Jet-flipping phenomenon in local scour below a sluice gate

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**NANYANG
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**JET-FLIPPING PHENOMENON
IN LOCAL SCOUR
BELOW A SLUICE GATE**

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**SCHOOL OF CIVIL AND ENVIRONMENTAL
ENGINEERING**

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**JET-FLIPPING PHENOMENON
IN LOCAL SCOUR
BELOW A SLUICE GATE**

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SUMMARY

This study shows that a jet-flipping phenomenon may occur during the local scour process caused by 2-D submerged wall jets over an apron downstream of a sluice gate. The jet-flipping consists of a digging and a filling phase. The former scours the bed and the latter re-fills the scour hole. The process is cyclical and there is no equilibrium scour condition. A novel webcam method is developed to record the scouring process continuously for a long period. At the end of digging, a dynamic equilibrium condition is reached with a stabilized scour profile which may last up to 10 days before the next filling phase occurs. Hence, if the run time is too short, the jet-flipping may not be observed.

The scour dimensions were found to change cyclically in accordance with the digging and filling phases, and multiple ridges may form. At the end of the digging and filling phases over many cycles, the scour profiles were found to be similar. The results showed that the scour depth during digging can be 60% more than the filling phase. A comparison of the maximum scour depth from past and present data shows that the scour is more severe with jet-flipping compared to the no jet flip conditions.

The velocity distributions during digging and filling phases were measured in two fixed-bed models at the threshold of jet-flipping. The flow pattern shows that for the digging phase, the jet dives and impinges on the bed after leaving the apron. The velocities are high near the bed which contributes to the severe scouring action. For the filling phase, the jet approaches the water surface immediately after leaving the apron. The high velocities are found near the apron and the path to the water surface and the latter causes the sediments on the ridge to slide down and back-fill the scour hole. The results show that jet-flipping could be triggered by the Coanda effect due to the jet's preference to attach to a relatively nearer boundary.

The effects of jet-flipping on the scour depth and the frequencies of jet-flipping were studied systematically. It was found that the maximum scour depth for both digging and filling phases increase as the tailwater depth becomes deeper, decrease as the

apron length becomes longer, and increase as the densimetric Froude number becomes larger. These results suggest that no jet-flipping will be observed if the tailwater is sufficiently deep or if the apron is too long. The results also show that the presence of an apron below the gate is necessary for jet-flipping to occur.

The results for the jet-flipping frequencies in terms of the Strouhal number show that they increase with the increase in densimetric Froude number and apron length but decrease as the tailwater increases. Based on the present data, prediction equations are proposed for the maximum scour depth at the end of digging and filling phases and for the frequencies of jet-flipping. A threshold diagram to predict the occurrence of jet-flipping is also presented and could be applied in design to avoid the undesirable phenomenon in local scour below a sluice gate.

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LIST OF SYMBOLS

ρ	=	Water density [kg/m ³]
ρ_s	=	Sediment density [kg/m ³]
Δd	=	Percentage difference in scour depth between digging and filling phases [%]
b	=	Length scale taken as the value of y where $u = 1/2u_m$ [m]
BJ	=	Bed jet
d_0	=	Jet opening size [m]
d_{16}	=	Sediment diameters that are finer than 16% of bed material [m]
d_{50}	=	Median sediment diameter corresponding to 50% finer [m]
d_{84}	=	Sediment diameters that are finer than 84% of bed material [m]
d_{h1}	=	Height of ridge formed from a previous cycle or the 1st cycle [m]
d_{h2}	=	Height of ridge formed in the current cycle [m]
d_{se}	=	Maximum scour depth at the equilibrium state [m]
d_{se-dig}	=	Maximum value of y_s recorded at the end-of-digging phases [m]
$d_{se-fill}$	=	Minimum value of y_s recorded at the end-of-filling phases [m]
F_0	=	Densimetric Froude number = $u_0/\sqrt{(S-1)gd_{50}}$
Fr	=	Flow Froude number = $\frac{u_0}{\sqrt{gd_0}}$
g	=	Gravitational acceleration [m/s ²]
hr	=	Hours
H_t	=	Tailwater depth [m]
JF	=	Jet-flipping
L	=	Apron length [m]
min	=	Minutes
n	=	Total number of digging-filling cycles recorded for a run
q_b	=	Sediment transport rate [m ² /s]
Q	=	Flow rate [m ³ /s]
R	=	Correlation coefficient
Re	=	Reynolds number
R_h	=	Hydraulic radius= ratio of the jet area to its perimeter [m]

S	= Specific gravity of sediment
S_{hu}	= Slope upstream of the scour hole = $\tan(\theta_{hu})$
S_{hd}	= Slope downstream of the scour hole = $\tan(\theta_{hd})$
S_{ru}	= Slope upstream of the ridge = $\tan(\theta_{ru})$
S_{rd}	= Slope downstream of the ridge = $\tan(\theta_{rd})$
s	= Seconds
SJ	= Surface jet
SN	= Series No.
St	= Strouhal number = d_0/u_0t
St_{T0}	= Average jet-flipping cycle frequency = d_0/u_0T_0
St_{Td0}	= Average digging frequency = d_0/u_0T_{d0}
St_{Td1}	= First digging frequency = d_0/u_0T_{d1}
St_{Tf0}	= Average filling frequency = d_0/u_0T_{f0}
T	= Period of jet-flipping [s]
T_e	= Equilibrium time [s]
T_0	= Average duration to complete one cycle of digging-filling phase [s]
T_{d0}	= Average digging duration [s]
T_{d1}	= Digging duration in the first cycle [s]
T_{di}	= Duration of digging phase in the i_{th} cycle [s]
T_{f0}	= Average filling duration [s]
T_{fi}	= Duration of filling phase in the i_{th} cycle [s]
t	= Scour time [s]
u	= Streamwise velocity [m/s]
u'	= Velocity fluctuation in streamwise direction [m/s]
u^+	= Normalized horizontal turbulence intensity component = $(\overline{u'u'})^{0.5}/u_0$
u_0	= Jet exit velocity [m/s]
u_m	= Maximum streamwise velocity in each vertical cross section [m/s]
u_t	= Mean flow velocity at the tailwater depth section downstream of the sluice gate [m/s]
V_s	= Volume of scour hole per unit width [m ²]
V_{s3}	= Volume of scour hole [m ³]
V_{s-max}	= Maximum scour volume per unit width at the digging phase [m ²]

V_{s-min}	=	Minimum scour volume per unit width at the filling phase	[m ²]
w	=	Vertical velocity	[m/s]
w'	=	Velocity fluctuation in vertical direction	[m/s]
w^+	=	Normalized vertical turbulence intensity component	$= (\overline{w'w'})^{0.5} / u_0$
x	=	Horizontal coordinate / horizontal distance from the edge of apron	[m]
x_e	=	Horizontal distance of the downstream extreme end of sand ridge at any instant of time	[m]
x_m	=	Horizontal extension of scour hole at any instant of time	[m]
x_r	=	Horizontal distance of the sand ridge from the edge of apron at any instant of time	[m]
x_s	=	Horizontal distance of the location of the maximum scour depth at any instant of time	[m]
y	=	Vertical coordinate / vertical distance from the flat bed	[m]
y_0	=	Initial water depth before the water depth abruptly increases during hydraulic jump	[m]
y_1	=	Water depth upstream of the sluice gate	[m]
y_2	=	Sequent depth at which the water surface becomes level after hydraulic jump	[m]
y_b	=	Brink depth at any instant of time	[m]
y_r	=	Height of the sand ridge at any instant of time	[m]
y_s	=	Maximum scour depth at any instant of time	[m]
y_{ws}	=	Depth of water surface above the maximum scour location at any instant of time	[m]
μ	=	Dynamic viscosity of water	[kg/sm]
σ_g	=	Geometric standard deviation	$= \sqrt{d_{84}/d_{16}}$
θ	=	Angle of the sediment bed	[°]
ϕ	=	Angle of repose	[°]

Subscripts

dig	=	Subscript _{-dig} indicates during digging phases
fill	=	Subscript _{-fill} indicates during filling phases

hd = Subscript_{-hd} indicates downstream of the scour hole
hu = Subscript_{-hu} indicates upstream of the scour hole
max = Subscript_{-max} indicates the maximum value
min = Subscript_{-min} indicates the minimum value
rd = Subscript_{-rd} indicates downstream of the ridge
ru = Subscript_{-rd} indicates upstream of the ridge

CHAPTER 1 INTRODUCTION

1.1 Background

The turbulent jets downstream of hydraulic structures, such as sluice gate, jet nozzle, spillway, or a weir may cause severe local scour. The scouring process is inherently complex due to the rapid change of turbulent flow characteristics against time. Excessive scour is undesirable and maybe detrimental to the foundations of the structures. Therefore, many researchers have studied scour by plane turbulent wall jets and tried to understand the effects of scour on the erodible bed and to obtain better scour prediction. These include the geometrical dimensions in the scouring process, the temporal development of scour and the turbulence properties in the scour hole. The scour development can be generally indicated by three distinct phases, an initial phase with a rapid rate of scouring; a development stage with a relatively slower rate of scouring; and an equilibrium phase where there is no observable scouring activity and the scour geometry achieved a stabilized shape. Also, at the equilibrium phase, the scour hole would have attained its maximum depth, and has no significant change over time. Most studies focused on the equilibrium scour state (Laursen 1952; Tarapore 1956; Rajaratnam 1981; Ali and Lim 1986; Dey and Sarkar 2006).

However, for certain hydraulic conditions, the equilibrium stage may not be reached. The scouring processes were associated with jet-flipping, a phenomenon in which the jet action would suddenly flip from the bed to the water surface and vice versa. Jet-flipping can induce an erroneous judgment of the equilibrium state and therefore inaccurate scour prediction. Coates (1976), Johnston and Halliwell (1986) and Shimada et al.(2004) observed that the jet flow can be a surface jet, bed jet or bed-surface jet in their studies under no sediment transport conditions. For situations with a sediment bed, Johnston (1990) and Mazurek et al. (2009) also noted these 3 types of jet behaviours. They observed in shallow tailwater submergence, the jet sometimes attaches itself to the bed boundary and in other situations it suddenly attaches itself to the free surface, i.e. jet-flipping. Balachandar and Kells (1997) observed the jet-flipping phenomenon with low submergence and recorded some

characteristic time periods for a typical test. Loh (1997) and Lim and Yu (2002) found the jet-flipping phenomenon under high submergence.

