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JET FLIPPING AND SCOURING CHARACTERISTICS
BY 2-D WALL JETS

ER JENN WEI

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

COLLEGE OF ENGINEERING
NANYANG TECHNOLOGICAL UNIVERSITY
2011/2012
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A Final Year Project presented to the Nanyang Technological University in partial fulfillment of the requirements for the Degree of Bachelor of Engineering

2011/2012
ABSTRACT

In this project, the result of an experimental investigation on scour of non-cohesive and uniform sediment beds downstream of a sluice gate, due to a submerged two-dimensional wall jets issuing from a sluice opening were presented. All the experiments were conducted under high flow submergence with or without an apron. The jet issued from the sluice gate and impinging on an erodible bed can produce two very different flow patterns, depending on the experimental conditions. The observations and characteristics of the sediment bed downstream of the sluice gate during the scouring process was being described and explained in this report.

The first is a bed jet where the jet always impinges towards the sediment bed with digging action occurring at the sediment bed. The second is a surface jet where the jet axis points towards the water surface after issuing from the sluice gate. The second flow pattern may drag the sediments in the downstream side of the scoured zone back to the upstream filling up the scour hole in the process. However, it also caused the maximum scour depth to be located closer to the sluice structure which may impose greater threat than the bed jet. These two flow patterns, i.e., digging with bed jet and filing with surface jet, occur alternatively and over many dig-fill cycles throughout the duration of the scouring process.

The results on the effect of the apron length on the jet flipping phenomenon showed that the duration of the filling phase is generally longer than the digging phase with longer apron length. The duration to complete one dig-fill cycle also decreases with increases in apron length. For apron length as a ratio of the jet opening, L/d_o greater than 35, there is no jet flipping and only bed jet was observed. Similarly, when there is no apron, i.e., L/d_o is equal to zero, there is no jet flipping in the scour hole.

Based on the results, it was found that generally the maximum scour depth, d_se-dig during the digging phase and minimum scour depth, d_se-fill during the filling phase increase as the apron length decreases. The difference between the d_se-dig and d_se-fill is larger with increases in jet discharge. At the downstream of the scour hole, the sand ridge formed is affected by the cyclical digging and filling action. There are two sand ridges formed with different heights during the dig-fill cycles. For apron length ratio, L/d_o lower than 2, the height of sand ridge during the filling phase is higher than that during the digging phase.

The threshold of jet-flipping with respect to a range of tailwater depths and jet discharges rates was also investigated. Preliminary results on this aspect showed that for a particular apron length ratio and jet discharge, there is a critical tailwater whereby jet flipping will not occur if
its value is above the critical value and vice versa. Similarly for a particular apron length ratio and tailwater, there is a critical jet discharge such that jet flipping will occur if its value is higher than the critical value and vice versa.
ACKNOWLEDGEMENTS

The author would like to acknowledge and express his utmost gratitude to Dr. Lim Siow Yong, Project Supervisor, for his invaluable advice and professional guidance throughout the project who has made the completion of his project a success. The assistance of Ms. Xie Chen in the preparation of this report is highly appreciated. In addition, the author would also like to thank Mr. Lim Kok Hin, Mr. Foo Shiang Kim, Mr. Chia Key Huat, Mr. Fok Yew Seng and Mr. Syed Alwi Bin Sheikh Bin Hussien Alkaff for providing the necessary laboratory support and assistance while conducting the experiments.
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LIST OF SYMBOLS

\( d_h \) = height of ridge at any time

\( d_{h1} \) = height of ridge form from previous cycle or 1st cycle

\( d_{h2} \) = height of ridge form in current cycle

\( d_{1H-dig} \) = height of ridge at equilibrium state during first digging phase

\( d_{1H-fill} \) = height of ridge at equilibrium state during first filling phase

\( d_s \) = depth of the movable plate below apron level

\( d_{se} \) = scour depth at equilibrium state

\( d_{se-dig} \) = maximum depth of scour at equilibrium state during each digging phase

\( d_{se-fill} \) = minimum depth of scour at equilibrium state during each filling phase

\( d_{1se-dig} \) = maximum depth of scour at equilibrium state during first digging phase

\( d_{1se-fill} \) = minimum depth of scour at equilibrium state during first filling phase

\( d_{st} \) = scour depth at any time

\( d_0 \) = sluice gate opening or height of jet opening

\( d_i \) = grain diameter corresponding to \( i\% \) finer

\( d_{50} \) = median grain diameter corresponding to 50% finer

\( \sigma_g \) = standard deviation of particle size distribution

\( g \) = acceleration due to gravity

\( L \) = length of rigid apron

\( \mu \) = viscosity of water

\( \rho \) = density of water

\( S \) = specific gravity of sediment

\( \rho_s \) = density of sediment
$H_t = \text{tailwater depth}$

$Q = \text{Flowrate or Discharge}$

$Cc = \text{contraction coefficient}$

$u_0 = \text{mean jet velocity}$

$Fr = \text{Froude number}$

$F_0 = \text{Densimetric Froude number}$

$L = \text{length from apron edge}$

$L_R = \text{length from apron edge to peak of dune at equilibrium state}$

$L_{se} = \text{length from apron edge to section of maximum scour depth}$

$L_m = \text{length of the scour hole at equilibrium state}$

$\Delta d_s (\%) = \% \text{scour depth difference of } d_{se-dig} \text{ and } d_{se-fill}$

$\Delta d_h (\%) = \% \text{ridge height difference of } d_{1H-dig} \text{ and } d_{1H-fill}$

$t = \text{duration of scouring}$

$t_0 = \text{average time to complete one cycle of digging-filling phase}$

$t_{d0} = \text{average digging time}$

$t_{f0} = \text{average filling time}$
CHAPTER 1  INTRODUCTION

1.1 Purpose

This report is to write up on the past 1 year experimental study, analysis and database of the author’s Final Year Project. The main objective is to observe and study the scouring characteristic downstream of a sluice gate with an apron which consists of two separate phases, digging and filling phase.

1.2 Background

Water jet discharge through hydraulic structure such as sluice gate will erode the unprotected channel bed downstream of the hydraulic structure. This is a common incident in hydraulic engineering. The water jet issuing from sluice gate has excessively high velocity hence high kinetic energy and capable of causing scour hole. The excessive erosion below unprotected outlet is one of the factors that lead to the instability or failure of the hydraulic structure.

In most of the cases, the digging phase will reach equilibrium after some period. However, under certain flow conditions, the equilibrium of digging phase may not be reached and the jet action will rapidly flip from bed to water surface. This is the commencement of filling phase. The switching of jet direction is called jet flipping phenomenon and these two phases will occur alternative to each other.

Scouring development for digging phase consists of three stages, an early stage with a rapid rate of scouring; a development stage with a slower rate of scouring; and late stage with a less observable scouring activity. At the late stage, a pseudo-equilibrium or asymptotic condition is attained, where the scour hole will retain its profile, and has no significant observable changes over time. On the other hand, the scour recovery for filling phase has a relatively stable rate of filling. However, the position of maximum scour depth move closer towards the hydraulic structure, hence it might pose a greater threat to the stability of the hydraulic structure.

