratio, Velocity, Test Duration

I. INTRODUCTION

Scour is a natural phenomenon caused by the flow of water in rivers and streams. It is most pronounced in alluvial materials, but extensively weathered rock can also be vulnerable in certain circumstances. Scouring occurs naturally as part of the morphologic changes of rivers, and also as a result of man-made structures. Particularly local channel scour is a problem of considerable importance in hydraulic engineering practice. Scour is the removal by hydrodynamic forces of granular bed material and occurs whenever hydrodynamic bottom shear stresses exceed a critical value. Consequently, scour will occur if the flow velocity exceeds a critical value that would initiate the movement of particles [1]. The volume eroded depends on the magnitude and duration of the excess velocity. Scouring can progressively undermine the foundation of a structure.

Complete protection against scouring is usually expensive and engineers seek ways to guide and control the process so as to minimize the risk of failure. Guidance comes from controlled studies in laboratories and from field experiences. In particular, the failure of structures has led to improved design criteria.

Scour due to submerged wall jets can be found downstream of vertical gates and other outlet structures. Water jets emerging from culverts and storm drainage pipes can cause scour. Structures such as bridge piers or spur dikes cause obstruction and disruption to uniform flow patterns and are conductive to the evolution and development of localized scour [2]. Obstruction-related scour can also be found downstream of outlet and intake works of hydraulic structures, local channel works or natural channel irregularities. The safety of these structures depends partly on the prediction and control of the localized scour around them. [3] point out that a very large percentage of bridge failures can be attributed to pier and abutment scour. It was indicated in the Transportation Research Board’s annual report [4] that scour causes more bridge failures than all other factors combined and that better methods of scour prediction are needed. The provision of means for spilling excess water by hydraulic structures like submerged sluice gates, stilling basins has long been recognized as a problem by engineers. The difficulty does not so much lie in conveying the water to the downstream river bed. Rather, it lies in being able to do this in such a way that catastrophic scour does not occur downstream of the structure.

As in other aspects of sediment transport, far there is no entirely satisfactory theoretical solution which describes scour completely. The complexity of the non-steady flow patterns and the mechanisms by which the flow entrains an erodible sediment from the bed is presently not analytically solvable. The predictability of scour becomes more difficult because most of the flow related to scour is turbulent and turbulence is still an outstanding difficult subject to understand comprehensibly. Consequently, most studies in this field involve systematic experimentation to delineate the significant variables and to develop empirical relationships between the flow patterns, the scour characteristics and the properties of the bed material [5].
II. LITERATURE REVIEW

An excellent review of the different types of jet scour can be found in [6]. 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 and details can be found in [5]. All studies have noted the development of scour to be rapid in the early stages and progressing towards a quasi-asymptotic stage where the scour profile does not change significantly with time.

[7] investigated the local scour downstream of a rectangular slot with a deep tailwater depth and identified two stages of local scour development:

(i) an initial stage of local scour which occurs rapidly.
(ii) a progressive stage which approaches equilibrium after a very long time.

They observed that the equilibrium depth for short-term scour is established within less than 1% of the development time for the long-term scour; the short-term scour although not as deep as the long-term scour occurs closer to the apron; the bed in the short-term scouring regime is more highly fluidized than in the regime that governs the long-term scour. They have also mentioned that short-term scour due to plane horizontal, supercritical jets under low tailwater conditions is related to the energy dissipation regime that dominates the flow. They have identified the presence of seven different flow regimes.

1. attached jet
2. attached jet with adverse hydraulic jump
3. moving hydraulic jump
4. wave jump
5. surface jet/inverted jump
6. plunging/B-jump
7. classical jump in the stilling basin

The more rapid short-term scour was associated with regimes 1, 2, 3 and 6; while the deeper long-term scour was associated with regimes 4 and 5.

In observing scour hole development in the presence of shallow tailwater depths, [8] noted three different scour hole regimes. Two are formed when the jet permanently attaches itself to either the bed or free surface boundary whilst the third is produced when the jet periodically flicks between the free and solid bed boundaries.

[8] also observed that in certain shallow tailwater conditions the development of a scour hole downstream of a slot jet is more complicated than in relatively deep conditions. [8] found that while in deep conditions the scour hole development is orderly and invariably reaches a well defined asymptotic state, in shallow conditions such a state is sometimes not reached. The proximity of the bed and free surface has a considerable influence on the nearfield flow pattern and can promote the flicking of the jet from one boundary to another.