Most of the researchers observed jet-flipping by chance or the occurrence was usually monitored for a relatively short period. Balachandar and Kells (1998) used a Hi-8 CCD video camera to observe the jet-flipping phenomenon and the PROSCAN software to capture the dynamic profiles of the scouring process. One common limitation of this setup is that it required very large data storage space and hence is not suitable for long term recording of the scouring process. Deshpande et al. (2007) and Bey et al. (2008) found the jet-flipping indirectly by recording the streamwise velocity histories using a laser Doppler anemometer (LDA). Younkin and Hill (2009) captured the jet-flipping phenomenon in a test run accidentally when recording data by planar laser sheet method. The laser method is able to observe the sediment bed motion without disturbing it, and is less time consuming than the traditional manual method. However, the laser facility cannot be used for long-term observations, and hence they used the technique, only for the first 300s in their study.

The flow field in a scour hole with digging action at an equilibrium state by 2-D jet has been previously investigated by researchers such as Dey and Sarkar (2008). However, there are far fewer measurements in the flow field involving a jet-flipping phenomenon. Kurniawan and Altinakar (2002) measured the flow vectors in the x-y plane for a surface jet downstream of a sluice gate using an Acoustic Doppler Velocity Profiler (ADVP). Balachandar et al. (2000) measured the streamwise and vertical mean velocity distributions with jet-flipping by LDA, but the measurements were done while the sediment bed was still changing, and thus the results may be affected. These works are rather preliminary. The trigger mechanism of jet-flipping and its associated scour formation is still unclear. There is a need to systematically investigate the effects of jet-flipping on local scour caused by 2-D wall jets downstream of a sluice gate.

1.2 Objectives and scopes of study

The main objectives of the present study are to systematically investigate the effects of jet-flipping on the local scour process caused by 2-D wall jets downstream of a sluice gate, to evaluate the hydraulic conditions that will cause the jet to flip, to understand the flow fields in the critical scour hole profile which triggers the jet-flipping phenomenon and to predict its occurrence. To achieve these objectives, the scopes of the work performed are as follows:

1. The previous studies on local scour caused by turbulent wall jets with or without jet-flipping were compiled, summarized and analysed.
2. Experiments were conducted systematically. A novel webcam recording method was used to observe the long term scouring process continuously, up to 1 month or even longer. The device allows the experimental flume to be under constant observation. The evolutions of the scour hole with jet-flipping during the scouring processes can be clearly observed and analysed.
3. The effects of the jet-flipping on the scour dimensions such as the time development of scour size, the maximum scour depths, ridges, and volume of scour were investigated.
4. The effects of the different hydraulic parameters, i.e. tailwater depth, jet densimetric Froude number and length of apron, on the occurrence of the scour development and jet-flipping frequencies were studied.
5. The frequencies of jet-flipping and the time when flipping happened were recorded and analysed.
6. The possible trigger mechanisms of the jet-flipping phenomenon were investigated by experiments. The flow fields in the scour hole were measured using ADV on 2 fixed-bed aluminium models based on the scour profiles at the threshold of jet-flipping.

7. Based on the experimental data collected, formulas were proposed for the prediction of maximum scour depth with jet-flipping, the minimum scouring time required to observe jet-flipping in an experiment and the prediction of the jet-flipping frequencies. More importantly, a threshold diagram on the criteria to assess whether jet-flipping occurs under certain hydraulic conditions was suggested as a guideline for practical use.

1.3 Thesis organization

This thesis consists of seven chapters. Chapter One introduces the background, objectives and scope of the research. Chapter Two reviews the relevant previous studies carried out in the field of local scour caused by 2-D turbulent wall jet. Chapter Three provides the details of the experimental facilities, hydraulic conditions, the measuring and data acquisition techniques in the present study. Chapter Four presents the observations on the scouring process with jet-flipping, the flow patterns and the evolution of the scour hole, ridges and the scour volume. In addition, some defining terms describing the flipping phenomenon are discussed. Chapter Five presents the velocity measurement results of the flow field on 2 fixed-bed aluminium models based on the scour profiles at the threshold of jet-flipping. This chapter also examines the possible trigger mechanism of the jet-flipping. Chapter Six presents the effects of the tailwater depth, densimetric Froude number and apron on jet-flipping frequencies and the scour depth during the local scour process downstream of the sluice gate. A threshold criterion for the occurrence of the jet-flipping phenomenon, the prediction formulas of jet-flipping frequencies and maximum scour depth during digging and filling phases are suggested. Finally, the conclusions and recommendations for further researchers, drawn from the results of the present study, are presented in Chapter Seven.

CHAPTER 2 LITERATURE REVIEW

This chapter reviews the previous literature of the local scour process on a non-cohesive sediment bed caused by 2-D turbulent horizontal jets. The present study focuses on the cyclical jet-flipping occurrence which is a special flow phenomenon associated with the local scouring processes. Previous works have reported on this phenomenon, but few researchers have studied the effects of the jet-flipping action on the scour dimensions systematically. These studies with observations on jet-flipping are reviewed. For a thorough investigation of the jet-flipping phenomenon, it is necessary to also understand the local scour process without jet-flipping, and there are many previous studies on this aspect of jet scour. The characteristics of the turbulent wall jet, dynamics of the evolving local scour processes, their corresponding flow characteristics and effects of different hydraulics parameters on the local scour are highlighted in the review.

2.1 Local scour by turbulent wall jet

2.1.1 Two-dimensional turbulent wall jet

In general, the term ‘two-dimensional jet’ refers to jets under hydraulic structures which are sufficiently wide. The flow is regarded as infinitely wide laterally and therefore, can be simplified into a two-dimensional flow for ease of investigation by considering the phenomenon and its characteristics in the flow direction only.

Figure 2-1 shows a typical definition sketch of plane turbulent wall jets (Rajaratnam 1976). The term wall turbulence means the turbulence is generated in the shear flow near a solid boundary (Daily and Harleman 1966). As the jet leaves the nozzle, due to the velocity discontinuity, a shear layer develops on the fluid side and a boundary layer develops on the wall side. When the boundary layer meets the penetrating shear layer, the potential core of the jet is consumed and beyond this section, the flow is said to be fully developed. The region from the wall to the maximum velocity level is known as the boundary layer and the region above this is generally known as the free

mixing region. Launder and Rodi (1979) formally defined the submerged plane horizontal wall-jet as a jet of fluid that intrudes tangentially on a rigid wall surrounded by the same fluid (stationary or moving) progressing along the wall. As a result of the supplied momentum at the onset, the streamwise velocity (u) in the jet-layer is greater than that in the external flow over a downstream reach.

Figure 2-1 Definition sketch of plane turbulent wall jets (Rajaratnam 1976)

The streamwise velocity (u) distribution versus the vertical coordinate (y) of the turbulent wall jet is often regarded as a double layered structure, a near bed inner layer and an outer layer as mentioned above. Barenblatt et al. (2005) demonstrate that a turbulent wall jet flow is a triple-layered structure. It consists of two self-similar layers: a top layer and a wall layer, separated by a mixing layer where the velocity is close to maximum. The top and wall layers both exhibit incomplete similarity, as shown in Figure 2-2.

Figure 2-2 The triple-layered structure of wall jet flow: (1) top self-similar layer; (2) wall self-similar layer; (3) mixing layer (Barenblatt et al. 2005)

Whether it is double or triple layered, the velocity distributions of a wall jet show a self-similar property. Forthmann (1936) was the first to conduct experiments on plane turbulent wall jets. The velocity distributions of different cross-sections can fall on a single curve by proper scaling laws, which is convenient for further investigations (see Figure 2-3). The velocity scale is generally represented by u_m and the length scale b , where u_m is the maximum streamwise velocity in each vertical cross section and b is taken as the value of y where $u = 1/2u_m$.

Figure 2-3 Similarity of velocity profiles in plane wall jets (Forthmann 1936)

For the wall jet downstream of the sluice gate, there are three zones, developing zone, fully developed zone and recovering zone, as shown in Figure 2-4. In the developing zone, the jet issuing from the sluice gate undergoes a rapid transition from supercritical to subcritical flow, which causes a hydraulic jump, as shown in Figure 2-5. The hydraulic jump only occurs in the supercritical flow (Munson 2010), i.e. the upstream Froude number must be restricted to $Fr \geq 1$, where $Fr = \frac{u_0}{\sqrt{gd_0}}$, g is the acceleration due to gravity, d_0 is the sluice gate opening and u_0 is the jet exit velocity. Eq. (2-1) is the well-known Belanger equation, where y_0 is initial depth before the water depth abruptly increases and y_2 is the sequent depth at which the water surface becomes level. If the tailwater depth $H_t < y_2$, it is a free jump (Figure 2-5(a)).

Otherwise, when $H_t > y_2$, it is a submerged jump (Figure 2-5(b)). In the present study, $H_t > y_2$ for all the experiments except Run H1-215 (see Appendix A).

$$\frac{y_2}{y_0} = \frac{1}{2} (\sqrt{1 + 8Fr^2} - 1) \quad (2-1)$$

Figure 2-4 Schematic diagrams of flow zones in a submerged wall-jet (Dey et al. 2010)

Figure 2-5 Definition sketches for free and submerged jumps including velocity distribution (Wu and Rajaratnam 1995)

The typical streamwise velocity (u) distributions of the submerged jumps immediately downstream of the sluice gate are shown in Figure 2-5(c). It is a bit

different from the distributions in the recovering zone. In the present study, most of the experiments have an apron and a relative high tailwater depth. The velocity distributions of the flow immediately downstream of the sluice gate are similar to the case in Figure 2-5(c).

2.1.2 Introduction of scour

The scour can be divided into three types, general scour, constriction scour and local scour. General scour occurs in a river or stream as the result of natural processes regardless of the present of hydraulic structures. Constriction scour arises from the constriction of waterways by a structure. This scour occurs in conditions like narrowing of a water course, rechanneling of berm or flood plain flow. Localized scour results directly from the effects and interactions of the structure on local flow pattern. This scour may be superimposed on constriction scour and general scour. Flow under a sluice gate has a considerable potential for local scour if the downstream bed consists of erodible materials.

Clear-water scour and live-bed scour are two different conditions to describe the scour transport processes. Clear-water scour occurs in conditions when the bed material upstream of the scour area is at rest. In other words, the bed shear stresses in areas located some distance away from the structure are less than the critical shear stress for initiation of bed material movement. Live-bed scour occurs under conditions that general sediment transportation has taken place from upstream to the scour zone. In this case, the shear stresses on the bed are greater than the critical shear stress. Equilibrium scour depth is reached when the amount of materials removed from the scour hole is equalled to the amount of material supplied from the upstream. In the present study, there is no sediment transported from upstream and the type of scour considered all belongs to the clear-water scour conditions.