The investigation of the changes and characteristics of scour development in the digging as well as filling phase is necessary. A series of experiments was carried out to find the effect of apron length on the scour development during the digging and filling phases for flow below a sluice gate and over an erodible bed.
1.3 Scope of Study

The objectives of the present work are:

1. To observe the development of the scouring process, and scouring characteristics with jet flipping caused by a two-dimensional horizontal jet discharging from a sluice gate.
2. To study the effect of apron length (L) and discharge (Q) in the formation of the scour hole and ridge height during the digging and filling phases.
3. To find out the effects of different parameters such as tailwater depth and flowrate on the occurrence of jet flipping.

1.4 Organization of the report

This report consists of 5 chapters. The first chapter is an introduction to the background of the present study. The second chapter discusses the relevant studies carried out in this field. In Chapter Three, the methodology of the experiments is introduced. Chapter Four focuses on the discussion and analysis of the experimental results. The last chapter is the conclusions of the present study.
CHAPTER 2   LITERATURE REVIEW

2.1 Jet Flipping Phenomenon

Generally the evolution of a scour can be divided into 4 phases, initial phase, development phase, stabilization phase and equilibrium phase (Hoffmans and Verheij 1997). There are other classifications of the scour phases with the same basic concept. However, some researchers found the equilibrium stage would never arrive under certain hydraulic conditions and a jet flipping phenomenon was observed during the scouring process (Johnston 1990; Balachandar and Kells 1997)

2.1.1 Occurrence of Jet Flipping

The tailwater ratio ($H_t/d_o$) or tailwater depth is the main parameter of jet flipping and some researchers have used jet flipping as the distinction between high and low submergence. Balachandar et al. (2000) and Bey et al. (2007) defined high jet submergence as a state where no flipping of the jet between the surface and bed was observed. Most of the researchers found that jet flipping only occurred at low submergence.

Ali and Lim (1986) studied the situation where the tailwater depth was between these two extremes. They showed that in large tailwater depth ($H_t/d_o > 10$), an asymptotic depth of scour was reached in a continuous manner. However, at smaller tailwater depth ($H_t/d_o < 5$), the data suggested that the scour hole did not undergo a continuous growth to the equilibrium stage. Johnston (1990) studied the plane jet emerged through a slot and the jet flipping was only observed under shallow submergence ($D/d_o = 2.33$ and $3.48$, $D$ is defined as vertical distance from jet centre line of the slot to the free surface and $d_o$ is the slot width).

In Balachandar and Kells (1997)’s work, 1 cm of apron length was applied downstream of the sluice gate, and the jet flipping only occurred under shallow jet submergence ($H_t/d_o = 6.5$). Deshpande, Balachandar and Mazurek (2007) confirmed the jet flipping phenomenon occurred in low submergence ($H_t/d_o = 4$) by measuring the velocity.

However, in the present study, jet flipping phenomenon was found under high submergence $H_t/d_o = 12.7$, which means the shallower submergence ratio was no longer the only reason to induce jet flipping. The occurrence of jet flipping might be related to the flow direction, jet exit velocity profile and the presence of apron length. The influence of flow direction and jet exit velocity profile will be further discussed in Section 2.2.1.
2.2 Scour Downstream of a Sluice Gate

Several researchers had studied the scouring process downstream of a sluice gate (Rajaratnam 1981; Rajaratnam and Macdougall 1983; Nik Hassan and Narayanan 1985; Ali and Lim 1986; Balachandar and Kells 1997; Karim and Ali 2000; Bey, Faruque et al. 2007; Deshpande, Balachandar et al. 2007; Dey and Sarkar 2007; Lim and Xie 2011). Dey and Sarkar (2006 & 2007) presented the scaling of time variation of scour depth by an exponential law and the effect of apron length, densimetric Froude number, sediment size, sluice opening as well as tailwater depth to the equilibrium scour depth.

Rajaratnam and MacDougall (1983) studied the erosion of sand bed by plane water wall jets with minimum tailwater depth and Deshpande, Balachandar and Mazurek (2007) had carried out the difference in scour profile due to 3 kind of stratup conditions and the effect of high submergence to the local scour.

2.2.1 Velocity Profile in the Scour Region

The velocity profiles and distribution in the scour region were used by researchers to understand and explain the characteristics of the scouring and refilling process. Nik Hassan and Narayanan (1985) measured the mean velocity distributions after the scour reached equilibrium at the later stages and expressed the maximum velocity as a function of the distance along the apron:

\[
\frac{U_m}{U_1} = 3.83 \left( \frac{x_L}{y_1} \right)^{-0.5}
\]

(2.1)

where \(U_m = \) the maximum velocity

\(X_L = \) longitudinal distance from the sluice gate

\(y_1 = \) thickness of the jet at the vena contracta

\(U_1 = \) average velocity through vena contracta

They also expressed the rate of the scour with respect to time using a semi-empirical analysis as follows:

\[
\frac{1}{(n + 1)} \frac{dh}{dt} = \beta \left[ \frac{U_m^2}{g(s - 1)h} \right]^n \left[ \frac{U_m^2}{g(s - 1)D} \right]
\]

(2.2)

\(h = \) maximum scour depth

\(\beta = \) a dimensionless coefficient

From the above equation, \(n = 2\) gives the best shape of the curve of scour depth versus time.
Kurniawan and Altinakar (2002) measured the velocity distribution of the scour hole with (Fig 2.1 Exp C) and without (Fig 2.1 Exp B) apron by using Acoustic Doppler Velocity Profiler (ADVP). For Exp B, without apron, the measurement shows that the flow issued from the sluice gate impinges on the bed. In present study, this is called bed jet and it occurs in digging phase. When apron is applied (Exp C), the jet is deflected towards surface instead of impinged to the bed, this is named as surface jet in present study and it occurs in filling phase.

The results were in a good agreement with Balachandar and Kells (1997) which observed the flow pattern by dye injection (Fig 2.2). From Fig 2.1 and 2.2, two recirculation regions are observed in both phases.

Figure 2.1 Magnitude of velocity vector in the x-z plane (Kurniawan and Altinakar 2002)
2.2.2 Effect of Tailwater Depth

The tailwater depth, $H_t$, is an important parameter in the scour depth during equilibrium or pseudo equilibrium stages. Generally, the equilibrium scour depth increases with decreases in tailwater depth.

However, under shallow tailwater conditions, the process of scour development is more complex compared to relatively deep tailwater conditions. Ali and Lim (1986) studied the scour due to two and three-dimensional submerged wall jets in shallow tailwater conditions. They found that there was a critical tailwater depth, beyond which scour depth tends to increase irrespective of the increase of tailwater depth.

Rajaratnam and Macdougall (1983) considered the erosion of sand beds by plane turbulent water wall jets when the tailwater depth was approximately equal to the jet thickness. The results of the experiment showed the maximum depth of erosion were smaller than usual cases where the tailwater depth was larger (Figure 2.3). From Figure 2.4, it indicates the maximum scour section is located further downstream from the gate. In this case, there was no formation of sand ridge downstream of the scour hole, all the suspended material was transported by the flow out of the test section of the flume.

Figure 2.2 Schematic view of the flow field during (a) digging phase and (b) refilling phase (Balachandar and Kells 1997)
Deshpande, Balachandar and Mazurek (2007) studied the effect of submergence to the scour. Figure 2.5 shows the centreline scour profiles for three tailwater depths ($y_t/b_o = 8, 12, 20$). The profiles for two larger tailwater ratio ($y_t/b_o = 12, 20$) are similar. However, for smaller tailwater ratio ($y_t/b_o = 8$), scour depth increase with decreasing submergence.
2.2.3 Effect of Apron Length

Dey and Westrich (2003) had studied the scouring of a cohesive bed downstream of an apron due to a submerged horizontal jet issuing from a sluice opening. They had used a relatively longer apron length (> 0.30 m) to conduct the experiment. In Table 2.1, the experiments have done in different set of parameters and the result of scour depth is shown.