III. EXPERIMENTAL SETUP

A schematic drawing of the open channel flume and experimental setup is shown in Figure 1. Experiments were carried out in a 9-m long rectangular open channel flume (cross-section 1100 mm wide by 920 mm deep). The header tank upstream of the rectangular cross-section was 1.2 m square and 3.0 m deep. Nozzle with square exits (width \(b_o = 76\)) was used to generate the jets. Details are provided in Figure 2. The nozzle assembly was positioned near the upstream end of the flume. The inside of the nozzle was spray painted and finished to be smooth. The upstream end of the nozzle had a flow straightener to reduce the turbulence level. The nozzle provided an area contraction of 16:1 and the corresponding jet expansion ratio (\(B/b_o\)) was 14.5. This value of the expansion ratio is greater than the recommended value of 10 [9]. Prior to the start of the experiments, the quality of the flow was verified by conducting velocity measurements in a deeply submerged free jet. The velocity profiles (Figure 3) were symmetrical and uniform over the nozzle cross-section at a section 1.3\(b_o\) from the nozzle exit. In Figure 3, \(U\) is velocity at any point and \(U_{\infty}\) is velocity at centre for particular section.

A bed made up of sand particles was leveled to the invert of the nozzle outlet and the characteristics indicate that the sand can be considered to be reasonably uniform. More details of the sand selection is available in [5]. The bed was 325 mm deep and 3 m long. The flow conditions were maintained to permit local scour to occur (i.e., no general scour) and there was no net transport of sand beyond the edge of the bed. Downstream of the bed, a sand trap was provided to prevent any accidental transport of sand particles into the pump/piping assembly.
Three different tailwater depths (H), corresponding to 2b₀, 4b₀, and 6b₀ (tests A, B and C) were chosen for the study. The jet exit velocity was held constant at 1.31 m/s for all the tests. This corresponds to a jet exit Reynolds number (Reⱽ = Uⱽb₀⁵) of 1 x 10⁵. This value can be considered to be high enough for fully turbulent conditions to prevail. More details are available elsewhere and avoided here for brevity [10][5]. Some of the tests were repeated to ensure repeatability. For tests A and B, the scour profiles were obtained at 1, 3, 6, 12, 24, 48 and 72 hours. 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 [10][5]. This test was discontinued beyond three hours.

Laser Doppler anemometry is the measurement of fluid velocity by detecting the Doppler frequency shift of laser light that has been scattered by small particles moving with the fluid. A typical system consists of a laser source, an optical arrangement, a photo-detector that converts light into electrical signals and a signal processor. The LDA system used in these tests was powered by 300-mW argon-ion laser. The optical systems include a Bragg cell, a beam expansion unit and a 500-mm focusing lens. The LDA system has been used in several other studies and avoided here for brevity [10][5][11].

The sand surface was leveled to provide zero-slope and saturated prior to the start of the test. Water was filled in the flume to the required level. Preliminary tests were performed for each flow condition to ensure the use of proper operating condition to achieve the required flow field.

For each test type, the run was continued to ensure that the equilibrium scour condition has been attained. The scour profiles were obtained using a point gauge fit with an electronic display unit after stopping the flow and slowly draining the water from the bed. The point gauge was set on a traverse which can be moved in the longitudinal as well as the transverse direction. The point gauge electronic display could be read up to the nearest 0.01 mm. Maximum scour dimensions were measured with respect to the original bed level. Volume of scour and ridge were calculated analytically from profile data. Digital photographs were taken after each test run. For some tests, sand particles were collected from selected locations in the scoured region. More details on test procedure are available in [5].
IV. RESULTS AND DISCUSSION

A. Velocity Profile

Figures 4a – 4c show the longitudinal mean velocity measurements at three different sections at various instants from the start of the test. The velocity measurements were carried out along the plane containing the nozzle axis. Figure 4a shows that the velocity is uniform close to the nozzle exit and is similar over the entire test duration. At the second (Figure 4b) and third sections (Figure 4c), negative values of velocity occur at farther distances from the bed indicating the presence of a reverse flow closer to the free surface. The figures also indicate 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 are consistent with the development of the scour profiles.

B. Volume Balance of Scour and Ridge

Table 1 shows the comparison of scour volume with ridge volume. Volume was calculated from the scour/ridge contours. Scour profiles were obtained every 50 mm in longitudinal (x) direction and every 25 mm in transverse (y) direction. From the table it is apparent that scour volume increases with time and the equilibrium stage is reached after 48 hours for Test A. This is very similar to the time development of scour profiles (Figure 4.4 in [5]). For 72 hours test of Test B, there is a significant increase in scour volume when compared with t = 48 hours. This is due to the expansion of the scour hole perimeter laterally at H/b_o = 4 and at 72 hours. The 72 hours 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. 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 [10][5]. Similar to the scour profile, the volume of scour is consistently larger (albeit only slightly) for $H/b_0 = 6$ compared with $H/b_0 = 4$.