2.1.3 Local scour process

Figure 2-6 shows a definition sketch of the scour bed, where u_0 is the jet exit

velocity, d_0 is the jet opening size, L is the apron length, H_t is the tailwater depth, x denotes horizontal distance from the edge of the apron, y is the vertical distance from the flat bed, y_s is the maximum scour depth at any instant of time, x_s is the horizontal distance of the location of the maximum scour depth, y_{ws} is the depth of the water surface above the maximum scour location, x_e is the horizontal distance of the downstream extreme end of the sand ridge, x_r is the horizontal distance of the sand ridge from the edge of the apron, y_r is the height of the sand ridge and y_b is the brink depth at any instant of time.

Figure 2-6 Definition sketch of the scour hole dimensions

Figure 2-7 shows a typical evolution of the scour bed centreline profiles by a plane turbulent wall jet. It can be seen that the scouring development can be generally indicated by three distinct phases. An initial phase with a rapid rate of scouring; a development stage with a relatively slower rate of scouring; and an equilibrium phase where there is no observable scouring activity and the scour geometry achieved a stabilized shape (Laursen 1952; Rajaratnam 1981; Nik Hassan and Narayanan 1985; Hoffmans and Verheij 1997). As shown in Figure 2-7(b), the maximum scour depth develops and increases with time, and when $t > 10^3$ s (s = seconds), the maximum scour depth is almost unchanged, i.e. it reached an equilibrium phase. The centreline bed profiles for all the jet sizes, tailwater depths and scouring times are similar (Ali and Lim 1986). Lim and Yu (2002) indicates the scour profiles could be described as

a sine function by using proper scaling lengths as shown in Figure 2-8, where d_{50} is the median sediment diameter corresponding to 50% finer. It seems that the sine function is more suitable for the scour hole than the ridges. For example, the ridges in Figure 2-7 are not shaped like sine curves, and in the present study, more than one ridge were observed in some experiments which is not easily described by a single sine function.

Figure 2-7 Growth of erosion with time by plane wall jets (Rajaratnam 1981)

Figure 2-8 Similarity of centreline scour profiles, $H_t/d_0 = 24.3$, $L = 30\text{mm}$, $d_0 = 10\text{mm}$, $d_{50} = 2.94\text{mm}$, $u_0 = 1.18\text{ m/s}$ (Lim and Yu 2002)

The time to reach the equilibrium state is affected by the hydraulic conditions. Chatterjee et al. (1994) developed an empirical expression (Eq. (2-2)) of the time to the equilibrium state using experimental data, where T_e is the equilibrium time. It can be seen that the equilibrium time is closely related to the jet exit velocity and the grain size. It requires more time to reach equilibrium with a smaller jet exit velocity or with coarser grains.

$$T_e = e^{4.67d_{50}^{0.172}} u_0^{-0.667} d_{50}^{-0.014} \quad (2-2)$$

In the present study, 40 runs were observed to have jet-flipping. The minimum time taken for the first flipping to occur was recorded in each run. By applying Eq.(2-2), it was found 47.5% (19 out of 40 Runs) of the predicted time were sufficient to see the first flipping. The other 52.5% (21 out of 40 Runs) were insufficient to see the jet-flipping. However, it is noted that the range of time used to formulate Eq.(2-2) is rather short, whereas the first flipping time for the present study is usually very long. Hence, the minimum time to observe the first flipping occur is further investigated in the present study.

Many equations have been proposed for the relationships between the dimensions of

the scour hole, i.e. y_r , y_b , y_s , etc. Some of these geometries show relationship to the maximum scour depth. Ali and Lim (1986) indicate that the dimensionless volume of the scour hole (V_{s3}/R_h) follows the power law of the dimensionless maximum scour depth (y_s/R_h), where V_{s3} is the scour volume and R_h is the hydraulic radius = ratio of the jet area to its perimeter, i.e.,

$$\frac{V_{s3}}{R_h^3} = 181.72 \left(\frac{y_s}{R_h} \right)^{2.28} \quad (2-3)$$

Lim and Yu (2002) investigated the maximum brink scour depth, y_{bmax} , which represents the erosion at the interface between the solid apron and the sand bed, and is linearly related to the maximum scour depth at the equilibrium state (d_{se}), i.e.

$$y_{bmax} = 0.44 d_{se} \quad (2-4)$$

For experiments with jet-flipping, the relationships between these dimensions of the scour hole were investigated in the present study.

Figure 2-9 Relationship between maximum brink depth with maximum scour depth (Lim and Yu 2002)

2.1.4 Effects of various hydraulic parameters on local scour

2.1.4.1 Effect of densimetric Froude number

The scour profiles are mainly affected by the hydraulic conditions, i.e. tailwater depth (H_t), jet exit velocity (u_0), apron length (L), etc. Significant research has been directed at finding the relationships between the scour hole geometries with the hydraulic parameters, especially, the maximum scour depth at the equilibrium state (d_{se}). In the present study, the effects of these parameters on local scour with jet-flipping are investigated in Chapter 6.

One of the characteristic parameter in the previous studies is the jet densimetric Froude number, defined as

$$F_0 = \frac{u_0}{\sqrt{(S-1)gd_{50}}} \quad (2-5)$$

where $S = \rho_s/\rho$ is the specific gravity of the sediment, ρ_s is sediment density and ρ is the water density. Physically, F_0 represents a measure of the ratio of the tractive force ($\rho u_0^2 d_{50}^2$) acting on the sand grain to the submerged specific weight $[(\rho_s - \rho)gd_{50}^3]$ of the grain. Compared to the flow Froude number $Fr = u_0/(gd_0)^{0.5}$, the densimetric Froude number F_0 takes the property of the sediment into account which is more appropriate for the local scour problem. This parameter is commonly used by many researchers in the correlation of localized scour phenomena (Rajaratnam and Berry 1977; Rajaratnam 1981; Ali and Lim 1986; Lim 1993; Lim 1997; Aderibigbe and Rajaratnam 1998; Dey and Sarkar 2006; Sarathi et al. 2008).

Chiew and Lim (1996) found that the densimetric Froude number was the characteristic parameter in describing the scour hole dimensions for both the air and water jets. Rajaratnam and Berry (1977) studied the scour produced by circular wall jets interacting with erodible sand and polystyrene beds. Using both air and water jets, they concluded that the main geometric characteristics of the scour hole are function of the densimetric Froude number. Aderibigbe and Rajaratnam (1998)

found the maximum depth of scour was larger at deeper submergences and higher values of F_0 . And a longer time was required to attain an equilibrium state at higher values of F_0 . Sarathi et al. (2008) indicated that at a given tailwater depth, the geometrical dimensions tended to increase with increasing F_0 and the effect was prominent at all tailwater depths. The present study shows similar conclusions. For experiments with jet-flipping, at higher values of F_0 , the maximum scour depth at the end of digging phase was larger and the duration of the first digging phase was longer.

Eq.(2-6), Figure 2-10 and Figure 2-11 show that the geometrical dimensions increases with an increase in F_0 . For example, the following equation shows that the dimensionless ridge height, y_r/d_0 can be simply described by a linear variation with F_0 .

$$\frac{y_r}{d_0} = 2.5 (F_0 - 3.0) \quad (2-6)$$

The above equation was suggested by Rajaratnam (1981).

In Figure 2-10, for water-sand conditions, the dimensionless maximum equilibrium scour depth (d_{se}/d_0) and the dimensionless distance of the section of maximum erosion (x_s/d_0) increases linearly with F_0 at a decreasing rate.

Figure 2-10 Effect of F_0 on maximum scour depth and distance of section of maximum erosion (Rajaratnam 1981)

Figure 2-11 shows that d_{se}/d_0 increases with increase in F_0 . For the same sediment, F_0 can simply represent the strength of the incoming flow, i.e., the geometrical dimensions increase with increase in u_0 . The figure also indicates that with longer apron, the scour hole is shallower. The present study has the same conclusion.

Figure 2-11 Variation of d_{se}/d_0 with F_0 for different L , d_0 , and d_{50} (Dey and Sarkar 2006)

2.1.4.2 Effect of tailwater depth

The effect of tailwater depth (H_t) on scour depth is complex.

Under certain hydraulic conditions, for shallow tailwater depth, d_{se} decreases with increase in H_t ; for relatively deeper tailwater depth, d_{se} increases with increase in H_t , i.e., the bottom 3 curves in Figure 2-12 and Figure 2-13(e), (f) and (g).

$F_0 = \frac{u_0}{\sqrt{(s-1)gd_{50}}}$ represents the intensity of the incoming flow compared to the bed stability. Both Figure 2-12 and Figure 2-13 show that, at a given tailwater depth, the maximum scour depth tended to increase with increasing F_0 and the effect was prominent at all tailwater depths. This indicates the effect of the incoming flow on the bed stability is strong. According to the continuity equation, $H_t/d_0 \approx u_0/u_t$, where u_t is the averaged flow velocity at the section measuring the tailwater depth downstream of the sluice gate. u_0/u_t represents the intensity of the incoming flow compared to the tailwater. Below a critical u_0/u_t , the bed stability increases with the increase in the intensity of the incoming flow, while above the critical u_0/u_t , the bed stability decreases with the increase in the intensity of the incoming flow. The figures show that the value of the critical u_0/u_t increases with increasing F_0 . And in Figure 2-12, the effect of the intensity of the incoming flow compared to the tailwater becomes insignificant when H_t/d_0 is beyond 16.

In some experiments, there is no significant trend for tailwater depth versus d_{se} , i.e., Figure 2-13(a) and (b) show the data points scattered in a horizontal band without any clear increasing or decreasing trend.

Figure 2-12 Effect of tailwater depth on maximum scour depth (Ali and Lim 1986)

Generally, when H_t is high enough, researchers found the tailwater have a minimal effect on d_{se} .

The possible reason for the complex nature of tailwater is that the changes in tailwater depths cause the modification in the flow field and therefore affects the scour process.

Figure 2-13 Effect of tailwater depth on maximum scour depth (Dey and Sarkar 2006)

Under shallow tailwater conditions, the process of scour hole development is more complex compared to relatively deep tailwater conditions. Hence, researchers preferred the laboratory studies to be done in deep submergence, i.e. H_t/d_0 greater than 10.

Rajaratnam and Macdougall (1983) studied the erosion by plane wall jets with minimum tailwater (Submergence $H_t/d_0 = 1$). During the development stage, the flow

near the sluice gate fluctuated continuously from a surface jet to a hydraulic jump, to submerged hydraulic jump and back to the surface jet. The intensity as well as the frequency of these flow sequences reduced considerably as the asymptotic state was approached, i.e. the scour hole attains its maximum depth. There is no ridge at the downstream end of the scour hole as shown in Figure 2-14. And d_{se}/d_0 for minimum tailwater are lower than the corresponding results from Rajaratnam (1981) for deep tailwater depths as shown in Figure 2-15.