Table 2.1 Experimental data and results (Dey and Westrich 2003)

<table>
<thead>
<tr>
<th>Run number</th>
<th>L (m)</th>
<th>b (m)</th>
<th>U_j (m/s)</th>
<th>h (m)</th>
<th>\Delta h (m)</th>
<th>d_e (mm)</th>
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<tr>
<td>1</td>
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<td>0.02</td>
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<td>2</td>
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<td>0.02</td>
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<td>0.127</td>
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</tr>
<tr>
<td>3</td>
<td>0.45</td>
<td>0.02</td>
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<td>0.124</td>
<td>0.056</td>
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</tr>
<tr>
<td>4</td>
<td>0.45</td>
<td>0.03</td>
<td>0.025</td>
<td>0.132</td>
<td>0.044</td>
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</tr>
<tr>
<td>5</td>
<td>0.45</td>
<td>0.04</td>
<td>0.645</td>
<td>0.121</td>
<td>0.024</td>
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</tr>
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<td>9</td>
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<td>10</td>
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<td>12</td>
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<td>0.484</td>
<td>0.120</td>
<td>0.017</td>
<td>3.0</td>
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The effect of apron length can be seen by comparing a few sets of data in Table 2.1, for example, Run 1, 2 and 7, Run 3 and 8, Run 4 and 9, Run 5 and 10. These sets of data show that deeper scour depths have been observed by decreasing apron length.

In Dey and Sarkar (2006)’s work, again, their conclusion was the equilibrium scour depth increased with decreased in apron length. Besides, they had studied the reduction of scour depth by placing a launching apron downstream of the rigid apron, and the results showed that the reduction could reach a maximum of 57.3%.
CHAPTER 3 EXPERIMENTAL SETUP AND PROCEDURES

3.1 Setup

Experiments were performed in the Hydraulics Laboratory at Nanyang Technological University. A deep glass-wall flume of length 8m, width 0.3m, and height 0.6m (Figure 3.1) with a recirculation arrangement of water was used for the experimentation. The glass-wall on both sides was provided for visual observations. A solid platform was mounted to simulate a rigid apron over which a vertical sharp edge sluice gate was installed. The sluice gate can be slide to any location along the apron, and the opening size can be changed. This arrangement facilitates the study of the effect of apron length on scouring characteristic downstream of a sluice gate. The length of apron (L) is measured from the right edge of apron to the tip of the vertical sharp edge sluice gate.

In sediment bed (Figure 3.2), uniform green sand with median grain diameter \(d_{50}\) of 0.73 mm was used and the geometric standard deviation \(\sigma_g\) was 1.12. The sand bed was 20.6 cm thick and was heightened with the rigid apron.

![Figure 3.1 Schematic Layout of Experimental Flume](image)
Figure 3.2 Initial setting of sediment bed

Water was pumped from the water storage tank into the inlet of flume by a series of pipes. The pipes were arranged in a honeycomb to reduce the turbulence of the incoming flow. The sand bed was connected with a sediment box to retain or trap the sand. The flow from the outlet or tailgate of the flumes was collected by a storage tank for recirculation within the flow circuit.

A high resolution webcam connected to a computer was used to record the scouring process continuously for a long period of time. Video software was used to automatically save the recorded video images every hour. This set up require less storage volume and good for long duration record of the scouring process. The video recording used up to 2 GB data storage per day and it allowed the long period experiments to be viewed subsequently. Most importantly, this set up allowed the author to observe whether jet flipping occurred during the scouring process and decided the duration of the experiments.

3.2 Bed Sediment - Sieve Analysis

Soil materials from the sediment bed, maybe classified as: non-cohesive sediments and cohesive sediments. As the term implies, non-cohesive sediments are those consisting of discrete particles, the movement due to a given erosion forces, depends only on particle properties, e.g. shape, size, density, and the relative position of the particle with respect to surrounding particles. The present study will focus on the non-cohesive sediment and the same soil material is used for all the experiments.

Unified Soil Classification System (USCS) is used to quantify the percentage of distribution of different grain sizes. Grain size distribution, also known as gradation, is widely used for soil classification systems. It is a plot of the distribution of various grain sizes in a soil sample against the function of the percentage by weight passing a given sieve size. Gradation are
determined by sieve analysis, where soil sample is dried in oven and poured into a series of sieves stacked in descending sieve opening size. The sieves are then vibrating using a mechanical shaker and the retention soil on each sieve is weighed. Table 3.1 and Figure 3.3 show the result of sieve analysis of the soil material used in sediment bed.

The standard deviation of the grain size distribution, $\sigma_g$, is estimated using:

$$\sigma_g = \sqrt{\frac{d_{84}}{d_{16}}}$$

where $d_{84}$ and $d_{16}$ are the grain diameter in 84% and 16% passing respectively.

The sediment will be categorized as uniform when $\sigma_g < 1.5$, and non-uniform when $\sigma_g \geq 1.5$.

From Figure 3.3, the mean sediment size $d_{50} = 0.73$ mm, $d_{84} = 0.82$ mm and $d_{16} = 0.65$ mm. Thus, $\sigma_g = 1.12$ for the soil used and it can be classified as uniform. The specific gravity of the sand is 2.65.

Coefficient of uniformity, $C_u$, and coefficient of curvature, $C_c$, are the two parameters used in Unified Soil Classification System (USCS) to determine the soil gradation, i.e. well or poorly graded, high or low plasticity. Eq. 3.2 and 3.3 represent the equation for coefficient of uniformity, $C_u$ and coefficient of curvature, $C_c$

$$C_u = \frac{d_{60}}{d_{10}}$$

$$C_c = \frac{d_{30}^2}{d_{60} \times d_{10}}$$

where $d_{10}$, $d_{30}$ and $d_{60}$ are the grain diameter in 10%, 30% and 60% passing respectively.

From Figure 3.3, $d_{10}$, $d_{30}$ and $d_{60}$ are 0.61 mm, 0.70 mm and 0.78 mm. Thus $C_u = 1.28$ and $C_c = 1.03$. From Table 3.2, the sand used in bed sediment is poorly graded sand (mark in red circle).
Figure 3.3 Particle size distribution of sediment used

<table>
<thead>
<tr>
<th>Sieve size (µm)</th>
<th>Mass of sieve (g)</th>
<th>Mass of sieve &amp; sediments (g)</th>
<th>Mass Retained (g)</th>
<th>Retained %</th>
<th>Cumulative Retained %</th>
<th>Finer %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1180.0</td>
<td>401.200</td>
<td>401.200</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>100.00</td>
</tr>
<tr>
<td>850.0</td>
<td>355.700</td>
<td>414.800</td>
<td>59.100</td>
<td>12.256</td>
<td>12.256</td>
<td>87.744</td>
</tr>
<tr>
<td>710.0</td>
<td>351.500</td>
<td>618.600</td>
<td>267.100</td>
<td>55.392</td>
<td>67.648</td>
<td>32.352</td>
</tr>
<tr>
<td>600.0</td>
<td>348.200</td>
<td>496.600</td>
<td>148.400</td>
<td>30.776</td>
<td>98.424</td>
<td>1.576</td>
</tr>
<tr>
<td>500.0</td>
<td>342.000</td>
<td>349.400</td>
<td>7.400</td>
<td>1.535</td>
<td>99.959</td>
<td>0.041</td>
</tr>
<tr>
<td>425.0</td>
<td>326.400</td>
<td>326.500</td>
<td>0.100</td>
<td>0.021</td>
<td>99.979</td>
<td>0.021</td>
</tr>
<tr>
<td>300.0</td>
<td>313.400</td>
<td>313.500</td>
<td>0.100</td>
<td>0.021</td>
<td>100.00</td>
<td>0.000</td>
</tr>
<tr>
<td>250.0</td>
<td>304.400</td>
<td>304.400</td>
<td>0.000</td>
<td>0.000</td>
<td>100.00</td>
<td>0.000</td>
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<tr>
<td>Pan</td>
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<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>100.00</td>
<td>0.000</td>
</tr>
<tr>
<td>Sum</td>
<td></td>
<td></td>
<td>482.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.3 Procedures