### TABLE I

**Comparison of Scour Volume with Ridge Volume for Various Tests**

<table>
<thead>
<tr>
<th>TEST #</th>
<th>DURATION (hr)</th>
<th>SCOUR ($m^3$)</th>
<th>RIDGE ($m^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>0.018</td>
<td>0.020</td>
</tr>
<tr>
<td>A</td>
<td>3</td>
<td>0.022</td>
<td>0.026</td>
</tr>
<tr>
<td>A</td>
<td>6</td>
<td>0.025</td>
<td>0.028</td>
</tr>
<tr>
<td>A</td>
<td>12</td>
<td>0.029</td>
<td>0.031</td>
</tr>
<tr>
<td>A</td>
<td>24</td>
<td>0.036</td>
<td>0.034</td>
</tr>
<tr>
<td>A</td>
<td>36</td>
<td>0.037</td>
<td>0.040</td>
</tr>
<tr>
<td>A</td>
<td>48</td>
<td>0.042</td>
<td>0.045</td>
</tr>
<tr>
<td>A</td>
<td>72</td>
<td>0.041</td>
<td>0.044</td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>0.017</td>
<td>0.019</td>
</tr>
<tr>
<td>B</td>
<td>3</td>
<td>0.021</td>
<td>0.023</td>
</tr>
<tr>
<td>B</td>
<td>6</td>
<td>0.025</td>
<td>0.027</td>
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<tr>
<td>B</td>
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<tr>
<td>B</td>
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</tr>
<tr>
<td>B</td>
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<td>0.043</td>
<td>0.036</td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>0.018</td>
<td>0.018</td>
</tr>
<tr>
<td>C</td>
<td>3</td>
<td>0.023</td>
<td>0.031</td>
</tr>
</tbody>
</table>

### C. Mapping of Deposition of Sand Particle Size

Visual observations of the scoured region indicate a preferential pattern of deposition and particle separation by size. From visual observations five different zones of sand particle deposition were noticed. To study the preferred deposition pattern, sand was carefully scrapped from the top layer of the scoured bed. The different zones are indicated in Figure 5.a.

1. **Zone A**: This zone is formed around the juncture of edge of scour hole and the beginning of ridge and commenced to occur after 20 ~ 24 hours of scouring. With every turbulent burst the sand particles were moved downstream and when unable to cross over the ridge, the finest particles rolled back towards this zone.

2. **Zone B**: This region occurs from the tip of ridge and through the downstream slope. The particles of this zone are coarser than the original bed. The thickness of this zone varies from 12 mm to 25 mm and is larger than the other zones.

3. **Zone C**: This region occurs on the upstream face of the ridge and extends to the ridge top. This zone is very thin with 5 to 10 mm thickness and very fine particles were underlain below this zone.

4. **Zone D**: This is a sandwiched region between Zone B and Zone C and occurs mostly on the flattened part of the ridge. The thickness of this zone varies from 10 to 20 mm. The particles are coarser than zone C but finer than zone B.

5. **Zone E**: This zone is limited in thickness and has very large particles that are sparsely distributed over the entire region.

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**Figure 5**: Mapping of sand deposition. a) Definition Sketch for Mapping of Deposition. b) Particle Size Distributions for Different Zone
Figure 5b shows the particle size distribution for the different zones. Other than the very scattered thin layer of coarest particles (Zone E) and deposition of finest particles (Zone A), it is evident that there is a significant re-distribution of particles. The coarser particles were located on the downstream side of the ridge. This is contrary to the observation of [12], who noticed the deposition of finer particles on the downstream slope of the ridge. This is a further indication of the complexity of interaction between the flow and the sand particles.

V. CONCLUSIONS

The present study was carried out to understand the progression of the scour hole by a three-dimensional jet at different tailwater depth. The main findings are summarized as follows:

1. The finer particles constituting the original sediment mixture were deposited at the sides of the start of the ridge.
2. The top layer particles are coarser towards downstream of the ridge and the coarsest particles are deposited on the down slope of ridge.
3. Very fine particles were underlain below the top layer for the region on the upstream face of the ridge to the ridge top.
4. Velocity stays uniform close to the nozzle exit and is similar over the entire test duration.
5. Velocity measurements do not change significantly at the sections farther away from the nozzle as scour progresses.
6. At the sections farther away from the nozzle, negative values of velocity occur at farther distances from the bed indicating the presence of a reverse flow closer to the free surface.
7. Volume of scour increases with increase of time. However, for 72 hours test of Test B (H/b₀ = 4), there is a significant increase in scour volume when compared with t = 48 hours. This is due to the expansion of the scour hole perimeter laterally at H/b₀ = 4 and at 72 hours.
8. The volume of scour is consistently larger (albeit only slightly) for H/b₀ = 6 compared with H/b₀ = 4.

REFERENCES