Moreover, several researchers observed a special jet-flipping phenomenon during the local scour process in low submergence. This is discussed in Section 2.2.

Figure 2-14 Typical eroded bed profiles for $H_t/d_0 = 1$ (Rajaratnam and Macdougall 1983)

Figure 2-15 Effect of different tailwater depth on maximum scour depth versus F_0 in the equilibrium state (Rajaratnam and Macdougall 1983)

2.1.4.3 Effect of sediment size

Sediments can be divided into cohesive and non-cohesive materials. The division has been arbitrarily placed on the grain size distribution. Cohesive materials refers to sediments contains silt and clay, whereas non-cohesive material ranging from fine sand to coarse gravel. The major difference lies primarily in the mutual interaction of grains in the water environment. In the present study, non-cohesive sediments are used. Non-cohesive sediments in suspension behave independently from each other, with the exception of mechanical interaction in highly dense suspensions, while as a bed material only forces of interlocking and friction enter into the picture (Partheniades 2009). The median sediment size, d_{50} and the geometric standard deviation of the sediment size distribution σ_g are usually used to describe the properties of the sediment, where $\sigma_g = (d_{84}/d_{16})^{0.5}$, d_{84} and d_{16} are grain sizes for which 84% and 16% by weight, respectively, of the sediment finer (Vanoni 2006). Sediment gradations are determined by sieve analysis and σ_g is an important parameter to quantify the soil sample gradation. The sediment is considered uniform if σ_g is less than 1.5.

The sediment particle size has an effect on the sediment transport. The equilibrium scour depth and the volume of scour hole decrease with an increase in the sediment size, as shown in Figure 2-16. For non-uniform sediment, a shorter time is required for scour to reach equilibrium (Lim 1995), and with non-uniform sediment, the scour is less than that for uniformly graded sand of similar grain size (Dey et al. 1995; Aderibigbe and Rajaratnam 1998; Kells et al. 2001).

Figure 2-16 Effect of discharge and grain size on maximum scour depth (Kells et al. 2001)

2.1.5 Maximum scour depth at the equilibrium state

The prediction of the maximum scour depth is of most interest to researchers and engineers. The typical parameters mentioned above significantly affect the maximum scour depth. Most prediction equations are empirical and derived from laboratory tests. Some of the equations for cases with an apron for scour downstream of a sluice gate are summarized in Table 2-1. Lim and Yu (2002) presented an analysis using a relatively comprehensive database and proposed Eq.(2-7) focusing on the effect of a protective apron on scour depth. The equation is good for predicting both the cases with or without an apron. Dey and Sarkar (2006)'s Eq.(2-8) was developed from their experiments using many different uniform and non-uniform sediments. Recently, Melville and Lim (2013) used a K-factor method to develop two equations based on 305 laboratory data compiled from previous studies. Eq.(2-9) gives a reliably good prediction of the maximum local scour depth, while Eq.(2-10) is an

upper bound to predict the maximum possible local scour depth. Eq.(2-10) is convenient but the predicted range is too wide. These equations are compared with the present study in Section 4.4.2.

Table 2-1 Prediction equations for 2-D jet scour below a sluice gate from previous studies

Investigator	Equation	
Lim and Yu (2002)	$\frac{d_{se}}{d_0} = 1.04\sigma_g^{-0.69}F_0^{1.47}\left(\frac{d_0}{d_{50}}\right)^{-0.33}e^{-0.004\beta\left(\frac{L}{d_0}\right)^{1.4}}$ <p>where $\beta = \sigma_g^{-0.5}F_0^{-0.35}\left(\frac{d_0}{d_{50}}\right)^{0.5}$</p>	(2-7)
Dey and Sarkar (2006)	$\frac{d_{se}}{d_0} = 2.59F_0^{0.94}\left(\frac{L}{d_0}\right)^{-0.37}\left(\frac{H_t}{d_0}\right)^{0.16}\left(\frac{d_{50}}{d_0}\right)^{0.25}$	(2-8)
Melville and Lim (2013)	$\frac{d_{se}}{d_0} = 3FrK_{d50}K_{Ht}K_{\sigma}K_L$ <p>where $K_{d50} = 1.0, \left(\frac{d_{50}}{d_0} < 0.6\right),$ $K_{d50} = 0.6\left(\frac{d_{50}}{d_0}\right)^{-1}, \left(\frac{d_{50}}{d_0} \geq 0.6\right),$ $K_{Ht} = 0.01\left(\frac{H_t}{d_0}\right)^{2.6}, \left(\frac{H_t}{d_0} < 6\right), K_{Ht} = 1, \left(\frac{H_t}{d_0} \geq 6\right),$ $K_{\sigma} = 1.2\sigma_g^{-0.24}, (\sigma_g > 2.2), K_{\sigma} = 1, (\sigma_g \leq 2.2),$ and $K_L = 1 - \tanh\left[\frac{0.013L}{d_0}\right].$</p>	(2-9)
Melville and Lim (2013)	$\frac{d_{se}}{d_0} = 3Fr$	(2-10)

2.2 Jet-flipping phenomenon

2.2.1 Observations on jet-flipping

Under normal circumstance, the scouring process will eventually reach an equilibrium phase. However, for certain hydraulic conditions, the equilibrium stage may not be reached. The scouring processes were associated with jet-flipping, a phenomenon in which the jet action would suddenly flip from the bed to the water

surface and vice versa. Table 2-2 summarizes the works of some researchers who have observed the jet-flipping phenomenon or similar flow patterns with or without sediment.

Figure 2-17 and Figure 2-18 show the scour and water surface profiles with jet-flipping observed by Balachandar and Kells (1997) and Loh (1997) during the local scour process downstream of a sluice gate with an apron. It can be seen that, the scour hole first extended with time and reached a maximum scour profile (Phase A in Figure 2-17), which is similar to the scour profiles at equilibrium state in previous studies. After that, the sediment on the ridge started to refill into the scour hole, and the position of the scour hole and the ridge moved upstream.

Figure 2-17 Variation of the scour profile with time (13min 39 s < t < 15 min 32 s) (Balachandar and Kells 1997)

Figure 2-18 Initial cyclical scour processes for Run SPC 1 (FIP and DIP mean filling and digging in progress; DS and FS refer to the start of digging and filling, respectively) (Loh 1997)

Balachandar and Kells (1997) indicated that the scour profile changes with time in a cyclical manner, with two distinct flow patterns observed over the entire period of the experiment. The first was a ‘digging phase’ by the jet action with a lot of the bed materials being eroded from the scoured zone. This process usually lasts for a certain period of time. The second flow pattern was accompanied by the movement of bed materials in the upstream direction, refilling the previously eroded portion of the bed, i.e. the ‘filling phase’. The refilling also occurred over a certain period of time. The filling phase and the digging phase occurred alternately. The water surface is different during these two phases as shown in Figure 2-18. The flow pattern in the digging phase is a jet attaching to the sand bed as a bed jet with an anticlockwise circulation (Figure 2-19(a)). In the filling phase the flow flips to the water surface and becomes a surface jet (Figure 2-19(b)).

Figure 2-19 Schematic sketch (not to scale) of the flow field during (a) digging process and, (b) refilling process (Balachandar and Kells 1997)

Table 2-2 Summary of the studies observed jet-flipping phenomenon by 2D horizontal jets

Authors	Source of 2-D jet flow	Jet size (d_0) (mm)	Sediment diameter (d_{50}) (mm)	Submergence (H_t/d_0)	Apron (L/d_0)	Fr	F_0	Duration of test (hours)	Observation method
Coates (1976)	Slot	10, 20	NA	3.0 to 10.0	0	4.5 to 28.0	NA	NA	Manual
Johnston and Halliwell (1986)	Slot	NA	NA	NA	0	3.4	NA	NA	Hot-film anemometer
Johnston (1990)	Slot	25	0.70	2.3, 3.5	0	0.7	3.6	1	Manual
Loh (1997) Lim and Yu (2002)	Sluice gate	10	2.94	24.5	43	6.4, 5.2	9.1, 7.5	360, 766	Manual
Balachandar and Kells (1997)	Sluice gate	10	0.98*	6.5	1	2.8	6.9*	144	Video camera
Balachandar et al. (2000)	Sluice gate	10	0.98*	4.0 to 8.9	1	1.9 to 3.1	4.7 to 7.6	36 to 96	Video camera
Kells et al. (2001)	Sluice gate	10	0.57 to 2.18	4.0 to 8.8	1	1.8 to 3.1	3.0 to 10.0	24	Video camera
Shimada et al.(2004)	Nozzle	5	NA	20.0*	0	1.8 to 3.4*	NA	NA	Video camera
Deshpande et al. (2007)	Nozzle	25	2.15	4.0	0	2.3	6.2	24	LDA
Bey et al. (2008)	Nozzle	25	2.15	2.0 to 6.0	0	1.5 to 2.3	4.0 to 6.2	24	LDA
Mazurek et al. (2009)	Nozzle	25	2.08	4.0 to 10.0	0	0.7 to 2.3	1.8 to 6.2	36 to 85	Manual
Younkin and Hill (2009)	Nozzle	10	0.73	25.0	0	1.1*	3.2	8 *	Digital camera and laser

Note: *Estimated based on the paper.

2.2.2 Effects of tailwater depth and velocity on jet-flipping

Tailwater depth is a key parameter influencing the occurrence of jet-flipping. Most of the researchers found that the jet-flipping or similar flow patterns occurred with relatively low submergence.

Coates (1976), Johnston and Halliwell (1986) and Shimada et al.(2004) observed that the jet regime can be a surface jet, a bed jet or an alternating bed-surface jet (jet-flipping) for experiments without an erodible sediment bed. Similarly, Lin et al. (2008) observed the oscillating flow patterns in vertical drop pool structures. Coates (1976) found that the jet behaviours depend on the tailwater depth (H_t/d_0) and the Froude number (Fr) as shown in Figure 2-20. Region 1 defines a zone in which only surface jets can exist and the tailwater depths are relatively shallow and the flow pattern is dominated by the water surface. Region 2 defines a zone in which only the bed jet can exist and the depths are relatively deep; hence the water surface no longer has much influence and the flow pattern is dominated by the bed. In Region 3, the jet can exist either as the bed or surface jet. Figure 2-20 indicates that the surface jet occurs under relatively high Fr and low H_t , while the bed jet occurs under relatively low Fr and high H_t . This finding is similar to the present study. Lin et al. (2008) also found the jet regimes depend on the Froude number ($\frac{u_0}{\sqrt{gL_p}}$) and downstream tailwater depth (H_t/L_p), where L_p is the pool length. They suggested a diagram to distinguish the regions of possible occurrence of periodic oscillation as shown in Figure 2-21. The diagram indicates that the skimming flow occurs under relatively high Froude number and low tailwater depth, while the napped flow occurs under relatively low Froude number and high tailwater depth. The finding is also similar to the present study as skimming flow behaves like a surface jet and napped flow as bed jet. Shimada et al.(2004) plotted Figure 2-22 to show the jet behaviours depend on the distance of the jet to the boundaries, where H/h is the distance from the jet exit centreline to the water surface, and D/h is the distance from the jet exit centreline to the solid bed. The figure reveals that there is a higher preference for flow to attach to a nearer solid surface.