First, adjust the tailwater depth to a determined level. Then, switch off the pump in order to flatten the sand bed profile. Before activate the pump, cover the sand bed profile with a metal plate to prevent the bed from being disturbed by the jet when tailwater depth is under the required depth. After that, turn on the pump and wait the tailwater depth reaches to the required height. At the same time, start the webcam to record the flow and scouring action. Once the tailwater depth reaches the required height, remove the plate gently to reduce the disturbance of metal plate to the sand bed. The sediments or sand particles start to move and a scour hole is formed immediately downstream of the gate. Normally digging phase is observed at the initial of the experiments. The development of the scour is recorded by the webcam, and a stop-watch is used to record the scouring duration as a back-up. The scour profile changes with respect to
time and the hole could be observed to lengthen and deepen during the digging phase. Scour profiles at different time are plotted on the glass-wall as a back-up.

Generally, the scouring or digging rate is rapid at the initial period. Then the scouring rate slows down after a certain time and reaches to a pseudo equilibrium state. The duration to reach the pseudo equilibrium state is dependent on the hydraulics conditions. In some cases, a filling phase will take over the digging phase (jet flipping occur) and the sand is filled back at a steady rate, this is a cyclical process when jet flipping occurs. Normally, experiments associated with jet flipping will run for 2 to 4 weeks, but for some cases, a 7 or 10 days period is enough for the experiments to reach the equilibrium state.

Figures 3.4 and 3.5 show a definition sketch of the digging and filling process. In Chapter 4, the definition of symbols in analysis and discussion will be based on these two sketches.
CHAPTER 4 RESULTS AND DISCUSSIONS

4.1 General Observations and Characteristics on Scouring Process with Jet flipping

Under certain flow conditions (see Table 4.1) there would be jet flipping, where the scouring process might not reach an equilibrium and water jet suddenly flipped from the bed to surface (Lim and Xie 2011; Ling 2011). During digging process, the direction of discharged water jet was unstable (Lim and Chiew 2001). The jet impingement point was oscillating in horizontal direction along the scour hole and the mean location of impingement was close to maximum scour depth (Bey, Faruque et al. 2007). Figure 4.1 shows the jet impingement point and flow direction after contact with the scour hole in the digging phase. Blue dye was used to indicate the water jet streamline. In Figure 4.1(a), concentrated blue dye is observed in the opening of sluice gate, followed by Figure 4.1(b) which shows the blue dye reaching the location of maximum scour depth. Then, the water jet spreads into two directions, a portion of water flow back to the direction of sluice gate opening and formed a recirculation region. This recirculation streamline is shown as yellow line in Figure 4.1(c). Another portion of water flow along downstream of the maximum scour depth and is indicated as red line in Figure 4.1(c). This portion of flow later will divide into two parts; the purple line in Figure 4.1(d) shows the portion of water that flows over the sand ridge and continues to the downstream of the sand ridge. The formation of sand ridge downstream of the scour hole was mainly caused by the accumulation of sand particles that were transported by this flow. The dark blue line in Figure 4.1(d) shows the water that flow back to the upper part of sluice gate and form another recirculation region. Therefore, at the digging process, two recirculation regions were formed and this observation is quite similar to the results of velocity measurements by Kurniawan and Altinakar (2002).

Throughout the entire process, the water jet is attached to the bed after releases from the sluice gate opening; this is defined as the bed jet. During the digging phase, water surface is very clam (see Figure 4.1).

After some period of continuous digging, the scour reached a pseudo-equilibrium state and the bed profile had no significant changes in geometry. At this stage, the bed jet suddenly would flip upwards and transformed into a surface jet and the water surface started to become very choppy. This was the indication of the commencement of the filling phase. During the filling process, the sand particles in sand ridge were filled back to the scour hole. The water flow
direction is shown in Figure 4.2. From Figure 4.2 (a), water jet that eject from the sluice gate flow to the water surface directly. After that, the water jet spreads into two directions, a small part of water flowed back to the upper part of sluice gate and formed a recirculation region. The other part of water flowed to the direction of sand ridge. Then, when the water flowed further downstream, it splits into two portions before it reached the maximum ridge height. The first portion of water flowed downward along the sand bed and ‘dragged’ the sand particles on the sand ridge back to the scour hole. This formed the second recirculation region in the filling phase. On the other hand, the second portion of water continued to flow over the sand ridge. In preliminary conclusion, there are two recirculation regions found in both phases, where the second recirculation region in filling phase is very important as it participates in the deposition of sand particles back to the scour hole.

Figure 4.1 Jet impingement point and flow direction in digging phase

Figure 4.2 Water flow direction in filling phase
Table 4.1 Summary of the experiments conducted for 2-D jets

<table>
<thead>
<tr>
<th>Run</th>
<th>( t_o ) (min)</th>
<th>L (mm)</th>
<th>( Q ) (L/s)</th>
<th>( H_i ) (cm)</th>
<th>( U_o ) (m/s)</th>
<th>( d_{so-ff} ) (cm)</th>
<th>( \Delta d_{ff} ) (%)</th>
<th>( d_{so-ff}/d_0 )</th>
<th>( H/d_o )</th>
<th>( F_o )</th>
<th>No. of flipping cycles / scour duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>257</td>
<td>210</td>
<td>2.128</td>
<td>12.7</td>
<td>0.71</td>
<td>6.5</td>
<td>4.6</td>
<td>29</td>
<td>6.5</td>
<td>12.7</td>
<td>6.53</td>
</tr>
<tr>
<td>14</td>
<td>23</td>
<td>300</td>
<td>2.128</td>
<td>12.7</td>
<td>0.71</td>
<td>3.9</td>
<td>2.8</td>
<td>28</td>
<td>3.9</td>
<td>12.7</td>
<td>6.53</td>
</tr>
<tr>
<td>15</td>
<td>936</td>
<td>150</td>
<td>2.128</td>
<td>12.7</td>
<td>0.71</td>
<td>8.1</td>
<td>5.1</td>
<td>37</td>
<td>8.1</td>
<td>12.7</td>
<td>6.53</td>
</tr>
<tr>
<td>17</td>
<td>44</td>
<td>210</td>
<td>3.33</td>
<td>11</td>
<td>1.11</td>
<td>7.2</td>
<td>2.8</td>
<td>61</td>
<td>7.2</td>
<td>11</td>
<td>10.21</td>
</tr>
<tr>
<td>18</td>
<td>31</td>
<td>210</td>
<td>2.5</td>
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<td>0.83</td>
<td>4.4</td>
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<td>6.53</td>
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<td>90</td>
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<td>0.71</td>
<td>9.6</td>
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<td>46</td>
<td>5.2</td>
<td>12.7</td>
<td>6.53</td>
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<tr>
<td>21</td>
<td>2349</td>
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<td>12.7</td>
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<td>12</td>
<td>8</td>
<td>33</td>
<td>12</td>
<td>12.7</td>
<td>6.53</td>
</tr>
<tr>
<td>22</td>
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<td>10</td>
<td>2.128</td>
<td>12.7</td>
<td>0.71</td>
<td>13.8</td>
<td>10.4</td>
<td>25</td>
<td>1.4</td>
<td>12.7</td>
<td>6.53</td>
</tr>
<tr>
<td>52</td>
<td>27</td>
<td>300</td>
<td>2.128</td>
<td>16</td>
<td>0.709</td>
<td>4.38</td>
<td>3.02</td>
<td>31</td>
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<td>16</td>
<td>6.526</td>
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<td>3524</td>
<td>90</td>
<td>1.818</td>
<td>12.7</td>
<td>0.606</td>
<td>8.47</td>
<td>7.1</td>
<td>16</td>
<td>8.47</td>
<td>12.7</td>
<td>5.575</td>
</tr>
<tr>
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<td>119</td>
<td>210</td>
<td>1.818</td>
<td>12.7</td>
<td>0.606</td>
<td>3.99</td>
<td>3.31</td>
<td>17</td>
<td>3.99</td>
<td>12.7</td>
<td>5.575</td>
</tr>
<tr>
<td>82</td>
<td>52</td>
<td>300</td>
<td>1.818</td>
<td>12.7</td>
<td>0.606</td>
<td>2.95</td>
<td>2.33</td>
<td>21</td>
<td>2.95</td>
<td>12.7</td>
<td>5.575</td>
</tr>
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<td>90</td>
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<td>7.9</td>
<td>42</td>
<td>13.6</td>
<td>16</td>
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<tr>
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<td>150</td>
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<td>16</td>
<td>0.833</td>
<td>9.17</td>
<td>7.9</td>
<td>14</td>
<td>9.17</td>
<td>16</td>
<td>7.666</td>
</tr>
</tbody>
</table>
4.1.1 Typical Centreline Scour Profiles with Jet flipping

Figures 4.3 and 4.4 show the typical shape of the centreline bed profiles during scouring process for a complete jet flipping cycle in Run 21 (1st Cycle). The profiles in Figure 4.3 constitute the digging phase by the attached bed jet and the total duration is around 253,000 seconds. The digging started with yellow lines; the duration of yellow lines was 100 seconds. Then the profile developed into green lines which had a total duration of the 900 seconds. In Run 21, the first 1,000 seconds had a rapid scouring rate which sees half of the total digging process completed with respect to its scour depth and scour width. After that, the profiles in blue lines correspond to the next 9,000 seconds and pink lines represent the profiles in the next 90,000 seconds. These two set of lines showed a lower scouring rate but the scouring process is still on going. Lastly, the late stage profiles were plotted in red lines with a total duration of 153,000 seconds. During this stage, only a few scouring activity was observed and a pseudo equilibrium state was reached.

After the last profile in Figure 4.3, the video recording showed that the jet suddenly flips towards the water surface and the filling phase begins. The surface jet caused the sand particles on sand ridge to roll down its slope and filled the scour hole. In Figure 4.4, the profiles from yellow to green, then blue and lastly pink gave the shapes of the scour hole during the filling process. It was noted that the height of ridge would increase at the initial stage before it decreased. This interesting observation will be explained in Section 4.4.1.

Duration of first filling process in Run 21 consumed about 36,000 seconds. At the end of filling phase, the ridge height was lower and the minimum scour depth was much shallower compare with the initial profile. In Run 21, the duration to reach a pseudo equilibrium stage for the filling phase is much shorter than the digging phase. The occurrence of digging and filling process was cyclical and many cycles had been documented over the recording period (see Table 4.1).
Figure 4.3 Shape of the centreline scour profiles for Run 21 during the first digging phase
Figure 4.4 Shape of the centreline scour profiles for Run 21 during the first filling phase

Scour hole being filled as time progresses

Height of sand ridge increases then decreases as time progresses
4.1.2 Time Scale of Dig and Fill Process

In Table 4.1, a time scale, \( t_0 \), which is the average time to complete one dig-fill cycle of digging and filling phase (Lim and Xie 2011), i.e. the time from the start of filling phase in \( i^{th} \) cycle to the end of digging phase in \( (i+1)^{th} \) cycle is proposed,

\[
t_0 = \frac{\sum_{i=1}^{n-1} (t_{fi} + t_{di+1})}{n-1}
\]

where \( n \) is the total number of digging-filling cycles recorded for an experiment or Run, \( t_{fi} \) and \( t_{di+1} \) are the duration of filling phase in the \( i^{th} \) cycle and duration of digging phase in the \( (i+1)^{th} \) cycle, respectively.

From the above equation, the duration of the digging phase in the first cycle is ignored in determining \( t_0 \). For most of the experiments that have jet flipping, it was observed that the period recorded for the digging time in the first cycle was much longer than the digging time of subsequent cycles. This is shown in the Figure 4.5, the digging time of first cycle are marked in circle. This difference in digging time can be explained as the scouring action for first digging begins from an original flatbed condition while the subsequent cycles start from the minimum scour depth, \( d_{se-fill} \) from the previous cycles’ filling phase. Therefore, extra time may be required for the first digging phase to dig to the maximum scour depth at equilibrium state during the first digging phase, \( d_{1se-dig} \). As a result, the first digging time may be ignored when calculating the \( t_0 \).

In addition, the average digging time, \( t_{do} \) and filling time, \( t_{fo} \) can be defined as follow,

\[
t_{do} = \frac{\sum_{i=1}^{n-1} (t_{di+1})}{n-1}
\]

\[
t_{fo} = \frac{\sum_{i=1}^{n-1} (t_{fi})}{n-1}
\]

And the relationship between \( t_0, t_{do} \) and \( t_{fo} \) can be expressed as,

\[
t_0 = t_{do} + t_{fo}
\]

4.2 Effect of Apron Length on Time Scale

Runs 13, 14, 15, 16, 20, 21, 22, 161 and 162 were conducted with the same tailwater depth (\( H_t = 12.7 \) cm), sluice gate opening (\( d_o = 10 \) mm), discharge (\( Q = 2.128 \) L/s), velocity (\( u_o = 0.71 \) m/s), Froude number (\( Fr = 2.267 \)) but different apron length (\( L \)) (Table 4.2). Figure 4.5 shows the total duration of each digging and filling phase along with the number of cycles for Runs that have jet flipping.
Figure 4.5 Time-sequence of each digging and filling phase for different apron lengths
Table 4.2 Summary of experimental data (d_o = 10 mm, H_t = 12.7 mm, Q = 2.128 L/s, u_o = 0.71 m/s, Fr = 2.267)