Figure 2-20 Schematic representation of the three regions of bed and surface jets (Coates 1976)

Figure 2-21 Region of possible occurrence of periodic oscillation (confined by dashed and dotted lines) (Lin et al. 2009)

Figure 2-22 Influence of H and D on deflection direction of jet ($Re=2.4 \times 10^3$ to 10^4) (Shimada et al. 2004)

From the above discussion, it is noted that the distance to the boundaries and the flow velocity significantly contribute to the change of flow behaviours. Coates (1976) and Shimada et al.(2004) indicated the pressure and the Coanda effect may be the main reasons for the change of the jet regime. In brief, the Coanda effect is described as the tendency of a jet to attach to a nearby surface. The principle was named after Romanian aerodynamics pioneer Henri Coanda, who was the first to recognize the practical application of the phenomenon in aircraft development. This effect occurs either if the wall is parallel, and positioned at a distance from the jet, or if the wall lies beside the jet and is inclined at an angle with the jet direction, as shown in Figure 2-23. The figure shows the checking of the surrounding fluid on one side of the stream by means of a flap which prevents the flow of the surrounding air from the space, and also the deflection, according to the arrows 3, of the issuing stream discharged from said nozzle (Henri 1936). Lalli et al. (2010) studied the jet-wall interaction in shallow coastal water and found the Coanda effect generates a significant modification of the flow pattern. By performing simulations and experimental studies in a simple shaped domain (plane jet interacting with a parallel wall), Lalli et al. (2010) specified the physical processes underlying to Coanda effect, which basically consists in the deviation of the jet towards the wall. The

single terms of momentum equations contribute. As a result, Coanda effect is confirmed to be a typically inviscid phenomenon, driven by convective terms and free surface gradients. More precisely, the forcing terms giving rise to Coanda effect are the free surface gradients related to the vortex generated between the jet and the wall. Convective terms give rise to flow contraction as well. High values of bottom roughness will affect and cause the Coanda effect to vanish.

Figure 2-23 Jet deflects to the nearby flap due to Coanda effect (Henri 1936)

For situations with an erodible sediment bed, Johnston (1990) and Mazurek et al. (2009) also noted the three types of jet behaviours described earlier: surface jet, bed jet and bed-surface jet-flipping regimes. They observed qualitatively that in shallow tailwater submergence, the jet sometimes attaches itself to the bed boundary and in other situations it suddenly attaches itself to the free surface. Mohamed and McCorquodale (1992) distinguished the flow regimes by sketches as shown in Figure 2-24 specifically for flow with low submergence downstream of a sluice gate with an apron. They defined short-term scour as scour governed by regimes 1, 2, 3 and 6, and long-term scour by regimes 4 and 5.

Figure 2-24 Six flow regimes involved the local scour process with low tailwater (Mohamed and McCorquodale 1992)

Johnston (1990) developed a length scale $L_d = d_0 F_0^{1.33}$ as shown in Figure 2-25 to distinguish the jet regimes as surface only, bed only and bed-surface regimes for offset jet scour. This illustrates that with increasing tailwater depth, the jet regime can change from a surface jet to the flipping bed-surface jet and finally to bed jet only. Johnston (1990) also observed that the flipping is most likely to occur when the tailwater depth is approximately equal to the offset ratio. Mazurek et al. (2009) used Johnston (1990)'s plot and found that it agreed well with some of their laboratory results. In the present study, most of the jet regimes are not well predicted by Johnston (1990)'s diagram. The possible reasons are that the present study is downstream of a sluice gate and mostly with an apron while his diagram is for offset jet without an apron. Besides, many runs in the present study are under relatively higher tailwater depths. In Section 6.4, a threshold criterion for jet-flipping below the sluice gate under a wider range of tailwater will be discussed.

Figure 2-25 Scour hole regimes using $L_d = d_0 F_0^{1.33}$ as a length scale, redraw from Johnston (1990)

For most of the studies mentioned, it seems that the alternating of jet regimes mostly occurred with low tailwater submergence. Balachandar et al. (2000) found no jet-flipping with high jet submergence. However, Loh (1997) and Lim and Yu (2002) found that jet-flipping can occur even under a relatively high submergence of $H_t/d_0 = 24.5$. It means there is also an upper boundary where jet-flipping probably occurs under a relatively high submergence. The effects of tailwater depth will be investigated and purposely designed in the present study to cover a wider range of H_t/d_0 from 2 to 23.

The occurrence of jet-flipping with sediment bed also depends on the mean jet velocity. Bey et al. (2008) observed that there was a minimum tailwater depth beyond

which jet-flipping would not occur and that the critical depth is related to the jet exit velocity. The critical tailwater depth, which defines a flow region as high or low submergence, increases as the jet velocity increases. At a high jet exit velocity, the change in flow regime also depends on whether the tailwater level is rising or decreasing. In other words, they found that the tailwater depth and jet exit velocity collectively determine the occurrence of jet-flipping phenomenon. Also, it was observed that generally at low submergence the commencement of the filling phase is related to the jet velocity. The higher the velocity, the longer it took for jet-flipping to occur.

2.2.3 Time periods of jet-flipping

The time duration for the digging and filling phases are different and may change with the progress of the test. The records of the durations can help to better understand the mechanics of the jet-flipping, and is useful in the development of an appropriate jet-flipping prediction model. This is done in the present study in Section 6.6. Figure 2-26 shows the variation of the average digging (T_1) and refilling (T_2) time periods from Balachandar and Kells (1997), where T_1 and T_2 were calculated based on three successive flipping cycles. The data show that T_1 (10–25 s) is much shorter than T_2 (100–1000 s) and the former also shows a slower rate of increase.

Figure 2-26 Average time period variation during digging and refilling (Balachandar and Kells 1997)

Figure 2-27 Variation with time of normalized (a) digging time period and (b) refilling time period (Balachandar et al. 2000)

Balachandar et al. (2000) tried to scale their data points on to a single curve as shown in Figure 2-27, using dimensionless experimental time $t \sqrt{2g(y_1 - H_t)} / H_t$ as the x

coordinate and the dimensionless digging time $T_d\sqrt{2g(y_1 - H_t)}/\sqrt{V_s}$ or filling time $T_f\sqrt{2g(y_1 - H_t)}/\sqrt{V_s}$ as the y coordinate, where V_s is the volume of scour per unit width, T_d is the cyclic period over which digging of the bed occurs, T_f is the cyclic period over which refilling of the bed occurs and y_1 is the water depth upstream of the sluice gate. The spread of the data shows that more work is needed to find proper scaling parameters for the jet-flipping frequency. In the present study, the digging/filling frequencies were investigated in terms of a dimensionless Strouhal number, St , which is discussed in Sections 4.1 and 6.6.

2.2.4 Visualization techniques used to observe jet-flipping

With the limitations of the digital device, most of the researchers observed jet-flipping in their experiments, either by accident, or they managed to observe jet-flipping for only a short period. Some observed the jet-flipping occurrence during velocity measurement (Deshpande et al. 2007; Bey et al. 2008), while some recorded the phenomenon by video camera (Balachandar and Kells 1997; Balachandar et al. 2000).

Balachandar and Kells (1998) introduced the video camera system to observe the jet-flipping phenomenon, as shown in Figure 2-28. The video was recorded at a rate of 30 fps (frame per second) and then stored on 8 mm tapes. A PROSCAN software was used to capture the dynamic profiles during the scouring process continuously. However, Balachandar and Kells (1997) recorded only the initial part of the tests and 10 minutes for the latter part. This is due to the limitation of the device as the video data consumed a lot of data storage space. In the present study, the author developed a webcam recording method which is able to record the long-term scouring process continuously for up to a month (see Section 3.1.1).

Figure 2-28 Schematic arrangement of video imaging and analysis system (Balachandar and Kells 1998)

Deshpande et al. (2007) and Bey et al. (2008) observed the digging-refilling phases indirectly from the records of the velocity-time histories using laser Doppler anemometer (LDA). In Figure 2-29, it is clear that the velocity signals for digging and filling are different.

Figure 2-29 Velocity time history for submergence $H_t/d_0 = 2$ and 4 (Bey et al. 2008)

Younkin and Hill (2009) captured the bed profiles with planar laser sheet for flows with minimal suspended load. The advantage is that the measurements can be made

with the experiment running without disturbing the flow and the sediment bed, and is less time consuming than the traditional manual method. The flume centrelines have been combined to show the temporal evolution of the bed form, as shown in Figure 2-30. They found the jet-flipping accidentally, indicated by the solid line in Figure 2-30. At about time = 70s, the crest of the centreline profile suddenly moves back. The limitation for this facility is that the laser cannot be used for long-term observations. For example, in Figure 2-30 and Figure 2-31, the laser method is used only for the first 300s, and manual tracking was used for the latter part.

Figure 2-30 (a) Plan; (b) perspective views of the scour hole evolution with time (Younkin and Hill 2009)

Figure 2-31 Temporal evolution with laser method and manual method (Younkin and Hill 2009).

2.3 Flow field in the scour hole

2.3.1 Flow field without jet-flipping

Investigation of the velocity and turbulence characteristics in a scour hole can give better understanding of the scouring mechanics.

The velocity vectors of the flow field are shown in Figure 2-32. The results are measured by an Acoustic Doppler Velocimeter (ADV) by Dey and Sarkar (2008). It shows three different stages of the scouring process: flat bed, with a hole $y_s = 0.3d_{se}$ and at the equilibrium state with scour depth at d_{se} . It can be seen that, for all these three figures, the jet over the apron is a typical wall jet and the flow fields are quite similar. There is an anti-clockwise vortex formed immediately downstream of the sluice gate. The decay of the jet velocity is apparent. In the scour hole, the jet is attached to the sediment bed.

Figure 2-32 Two-dimensional normalized velocity vectors for (a) flat bed condition, (b) intermediate scour hole with $0.3d_{se}$ and (c) equilibrium scour depth, redraw from Dey and Sarkar (2008).

The decay of the normalized horizontal maximum velocity with streamwise distance x/d_0 is self-similar and decreases along x/d_0 , as shown in Figure 2-33. Compared with the smooth bed curve (Long et al. 1990) and classical wall jet curve (Rajaratnam 1976), the data in the apron region collapse on the curve of a smooth bed, while the rate of decay of the local maximum velocity u_0 increases within the scour hole region.