<table>
<thead>
<tr>
<th>Run No.</th>
<th>L (cm)</th>
<th>t_d0 (min)</th>
<th>t_f0 (min)</th>
<th>t_o/t_d0</th>
<th>t_o (min)</th>
<th>d_se-dig (cm)</th>
<th>d_se-fill (cm)</th>
<th>Δd_s (%)</th>
<th>Δd_h (%)</th>
<th>No. of flipping cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>0</td>
<td>--</td>
<td>--</td>
<td>0</td>
<td>None</td>
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<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>22</td>
<td>1</td>
<td>990</td>
<td>158</td>
<td>0.16</td>
<td>1149</td>
<td>13.8</td>
<td>10.4</td>
<td>25</td>
<td>-17</td>
<td>23 for 18 days</td>
</tr>
<tr>
<td>21</td>
<td>3</td>
<td>1612</td>
<td>737</td>
<td>0.46</td>
<td>2349</td>
<td>12</td>
<td>8</td>
<td>33</td>
<td>7</td>
<td>12 for 22 days</td>
</tr>
<tr>
<td>20</td>
<td>9</td>
<td>711</td>
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<td>1097</td>
<td>9.6</td>
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<td>46</td>
<td>21</td>
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</tr>
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<td>15</td>
<td>15</td>
<td>332</td>
<td>604</td>
<td>1.82</td>
<td>936</td>
<td>8.1</td>
<td>5.1</td>
<td>37</td>
<td>41</td>
<td>9 for 7 days</td>
</tr>
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<td>29</td>
<td>47</td>
<td>41 for 7 days</td>
</tr>
<tr>
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<td>2</td>
<td>21</td>
<td>10.50</td>
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<td>3.9</td>
<td>2.8</td>
<td>28</td>
<td>14</td>
<td>70 for 2 days</td>
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<td>--</td>
<td>--</td>
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<td>--</td>
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<td>--</td>
<td>--</td>
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<td>--</td>
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<td>--</td>
</tr>
</tbody>
</table>

Table 4.2 shows the summary of experimental data for all chosen Runs. For Runs 15, 13 and 14 which had longer apron length from 15 to 30 cm, the filling time was much longer than the digging time. According to the data, when the apron length became larger, the digging time decreases at a higher rate than the filling time over the recording period. Hence, more cycles were observed at a longer apron length and it could be as high as 35 cycles per day (Run 14).

As for shorter apron length, Runs 20, 21 and 22, where apron length was between 1 cm and 9 cm, the filling time was shorter than the digging time. When there was no apron and apron was longer than 35 cm (Runs 161 and 162), jet flipping phenomenon did not occur throughout the entire experiment.

Figure 4.6 shows the relationship between the ratio of average filling to digging time and the apron length ratio (L/d_o). This figure shows there are two critical apron lengths ratio, L_1/d_o and L_2/d_o that will affect the duration of digging and filling as well as the occurrence of jet flipping. When apron length ratio beyond L_2/d_o = 35, the effect of scouring was weak because of the long apron and no jet flipping was observed. This region is represented by the dash line, with t_o/t_d0 = 0 in Figure 4.6. For apron length ratio that is between L_1/d_o and L_2/d_o, the filling time was always lengthier than digging time, e.g. Runs 13, 14 and 15. Based on the graph, L_1/d_o is equal to 13.8 for t_o/t_d0 = 1 and when L/d_o < 13.8, the filling time is always shorter than the digging time and vice versa. More experiments should be conducted for 30 < L/d_o < 35 to establish the trend line.
Figure 4.6 Relationship of the ratio of the average digging to filling time, $t_f / t_d$ versus apron length ratio, $L/d_o$

Figure 4.7 shows the relationship between $t_o$, i.e. the average time to complete one full dig-fill cycle and the apron length ratio $L/d_o$. From the figure, $L/d_o = 3$ is a critical value that divides the profile into 2 zones. For $L/d_o < 3$, the duration to complete one full dig-fill cycle is longer as the apron length ratio increases. However, this trend does not continue after $L/d_o > 3$, in fact, the duration to complete one full dig-fill cycle becomes shorter when the apron length ratio increases and reduces to zero when $L/d_o = 35$, with no occurrence of jet flipping.

Figure 4.7 Relationship between $t_o$, average time to complete one full dig-fill cycle and the apron length ratio, $L/d_o$
4.3 Maximum and Minimum Scour Depth

Runs 13, 14, 15, 20, 21, 22 were selected to investigate the impact of apron length on scour depth and Runs 13, 18 and 81 were chosen to study the effect of flowrate on scour depth.

Figure 4.8 shows the changes of scour depth in the digging phases with respect to time in semi-log scale for Runs 20, 21 and 22. From this figure, it can be seen that the scour depth increases with time. However, the trends of the increase are different between the first cycle and subsequent cycles. This difference can be explained by comparing the scour profile at the commencement of first digging phase and the subsequent digging phases. The first digging phase started from a flat sand bed, i.e. no scour depth at the start of the run. However, the subsequent digging cycles began from the minimum scour depth, $d_{se-fill}$ position achieved from the previous cycles’ filling phase. This had led to the formation of a gap in the changes of scour depth between the first digging phase and subsequent digging phases. Though, at the end of each phase, the scour depth would reach a maximum depth, $d_{se-dig}$ and this value remained relatively constant throughout all the digging cycles in the experiment. This value indicates the maximum capability of the water in the digging process under this set of hydraulic parameters and the $d_{se-dig}$ would be different for different Runs. In Figures 4.8, the maximum scour depth at equilibrium state during the first digging phase, $d_{1se-dig}$ is used to calculate the dimensionless maximum scour depth, $d_{st-dig} / d_{1se-dig}$.

Figure 4.9 illustrates the changes of scour depth in the filling phases with respect to time for Runs 20, 21 and 22. Based on the graphs, the scour depth reduces during the filling phase. Hence, it has proven that the scour hole is filled by the sand particles from sand ridge which is located downstream. The trend of decreasing in scour depth is the same throughout all cycles. The minimum scour depth, $d_{se-fill}$ was almost the same for each filling phase. In Figure 4.9, the minimum scour depth at equilibrium state during the first filling phase, $d_{1se-fill}$ is used to calculate the dimensionless minimum scour depth, $d_{st-fill} / d_{1se-fill}$. 
Figure 4.8 Relationship between ratio of scour depth (d_{st-dig}) to equilibrium scour depth (d_{1se-dig}) and ratio of digging duration for each cycle (t) to t_o for Runs 20, 21, 22
Figure 4.9 Relationship between ratio of scour depth ($d_{st-fill}$) to equilibrium scour depth ($d_{1se-fill}$) and ratio of filling duration for each cycle ($t$) to $t_o$ for Runs 20, 21, 22
In Table 4.2, the relative scour depth, $\Delta d_s$, is used to compare the percentage of scour depth difference in different Runs.

The relative scour depth, $\Delta d_s$, is defined for the % scour depth difference, where

$$\Delta d_s = \left(\frac{d_{se-dig} - d_{se-fill}}{d_{se-dig}}\right) \times 100 \quad (4.5)$$

By keeping other parameters (flowrate, Q, tailwater depth, $H_t$) constant, the effects of apron length ratio, $L/d_o$ on maximum and minimum scour depth as well as $\Delta d_s$ are plotted in Figures 4.10 and 4.11. The results in Figure 4.10 show that the scour depths decrease with increasing apron length. In Figure 4.11, $\Delta d_s$ is not affected as much by the change in apron length as $\Delta d_s$ initially increases from $L/d_o = 1$ to a maximum at $L/d_o = 9$ but gradually decreases to reach a value almost the same as $L/d_o = 1$ as $L/d_o$ increases to 30.

From Table 4.2, flowrate does not show a direct effect on maximum and minimum scour depth, where by increasing the flowrate, maximum and minimum scour depth can be increased or decreased as well. However, the data show that relative scour depth can be affected by flowrate. The relative scour depth for Run 18 ($Q = 2.5$ L/s), Run 13 ($Q = 2.128$ L/s) and Run 81 ($Q = 1.818$ L/s) are 45%, 29% and 17% respectively.
4.4 The Observation of Sand Ridge

A sand ridge was formed downstream of the scour hole during the digging process. Observation showed that the formation and number of sand ridge were uncertain and mainly affected by the experiment conditions, especially the duration of digging and filling. The author had chosen Runs 21 and 13 for further discussion because the development and formation of sand ridge for these two Runs were varying widely.

In the following discussion, two different ridge heights ($d_h$) are used, $d_{h2}$ and $d_{h1}$. The $d_{h2}$ is defined as the height of ridge formed in the current cycle and $d_{h1}$ is defined as the height of ridge formed from previous cycle or the 1st cycle. For example, the $d_{h2}$ of first cycle will become the $d_{h1}$ of the second cycle and the $d_{h2}$ of second cycle become $d_{h1}$ in the third cycle and so on.

Run 21 had the longest duration of one full dig-fill cycle compare with other Runs (see Table 4.2). In Figure 4.12, the development of ridge height for the first three dig-fill cycles in Run 21 is plotted against time. The formation and changes of sand ridge in Run 21 was the most typical case where two sand ridges were formed in each cycle except the first cycle. The sand ridge formed in the first cycle (blue line) did not disappear, but reduced in height. The newly formed sand ridge (red line) for each cycle did not merge with the sand ridge formed in the first cycle. It had been noticed that the height of ridge will increase in the initial stage of the filling phase; this phenomenon will be explained in detail in Section 4.4.1. In Figures 4.12 and 4.13, ridge height at the equilibrium state during the first digging phase, $d_{1H-dig}$ is used to calculate the dimensionless ridge height, $d_h/d_{1H-dig}$.

On the other hand, Run 13 had a much shorter duration of one full dig-fill cycle than Run 21. In Run 13, most of the time only single sand ridge was observed (see Figure 4.13). At the beginning of the second filling phase, $d_{h2}$ was much higher than $d_{h1}$, however, after sometimes of filling, the current $d_{h2}$ overtopped on $d_{h1}$ formed from the previous cycle and $d_{h1}$ reduced to zero (black dotted circle in Figure 4.13). On the other hand, in the third filling phase, the current $d_{h2}$ merged below $d_{h1}$ formed from the previous cycle and $d_{h2}$ reduced to zero (black circle in Figure 4.13). This situation was totally different from the second filling phase. Figures 4.14 and 4.15 give a clearer image on the formation of sand ridge that stated earlier.
Figure 4.12 Development of sand ridge in the first 3 dig-fill cycles for Run 21

dh2/d1H-dig lower than zero means the sand ridge forms from the sand bed which is lower than y = 0 (see Figure 3.5)
Figure 4.13 Development of sand ridge in the first 3 dig-fill cycles for Run 13

dh2/dH-dig lower than zero means sand ridge forms from the sand bed which is lower than y = 0 (see Figure 3.5)
**Figure 4.14 Run 13: Sequence of the current \( d_{h2} \) formation overtopping on \( d_{h1} \) formed from previous cycle**

(a) Second filling phase (time: 19:57:48)
(b) Second filling phase (time: 20:10:06)
(c) Second filling phase (time: 20:30:05)

**Figure 4.15 Run 13: Sequence of the current \( d_{h2} \) formation merging below \( d_{h1} \) formed from previous cycle**

(a) Third filling phase (time: 22:39:16)
(b) Third filling phase (time: 22:52:54)
(c) Third filling phase (time: 23:25:51)
4.4.1 Effect of Apron Length on Height of Ridge

In Section 4.4, two kinds of ridge height, $d_{h1}$ and $d_{h2}$ were introduced and used to describe the formation and changes of sand ridge. In this section, only the height of ridge that formed in the current cycle, $d_{h2}$ will be used to carry out the investigation of ridge height under different apron length and the same Runs in Section 4.3 were used.

Figures 4.16 and 4.17 indicate the changes of ridge height in the digging and filling phases with respect to time, ridge height at the equilibrium state during the first digging and filling phase, $d_{1H\text{-dig}}$ and $d_{1H\text{-fill}}$ are used to calculate the dimensionless ridge height, $d_{h2}/d_{1H\text{-dig}}$ and $d_{h2}/d_{1H\text{-fill}}$. In Figure 4.16, the difference in the increasing trend between the first digging phase (1st cycle) and the later digging phases (2nd and 3rd cycle) is observed. This could be explained by the amount of sand particles in the first digging phase was more than others. When the filling phase occurred, only a portion of sand particles in the sand ridge was being filled back to the scour hole, therefore, it created the disparity in the amount of sand particles in the first and other digging phase. Thus the formation of gap in Figure 4.16 was due to the first digging phase had more sand particles to be pushed.

By observing Figure 4.17, for Runs 21 and 20, the height of ridge increases at the beginning of filling phase before it sinks. By referring to Figure 4.2, the backward movement of the sand is being dragged by the flow in the second recirculation region (dark blue line). The impingement point in this flow region is located half way on the sand ridge (red circle in Figure 4.2), and it initiates the sand particle movement in upper and lower parts of the sand ridge in two opposite directions, upward and downward respectively. At the beginning of filling phase, the ridge height continued to growth. However, after a period of time, the height decreased because the sand particles in lower part of the ridge had been moved back to the scour hole. At the same time, the sand particles in upper part rolled downwards to fill the sand lost in lower part. However, the situation in Run 22 was different, the ridge height was observed to increase throughout the whole filling process. By referring to Table 4.2, the total filling duration for Run 22 is around 158 min which is lower than Runs 20 (386 min) and 21 (737 min). Therefore, it might be insufficient time for the sand in upper part to roll back.
Figure 4.16 Relationship between ratio of ridge height ($d_{h2}$) to equilibrium ridge height ($d_{1H-dig}$) and ratio of digging duration for each cycle ($t$) to $t_o$ for Runs 20, 21, 22
Figure 4.17 Relationship between ratio of ridge height ($d_{h2}$) to equilibrium ridge height ($d_{1H-fill}$) and ratio of filling duration for each cycle ($t$) to $t_o$ for Runs 20, 21, 22.

- **Run 20**: $d_{h2}$ merging below $d_{h1}$ (discuss in Section 4.4).
- **Run 21**: 0.65 of $d_{1H-dig}$.
- **Run 22**: Increasing in height.
By modifying Eq 4.5, the percentage of ridge height difference, $\Delta d_h$ can be calculated, where

$$\Delta d_h = \left(\frac{d_{H-dig} - d_{H-fill}}{d_{H-dig}}\right) \times 100$$  \hspace{1cm} (4.6)

The ridge height at the equilibrium state in the first digging or filling phase is used instead of average ridge height; this is because normally the ridge height in the first phase is the highest. This can be seen from the dotted circles in Figures 4.16 and 4.17.

Figure 4.18 represents the percentage of ridge height difference ($\Delta d_h$) against apron length ratio ($L/d_o$). From the figure, in the region where $L/d_o$ is smaller than 2, negative $\Delta d_h$ is observed which means the ridge height in filling phase is higher than digging phase. However, for other $L/d_o$, higher ridge height in digging phase is recorded. The difference in the ridge height caused by apron length is quite significant, from -17% (Run 22) to 47% (Run 13).