Figure 2-33 Decay of the maximum streamwise velocity as a function of x/d_0 in equilibrium state, redraw from Dey and Sarkar (2008).

Figure 2-34 Vertical distributions of (a) u^+ and (b) w^+ in equilibrium state, redraw from Dey and Sarkar (2008).

For the turbulent jet, velocity fluctuation is defined as the difference between the velocity at any instant of time and the time-averaged velocity. Bey et al. (2007) and

Duan et al. (2011) indicated that the transport of sediment particles in the scour hole was caused by sweeps ($u' > 0, w' < 0$) and ejections ($u' < 0, w' > 0$) according to the quadrant analysis, where u' , w' are the velocity fluctuation in streamwise and vertical directions, respectively. The turbulence intensity, which represents the magnitude of the turbulence, is often defined as the square root of the mean square of the fluctuating velocity divided by the time average velocity (Munson 2010). The larger the turbulence intensity, the larger are the fluctuations of the velocity and other flow parameters. In Figure 2-34, $u^+ (= (\overline{u'u'})^{0.5}/u_0)$ is the normalized horizontal turbulence intensity component. Prominent protuberances are apparent as a result of flow reversal over the apron, while the protuberance does not exist within the scour hole. $w^+ (= (\overline{w'w'})^{0.5}/u_0)$ is the normalized vertical turbulence intensity component. The protuberances are not distinct. Generally, w^+ increases with an increase in the vertical distance y/d_0 attaining a maximum value at the middle of the flow depth and then decreases gradually with y/d_0 .

2.3.2 Flow field with jet-flipping

Balachandar et al. (2000) conducted three series of experiments with various tailwater depths to study the jet-flipping phenomenon. Figure 2-35 and Figure 2-36 show the streamwise mean velocity (u/u_0) in the scour hole downstream of a sluice gate during the digging and filling phases, respectively. Figure 2-37 shows the vertical velocity components (w/u_0). The u/u_0 at $x/d_0 = 0$ resembles that of a classical wall jet. In Figure 2-35, for $x/d_0 \geq 6$, u/u_0 below the initial bed level is positive, and in conjunction with v/u_0 in Figure 2-37, it is obvious that the jet is a bed jet attaching to the sediment bed in the scour hole. In Figure 2-36, for $x/d_0 \geq 6$, the u/u_0 below the initial bed level is negative, and in conjunction with w/u_0 , it can be seen that the jet flips to the water surface and it is a surface jet. For Figure 2-35(f) and Figure 2-36(f), due to the limitation of the experimental setup and device, it was reported that the profiles of the bed changed during measurement. Hence, the velocity results are less precise and should be viewed qualitatively.

Figure 2-35 Steamwise mean velocity at various downstream stations during a typical digging phase: (a) $x/d_0 = 0$; (b) $x/d_0 = 1$; (c) $x/d_0 = 6$; (d) $x/d_0 = 11$; (e) $x/d_0 = 16$; and (f) change in sand bed profile during measurements (Balachandar et al. 2000)

Figure 2-36 Steamwise mean velocity at various downstream stations during a typical refilling phase: (a) $x/d_0 = 0$; (b) $x/d_0 = 1$; (c) $x/d_0 = 6$; (d) $x/d_0 = 11$; (e) $x/d_0 = 16$; and (f) change in sand bed profile during measurements (Balachandar et al. 2000)

Figure 2-37 Vertical velocity components at various downstream stations during a typical digging and refilling phase: (a) $x/d_0 = 0.2$; (b) $x/d_0 = 1$; (c) $x/d_0 = 6$; (d) $x/d_0 = 11$; and (e) $x/d_0 = 16$ (Balachandar et al. 2000)

Kurniawan and Altinakar (2002) measured the flow field vectors downstream of a sluice gate using an Acoustic Doppler Velocity Profiler (ADVP). Figure 2-38 (a) and (b) clearly shows the bed jet and surface jet regimes in the scour hole, respectively. There is no apron in the experiment shown in Figure 2-38(a). The flow from the sluice gate behaves as a typical turbulent free-jet and impinges on the bed at about $x = 40$ cm. Downstream of the impingement point the main flow continues as a turbulent wall-jet. The magnitude of the vector $\left(\frac{\sqrt{u^2 + w^2}}{u_0}\right)$ near the sediment bed in the scour hole is larger. Figure 2-38(b) shows the velocity distribution with a short apron, $L/d_0 = 2$. The presence of the apron enables the jet to flip to the water surface once ejected from the sluice gate and there is no impingement on the bed, i.e. it is a surface jet. The magnitude of the vector near the water surface above the scour hole is larger. It was not mentioned in the paper, but the scour profile in Figure 2-38(b) may be at the end of the digging profile which is equivalent to the start of the refilling phase; hence the occurrence of the surface jet in the plot. In the present study, the velocities are specifically measured at the threshold scour profiles at the end-of-digging and end-of-filling stages to study in detail the mechanics of the jet-flipping phenomenon (see

Section 5.1).

Figure 2-38 Magnitude of velocity vector in the x-y plane (Kurniawan and Altinakar 2002)

2.4 Summary

In this chapter, the literature on the 2-D localized scour caused by horizontal jets is reviewed. The essential knowledge about turbulent wall jet and local scour is reviewed first, followed by a discussion on the important parameters that affect local scour based on some previous studies. More importantly, studies about jet-flipping are reviewed in some detail, this being a special phenomenon during the 2-D

localized scour process and being most relevant to the present study. The hydraulic conditions under which the jet-flipping were observed with respect to various characteristic parameters such as the tailwater submergence, jet exit velocity are reviewed. To this end, recording facilities are necessary to study the transient scouring phenomenon and some studies using video camera, velocity measuring equipment and laser imaging techniques are reviewed. Lastly, the turbulent characteristics of the flow field in the scour hole at equilibrium state or with jet-flipping are briefly introduced for better understanding of the local scour process.

It can be concluded there are some limitations for the study of jet-flipping based on the reviewed literature.

1. Previous studies mainly focused on the effect of shallow tailwater submergence with limited observation at high submergence (for $H_t/d_0 > 10$). The review shows there is a lack of scour data with jet-flipping for the effects of jet velocity, sediment size and apron length.
2. Most researchers observed jet-flipping by accident. Even though some of them did continuous observations, the recorded period is quite short. For long-term scouring process, such as one week or even one month, the device mentioned above cannot meet the stated purpose.
3. Studies mainly focused on whether jet-flipping occurs. It is necessary to focus attention on systematic study of the detailed geometries of the sediment bed, the frequencies and the durations of jet-flipping, which can help to better understand and even predict the jet-flipping phenomenon.
4. Most importantly, there is as yet no guideline or formula to help assess the occurrence of jet-flipping downstream of a sluice gate, e.g., a threshold diagram to estimate whether jet-flipping occurs and the hydraulic conditions that will trigger its occurrence.

CHAPTER 3 EXPERIMENTS AND PROCEDURE

3.1 Observations of jet-flipping during scouring process

3.1.1 Experimental apparatus

The experiments were conducted in two identical glass-wall flumes, 8.0 m long, 0.3 m wide and 0.6 m deep, with a recirculation flow system. A solid stainless steel platform was mounted to simulate a rigid apron and above it a vertical sharp-edged sluice gate was installed, as shown in Figure 3-1. The apron length (L) can be adjusted by sliding the sluice gate along the apron. L is given by the distance between the right edge of apron and the bottom tip of the sluice gate. The sediment bed was 2.0 m long, 0.2 m thick and levelled to the height of the rigid apron.

Figure 3-1 Sketch of the experimental apparatus (not to scale), (a) side view and (b) top view

A centrifugal pump connecting the header tank and the storage tank was used to

produce the required discharge. Experiments were conducted under steady flow conditions. The flow rate was adjusted using a valve and measured volumetrically against time. Water was pumped into the flume through a series of connecting pipes, arranged in a honeycomb configuration, to minimize the turbulence or disturbance of the incoming flow. Immediately downstream of the bed was a sand trap to retain the sediments. Water discharged at the downstream end of the channel was collected by the storage tank and re-circulated within the flow system.

A wide angle web camera connected to a computer was placed 1.0 metre from the flume, as shown in Figure 3-1(b). The webcam was used to record the scouring process continuously for a long period of time. The area of $x = 0$ to 85 cm and $y = -20$ to 40 cm on the side wall of the flume can be covered by the webcam. The scour profiles on the side wall and the profiles in the centrelines are almost the same ($\pm 3\%$). The measurement error is ± 1 mm. The specifications of the webcam are summarized in Table 3-1. The 'Video Camera Monitor v9.13' software was used and it enabled the recorded video to be saved automatically into the database every hour, as shown in Figure 3-2. The software has its own video compression algorithms based on the settings of the camera. In the present study, the video recording used 3.6GB of hard disk storage for every 24 hours recording at the frame rate of 25 fps and resolution of 640*480, which are clear enough to measure the scour dimensions. Table 3-2 shows the comparisons between the webcam and other video recording devices. In the present study, most of the experiments lasted more than one week and some even up to 1 month or longer. It can be seen that the webcam is most suitable for the present study. It is convenient because there is no need to change battery or memory card and due to the ease of carrying. Also, it is cheap and it uses little hard-disk storage.

The recordings allowed subsequent viewing of the entire scouring processes in detail, and more importantly to observe whether jet-flipping had occurred during the period of scouring. Also, the data can be readily extracted from the recorded video for close-up analysis of the scouring processes and the scour hole characteristics.

Figure 3-2 Screenshot of video files saved automatically at every hour of recording

Table 3-1 The specifications of the webcam

Brand & Model:	Creative, LIVE! CAM INPERSON 1080
Sensor:	Full HD 1080p (1920 x 1080) image sensor
Video resolution:	Full HD 1080p (up to 1920 x 1080 pixels)
Frame rate:	Up to 30fps @ Full HD 1080p quality
USB:	USB 2.0 Hi-Speed

Table 3-2 Comparison of the webcam and other video recording devices

	Webcam	Ordinary video camera	High-speed video camera
Brand & model (examples)	Creative LIVE! CAM INPERSON	Sony HDR-CX510E	Olympus i-SPEED 3
Max Resolution	1920*1080 pixels	1920*1080 pixels	1280*1024 pixels
Max Frame rate	30 fps	60 fps	150,000 fps
Example of storage per day (resolution@frame rate), (also base on software)	3.6 GB (640*480pixels@25 fps)	8 GB (1920*1080 pixels@50 fps)	3.6 GB (1280*1024 pixels@25fps)
Battery	No need	≈ 1.5 hours	≈ 45min or Power supply
Weight	≈ 200g	≈ 600g	≈ 5kg
Approx. Price	50 SGD	1000 SGD	>100,000 SGD

3.1.2 Bed material

As introduced in Section 2.1.4.3, soil material can be broadly classified into cohesive and non-cohesive sediment. The movement of the non-cohesive particles is solely dependent on particle properties such as shape, size and density. In the present study, non-cohesive sand was used for all experiments.