![Figure 4.18](image-url)

**Figure 4.18 Effect of apron length ratio on $\Delta d_h$**
4.5 Effect of Different Parameters on the Occurrence of Jet flipping

The occurrence of jet flipping is affected by parameters such as tailwater depth, flowrate and apron length individually while other parameters are constant. Most of the researchers found that jet flipping only occurred in shallow tailwater depth (Ali and Lim 1986; Johnston 1990; Balachandar and Kells 1997; Deshpande, Balachandar et al. 2007). However in the present study, it was discovered jet flipping also occur with large tailwater depth. In addition, it was found that flowrate and apron length were another parameters that would affect the occurrence of jet flipping. But, the distinctions between high and low flowrate as well as long and short apron length have not been clearly defined.

In Figure 4.6, when tailwater depth ($H_t = 12.7$ cm), sluice gate opening ($d_o = 10$ mm), discharge ($Q = 2.128$ L/s), velocity ($u_o = 0.71$ m/s), Froude number ($Fr = 2.267$) remain unchanged, a critical range of apron length ratio ($L/d_o$) between 30 and 35 may influence the occurrence of jet flipping.

Runs 121 and 85 as well as Runs 79 and 85 were used to find out the critical range of flowrate and tailwater depth respectively. All these Runs were carried out in the condition of high submergence or large tailwater depth ($H_t = 16$ cm and $12.7$ cm) and 90 mm of apron length (see Table 4.1).

### 4.5.1 Effect of Tailwater Depth

Runs 79 and 85 were conducted in high submergence manner, but jet flipping only occurred in Run 79 that had tailwater depth of 12.7 cm. Therefore there must be a critical range of tailwater depth that would affect the occurrence of jet flipping. The procedure is discussed in detail in this section.

First, $H_t = 13.5$ cm was chosen to conduct the experiment (Run 79 ($H_t=13.5$ cm)). Bases on Figure 4.19, the first digging phase in Run 79 consumes 3854 minutes, which is around 2 days. As a result, 8 days (4 times higher than 2 days) was chosen as the time limit to observe the jet flipping phenomenon. After 8 days of experiment, no jet flipping was observed and the author stopped the experiment.

Next another tailwater depth which was in the range from 12.7 cm to 13.5 cm was chosen to conduct the following experiments. In order to narrow the range, this process was repeated a few times until the range was lower to an acceptable level. A range of 0.5 cm was selected as the acceptable level. In conclusion, with apron length, $L = 90$ mm; flowrate, $Q = 1.818$ L/s; jet
flipping will occur when the tailwater depth is between 12.7 cm and 13 cm, whereas it will not occur when tailwater depth is between 13.5 cm to 16 cm. The summary of Run 79 is listed in Table 4.3.

![Figure 4.19 Time-sequence of each digging and filling phase for Run 79](attachment://figure419.png)

**Figure 4.19 Time-sequence of each digging and filling phase for Run 79**

### 4.5.2 Effect of Flowrate

In Table 4.3, Run 121 was conducted for 12 days and 12 cycles were observed. However for Run 85, all the parameters were similar to Run 121 except for the flowrate, \(Q = 1.818\) L/s, and no jet flipping was observed. Therefore there must be a critical range of flowrate that would affect the occurrence of jet flipping. The procedure is discussed in detail in this section.

First, the average value of 2.2 L/s for 2.5 L/s and 1.818 L/s was used to conduct the first experiment (Run 121 (\(Q = 2.2\) L/s)). Based on Figure 4.20, the duration of the first digging phase in Run 121 is 4276 minutes, which is nearly 3 days. Therefore, 8 days (about 2.7 times higher than 3 days) was chosen as the time limit to observe the occurrence of jet flipping. After 8 days of continuous experiment, no jet flipping was observed and the experiment was stopped.

Next, another flowrate was chosen which was in the range from 2.5 L/s to 2.2 L/s to conduct the following experiments. In order to narrow the range, this process was repeated a few times until the range is lower to an acceptable level. Due to time constraint, the author has selected a range of 0.1 L/s as the acceptable range. In conclusion, with apron length, \(L = 90\) mm; tailwater depth, \(H_t = 16\) cm; flowrate, \(Q = 2.2\) L/s to 2.3 L/s is the critical range of flowrate, above which jet flipping occurred and below which no jet flipping would happen.
Figure 4.20 Time-sequence of each digging and filling phase for Run 121

The summary of the data for the procedures in Sections 4.5.1 and 4.5.2 are listed in Table 4.3, set 1 and 2. From the data, by increasing the tailwater depth or increase the flowrate of Run 85, a threshold of jet flipping can be established, even under high submergence. More experiments need to be conducted to produce a demarcation diagram for the threshold of jet flipping as a function of the flowrate, tailwater depth and apron length.
Table 4.3 Summary of data

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<th>Ht(cm)</th>
<th>Uo (m/s)</th>
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CHAPTER 5  CONCLUSIONS

This study investigates the jet flipping and scouring characteristics for a submerged jet below a sluice gate and the conclusions are as follows:

1. It was found in the initial period, the jet issuing from the sluice gate impinges on the sand bed and the rate of scour development during this digging phase was rapid. Then the rate of scour slowed down and finally reached a pseudo equilibrium stage with no observable changes in the bed profile as time progresses. This is the bed jet phase where the jet attaches completely to the bed and digging it to a maximum scour depth, \( d_{se-dig} \).

2. Depending on a certain combination of the tailwater depth, jet discharge and apron length, it was observed that the bed jet would suddenly flip towards the water surface forming a surface jet phase. During this phase, the jet would erode the sand ridge in a reverse direction causing sand particles to be transported back into the scour hole. The rate of filling was relatively stable, and the filling phase stopped when it reached a minimum scour depth, \( d_{se-fill} \). The jet would then almost instantaneously revert back to a bed jet phase. The jet-flipping and its associated digging and filling processes are cyclical and repeated many times over the long scouring duration used in this study.

3. The results on the effect of the apron length on the jet flipping phenomenon showed that the duration of the filling phase is generally longer than the digging phase with longer apron length. The duration to complete one dig-fill cycle also decreases with increases in apron length.

4. For apron length as a ratio of the jet opening, \( L/d_o \) greater than 35, there is no jet flipping and only bed jet was observed. Similarly, when there is no apron, i.e., \( L/d_o \) is equal to zero, there is no jet flipping in the scour hole.

5. Based on the results, it was found that generally the maximum scour depth, \( d_{se-dig} \) during the digging phase and minimum scour depth, \( d_{se-fill} \) during the filling phase increase as the apron length decreases. The difference between the \( d_{se-dig} \) and \( d_{se-fill} \) is larger with increases in jet discharge.

6. At the downstream of the scour hole, the sand ridge formed is affected by the cyclical digging and filling action. There are two sand ridges formed with different heights during the dig-fill cycles. For apron length ratio, \( L/d_o \) lower than 2, the height of sand ridge during the filling phase is higher than that during the digging phase.

7. Preliminary results on the threshold of jet-flipping with respect to a range of tailwater depths and jet discharges rates showed that for a particular apron length ratio and jet...
discharge, there is a critical tailwater whereby jet flipping will not occur if its value is above the critical value and vice versa. Similarly for a particular apron length ratio and tailwater, there is a critical jet discharge such that jet flipping will occur if its value is higher than the critical value and vice versa.
REFERENCES