The grain size distribution, also known as sediment 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 (Dingman 2009). Sieve analysis is used to determine the plot, where an oven-dried soil sample of known mass is poured into a series of sieves stacked in descending sieve openings. The sieves are then shaken using a mechanical shaker (see Figure 3-3(a)) and the amount of soil retained on each sieve is weighed. The complete procedure for this test is outlined in the in the American Society for Testing and Materials (ASTM) C136 (2006).

The standard deviation of the grain size distribution, σ_g , is estimated using

$$\sigma_g = \sqrt{\frac{d_{84}}{d_{16}}} \quad (3-1)$$

where d_{84} and d_{16} are grain sizes for which 84% and 16% by weight, respectively, of the sediment finer.

In the present study, two types of sediment were used. The sand characteristics are of the quartz type and coloured into green and yellow. The specific gravity (S) is 2.65. Table 3-3 and Table 3-4 show the sieve analysis of these two sediments. The size distribution is characterized by the median grain size (d_{50}). The d_{50} , d_{84} and d_{16} can be

obtained from Figure 3-3(b). The sediment properties are summarized in Table 3-5.

Table 3-3 Sieve analysis for the green sand

Sieve size (µm)	Mass of sieve (g)	Mass of sieve and sediments (g)	Mass Retained (g)	Retained (%)	Cumulative Retained (%)	Cumulative passing (%)
1180.0	401.2	401.2	0.0	0.0	0.0	100.0
850.0	355.7	414.8	59.1	12.3	12.3	87.7
710.0	351.5	618.6	267.1	55.4	67.6	32.4
600.0	348.2	496.6	148.4	30.8	98.4	1.6
500.0	342.0	349.4	7.4	1.5	100.0	0.0
425.0	326.4	326.5	0.1	0.0	100.0	0.0
300.0	313.4	313.5	0.1	0.0	100.0	0.0
250.0	304.4	304.4	0.0	0.0	100.0	0.0
Pan	0.0	0.0	0.0	0.0	100.0	0.0
Sum	-	-	482.2	-	-	-

Table 3-4 Sieve analysis for the yellow sand

Sieve size (µm)	Mass of sieve (g)	Mass of sieve and sediments (g)	Mass Retained (g)	Retained (%)	Cumulative Retained (%)	Cumulative passing (%)
500.0	338.4	425.8	87.4	10.6	10.6	89.4
425.0	326.5	394.4	67.9	8.3	18.9	81.1
355.0	324.5	444.6	120.1	14.6	33.5	66.5
300.0	319.2	411.2	92.0	11.2	44.7	55.3
250.0	305.2	440.0	134.8	16.4	61.1	38.9
150.0	302.5	518.7	216.2	26.3	87.4	12.6
106.0	288.0	361.6	73.6	9.0	96.3	3.7
Pan	267.3	297.5	30.2	3.7	100.0	0.0
Sum	-	-	822.2	-	-	-

Figure 3-3 (a) Sieve analysis apparatus; (b) Particle size distributions for bed material

Table 3-5 Summary of the sediments used in the present study

Sand Type	S	d ₅₀ (mm)	d ₁₆ (mm)	d ₈₄ (mm)	σ _g
Green sand	2.65	0.73	0.650	0.820	1.12
Yellow sand	2.65	0.29	0.175	0.468	1.64

Pavement-Interactive (2007) indicates that uniformly graded refers to a gradation that contains most of the particles in a very narrow size range. In essence, all the particles are the same size. The curve is steep and only occupies the narrow size range specified. Aderibigbe and Rajaratnam (1998) found that experiments with uniform sediment mixtures provide conservative estimates of the scour hole size compared to the results obtained from the use of a non-uniform sediment mixture with the same d₅₀.

Breusers and Raudkivi (1991) indicate sediment can be considered to be non-uniform if σ_g>1.35. Dey et al. (1995) defined the sediment as uniform when σ_g ≤ 1.4, and

non-uniform, when $\sigma_g > 1.4$. Some other researchers regard the sediment as uniform when $\sigma_g < 1.5$. Thus, for the green sand, it is classified as uniform. However, for the yellow sand, it is considered to be slightly on the non-uniform side since σ_g is over 1.5 (see Figure 3-3(b)).

3.1.3 Determination of jet exit velocity (u_0)

Jet exit velocity can be got by applying the Bernoulli Equation between 2 points on the water surface; point 1 upstream of the gate and point 2 immediately downstream of the jet exit, i.e.,

$$u_2 = C_v \sqrt{2g(y_1 - y_2)} \quad (3-2)$$

Where u_2 is velocity of flow downstream of the sluice gate, y_1 and y_2 are the elevation head upstream and downstream of the sluice gate, respectively, g is the gravitational acceleration and C_v is the velocity coefficient due to energy losses.

Massey and Ward-Smith (2006) suggested that

$$C_d = C_v C_c \quad (3-3)$$

where C_d is the discharge coefficient defined as the ratio of the actual discharge to the ideal value, and C_c is the contraction coefficient which is the ratio between the area of the jet at the vena contract to the area of the jet opening. The typical value of C_c may be taken as 0.64 for a sharp-edged gate and the value of C_d is around 0.6 for most practical cases. As a result, $C_v = 0.94$ and u_0 is given by Eq. (3-4).

$$u_2 = 0.94 \sqrt{2g(y_1 - y_2)} \quad (3-4)$$

In this study, the sluice gate has a 45° sharp-edged entrance and the gate is 10 mm thick as shown in Figure 3-4. The velocity at the vena contracta, u_2 would have a velocity higher the average value immediately below the gate. Most of the experiments in this study were conducted with an apron which is relatively long compared to the jet opening size. The average velocity, u_0 at the sluice gate is used as the reference velocity in the data analysis. u_0 is calculated according to the continuity equation at the jet opening,

$$u_0 = \frac{Q}{Bd_0} \quad (3-5)$$

Where B is the transverse width of the flume, d_0 is the height of the sluice gate opening, and Q is the discharge read from the flow meter.

3.1.4 Experimental procedures

The experimental procedures for each run are summarized as follows:

1. Before each experimental run begins, the flow rate (Q), tailwater depth (H_t) and apron length (L) were adjusted to the pre-determined values.
2. Then the pump was turned off. The sediment bed was levelled to the height of the apron and covered with a metal plate before turning on the pump in order to prevent jet disturbance to the bed profile before the tailwater reaches its required depth.
3. The pump was turned on again. After the pre-determined tailwater depth was reached, the metal plate was carefully removed with minimal disturbance to the bed. It is noted that, for experiments longer than 24 hours, the velocity and scour profiles are more or less unaffected by the start-up method (Deshpande et

al. 2007). At the same time, the webcam was activated to record the scouring behaviour.

4. The tests were usually conducted for 1-4 weeks and were continued until at least one cycle of the digging-filling process was observed. For the runs conducted for 2 weeks with no jet-flipping observed and with no observable changes in the scour profile, these runs were regarded as attaining an equilibrium state and the jet-flipping would not happen. The results obtained from the experiments were analysed, tabulated and are discussed in Chapters 4 to 6.

3.1.5 Data acquisition

The time durations of each digging and filling phase (T_{di} and T_{fi} , respectively) for all the experiments can be read directly from the video recording. The accuracy is 1 second. These data are recorded in the Excel files as shown in Appendix B. With these time durations, the average digging duration (T_{d0}), the average filling duration (T_{f0}), the average digging-filling cycle duration (T_0), the digging duration in the first cycle (T_{d1}) and the corresponding frequencies (St_{Td0} , St_{Tf0} , St_{T0} and St_{Td1}) can be calculated (see Appendix A). The calculation method is discussed in Section 4.3.

Figure 3-4 Definition sketch of the scour hole dimensions

In the present study, two-dimensional scour profiles in the x and y span are investigated. x is the horizontal axis from upstream to downstream and y is the vertical axis. The apron edge is defined as the origin $(0, 0)$ as shown in Figure 3-4. The scour bed dimensions were extracted from the video recording, including y_s , which is the maximum scour depth at any instant of time, x_s , which is the horizontal distance of the location of the maximum scour depth, y_{ws} which is the depth of water surface above the maximum scour location, x_e , which is the horizontal distance of the downstream extreme end of the sand ridge, x_r , which is the horizontal distance of the sand ridge from the edge of the apron, y_r , which is the height of the sand ridge and y_b , which is the brink depth at any instant of time.

After each experiment, the scour hole dimensions were extracted from the video recording using the software 'WinDIG'. The software accepts any kind of 2D coordinate transformation. It accepts the axis system tilted by any angle from 0 to 360 degrees and even the two axes need not be perpendicular. The steps involved are as follows:

1. The first step is to save the snapshots from the video recordings. This can be done in many video players. The present study uses 'KMPlayer version 3.6'

and the snapshots taken are with a resolution of 640*480 pixels.

2. The next step is to define the x and y coordinates in the snapshots in 'WinDIG'. Three points need to be specified. These three points need not be on any particular axis, but all the three cannot be on the same line. In addition, the actual coordinates of these three points need to be known. For example, see the three yellow crosses in Figure 3-5. The three points have the coordinates of (0, 0), (50, 0) and (50, 15) (unit: cm) which are read from the ruler on the flume. Then these data are input into WinDIG. When this is completed, WinDIG will establish the transformation matrix. As a check, it will display the axis system tilt, and the angle between the two axes. This step can make the coordinates corresponding to that in the laboratory set-up because in practice, the recordings may not be in a perfectly horizontal or vertical direction.

3. After the coordinates system is defined, the cursor is moved to a point to digitize it by double clicking on the left mouse button. The x and y coordinates of the current point will then be added to the data list as shown in Figure 3-6.

4. Finally, the extracted data points are saved as a '*.dat' format file, which can be read by MATLAB and EXCEL.

Figure 3-5 Define the x and y coordinates of the snapshot

Figure 3-6 Data acquisition and saving using WinDIG

To test the accuracy of this method, grids were pasted on the glass wall of the flume. In Figure 3-7, the points (cross) on the grids were measured in the laboratory and also digitized using WinDIG. Table 3-6 and Figure 3-8 show the comparisons

between the measured coordinates in the laboratory and the digitized coordinates by WinDIG. The correlation coefficients R^2 can be as high as 0.999972 for x coordinates and 0.999911 for y coordinates. This indicates there is almost no distortion, and confirms the webcam method has high accuracy.

Figure 3-7 Grids on the flume wall and digitized in WinDIG

Figure 3-8 Comparisons of the measured coordinates in the laboratory and digitized by WinDIG (unit: cm)

Table 3-6 Comparisons of the measured coordinates in the laboratory and digitized by WinDIG (unit: cm)

x	y	x	y	x	y	x	y
Measured		digitized by WinDIG		Measured		digitized by WinDIG	
0	20	-0.2268	19.9990	70	10	69.8980	9.9768
10	20	9.8637	20.0450	80	10	79.9890	10.0230
20	20	19.7280	19.9760	10	0	9.9777	-0.0683
30	20	29.9320	20.0220	20	0	19.9550	-0.0229
40	20	40.0240	19.8410	30	0	29.8180	0.0219
60	20	60.2040	20.0460	40	0	40.0230	-0.0454
70	20	70.1820	19.8640	60	0	59.8630	0.1585
80	20	80.0470	19.7960	70	0	69.9530	0.3180
0	13	-0.0747	13.1810	80	0	79.8170	0.2492
20	13	19.8810	12.9310	0	-10	0.3981	-10.2250
30	13	29.9700	13.3180	10	-10	10.2630	-10.4080
40	13	40.1750	13.1370	20	-10	20.3530	-10.2480
60	13	60.0160	13.1140	30	-10	30.2160	-10.0900
70	13	70.1070	13.0460	40	-10	40.3070	-10.1580
0	10	-0.0560	9.8861	50	-10	50.2840	-10.1120
10	10	9.8070	10.0450	60	-10	60.1470	-9.9539
20	10	20.0110	10.0910	70	-10	70.1240	-9.7949
30	10	29.9890	10.0230	80	-10	79.8750	-9.9778
40	10	40.0800	9.9549	0	-15	0.6532	-15.2240
50	10	50.0580	9.7730	50	-15	50.3110	-14.8850
60	10	60.1480	9.8189	$R_x^2 = 0.999972, R_y^2 = 0.999911$			

3.1.6 List of experiments conducted

Altogether, 72 experiments were under taken in the present study, for which 40 runs featured jet-flipping. Table 3-7 and Table 3-8 list summaries of the ranges of the hydraulic conditions and results in the present study. The detailed hydraulic conditions and results are shown in Appendix A. Three parameters, the tailwater depth (Series H1 to H5), densimetric Froude number (Series F1 to F3) and apron (Series L1 to L6) were investigated systematically. The results are discussed in Chapter 6.

Some of these experiments were selected for other purposes. For example, Run 20 and Run 79 were selected to test the possible cause of the jet-flipping phenomenon. They were repeated for the ridge removal tests.

For Run 20, the sediment ridge formation was partially removed manually at the dynamic equilibrium state during the digging phase. The definition for the dynamic equilibrium state is introduced in Section 4.2.2. It is a state observed during the experiment with jet-flipping where there is no obvious scouring activity and the scour geometry achieves a stabilized shape. The removal was done quickly by taking the sediments of the ridge out of the flume using a flat dustpan. This usually took less than 3 minutes. This inevitably caused some disturbance to the flow but for a short time compared to the subsequently long observation period. For Run 79, the ridges were removed completely using the same procedures. The aim of ridge removal test was to determine whether the evolution of the ridge plays an important role in jet-flipping. The results are discussed in Section 5.2.

In addition, Run 122 was chosen to study the velocity distributions in the scour hole with jet-flipping. The detailed procedures are shown in the next section.

Table 3-7 Summary of experiments to study the effects of tailwater depth, densimetric Froude number and apron ($d_0 = 10$ mm)

Series	No. of runs	Run time (days)	d_{50} (mm)	Jet regime	H_t/d_0	F_0	L/d_0	d_{se-dig}/d_0	$d_{se-fill}/d_0$	max $\Delta d\%$
H1	12	2 to 20	0.29	SJ/JF/BJ*	2.0 to 23.0	8.8	9	3.2 to 14.1	2.1 to 9.4	36
H2	9	5 to 18	0.29	SJ/JF/BJ	5.0 to 23.0	10.4	9	3.8 to 16.4	3.3 to 11.1	35
H3	7	4 to 15	0.29	SJ/JF	5.0 to 21.5	12.2	9	4.2 to 18.8	1.7 to 12.8	60
H4	2	2 to 4	0.73	JF	12.7 to 16.0	6.5	30	3.9 to 4.4	2.8 to 3.0	31
H5	4	8 to 28	0.73	JF/BJ	12.7 to 16.0	5.6	9	8.7 to 8.9	7.1 to 7.8	16
F1	7	4 to 9	0.29	JF/BJ	10.0	5.4 to 16.2	9	5.8 to 10.8	4.6 to 8.1	36
F2	6	3 to 14	0.29	JF/BJ	16.0	6.8 to 16.2	9	8.1 to 17.1	8.3 to 11.0	45
F3	5	7 to 15	0.73	JF/BJ	16.0	6.7 to 7.7	9	11.1 to 13.6	7.9 to 10.6	42
L1	10	2 to 22	0.73	JF/BJ	12.7	6.5	0 to 45	2.0 to 14.7	2.8 to 10.4	46
L2	5	1 to 28	0.73	JF/BJ	12.7	5.6	0 to 30	3.0 to 12.7	2.3 to 7.1	17
L3	4	6 to 8	0.73	BJ	13.5	5.6	1 to 15	6.2 to 9.2	NA	NA
L4	2	3 to 15	0.73	JF/BJ	16.0	5.6	9 to 30	3.9 to 8.9	NA	NA
L5	2	12 to 18	0.73	JF	16.0	7.7	9 to 15	11.2 to 13.6	7.6 to 7.9	42
L6	8	6 to 15	0.73	BJ	3.0 to 17.8	5.6	0	11.3 to 18.1	NA	NA

*SJ = surface jet, BJ = bed jet and JF = jet-flipping

Table 3-8 Time durations and frequencies of jet-flipping

Series	T_0 (min)	T_{d0} (min)	T_{f0} (min)	T_{f0}/T_{d0}	T_{d1} (min)	St_{T0} (10^{-8})	St_{Td0} (10^{-8})	St_{Tf0} (10^{-8})	St_{Td1} (10^{-8})
H1	5.3 to 18688.0	0.3 to 6368.0	5.0 to 12320.0	1.9 to 17.0	0.8 to 7162.0	1.5 to 5189.2	4.3 to 91675.8	2.2 to 5500.6	3.8 to 34378.4
H2	5.8 to 5847.0	0.4 to 3486.0	5.4 to 2361.0	0.7 to 17.0	0.8 to 2816.0	4.0 to 4037.2	6.7 to 58740.6	10.0 to 4335.1	8.3 to 29370.3
H3	4.4 to 5688.0	0.4 to 2381.0	4.1 to 3427.0	0.9 to 15.2	0.5 to 14190.0	3.5 to 4504.5	8.4 to 54054.1	5.8 to 4914.0	1.4 to 42553.2
H4	23.0 to 27.0	2.0 to 3.0	21.0 to 24.0	8.0 to 10.5	14.0 to 54.0	869.4 to 1020.6	7824.7 to 11737.1	978.1 to 1117.8	434.7 to 1676.7
H5	3528.0 to 3528.0	2498.0 to 2845.0	680.0 to 1026.0	0.2 to 0.4	4076.0 to 6701.0	7.7 to 7.8	9.6 to 10.9	26.6 to 40.2	4.1 to 6.7
F1	14.2 to 2203.5	1.3 to 519.0	12.9 to 1684.5	3.3 to 15.2	2.0 to 663.0	16.2 to 1058.1	68.8 to 11289.5	21.2 to 1167.6	53.9 to 7507.5
F2	185.1 to 3383.0	30.8 to 830.0	154.3 to 2553.0	3.1 to 12.4	104.0 to 3907.0	8.1 to 81.1	33.1 to 487.0	10.8 to 97.3	7.0 to 144.4
F3	1076.0 to 3792.0	568.0 to 3433.0	267.0 to 590.0	0.3 to 1.0	3143.0 to 4666.0	7.9 to 18.9	6.1 to 35.4	34.0 to 76.1	4.5 to 6.9
L1	23.0 to 2349.0	2.0 to 1612.0	21.0 to 737.0	0.2 to 10.5	14.0 to 4220.0	10.0 to 1020.6	14.6 to 11737.1	31.9 to 1117.8	5.6 to 1676.7
L2	52.0 to 3524.0	3.0 to 2498.0	52.0 to 3524.0	0.4 to 16.3	10.0 to 6701.0	7.8 to 525.4	10.9 to 9107.5	26.6 to 557.6	4.1 to 2732.2
L5	1158.0 to 1839.0	568.0 to 1315.0	524.0 to 590.0	0.4 to 1.0	3377.0 to 4274.0	10.9 to 17.3	15.3 to 35.4	34.0 to 38.3	4.7 to 5.9

3.2 Measurements of flow field at threshold of jet-flipping

3.2.1 Fixed bed model

In order to measure the velocity distributions at the threshold point in time where jet-flipping occurs, two bed profiles at the end of the first digging phase for Run 122 (see profile A in Figure 3-9(a)) and at the end of the first filling phase for Run 122 (see profile B in Figure 3-9(d)) were extracted from the recorded video respectively. The hydraulic conditions for Run 122 were $F_0 = 7.67$, $H_t/d_0 = 16$, $L/d_0 = 15$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.83$ m/s and run time = 18 days.

Models of two bed profiles were then manufactured using aluminium alloy sheets. Sand was glued on the surface of the profile with a strong adhesive to simulate the actual bed roughness, as shown in Figure 3-9(b) and (e). Then the bed model was installed into the flume and fixed with silicone sealant (see Figure 3-9(c) and (f)). After it hardened several days later, the velocity profiles at different sections downstream of the sluice gate were measured. The fixed-bed models allow a long term velocity measurement without changing the shape of the sediment bed.

Figure 3-9 Run 122: (a) Aluminium bed profile A simulating the bed profile at the end of the first digging phase, (b) sands were glued to simulate the roughness, (c) installation of fixed-bed profile A; (d) Aluminium bed profile B simulating the bed profile at the end of the first filling phase, (e) sands were glued to simulate the roughness, (f) installation of fixed-bed profile B

3.2.2 Measurement of velocity using ADVP

The velocities were measured using the Acoustic Doppler Velocity Profiler (ADVP). The ADVP measures the instantaneous velocity vector at a number of layers within the water column (Lhermitte and Lemmin 1994). This instrument has been successfully used to measure the velocity distributions, turbulence characteristics and coherent structures in various free surface flows (Song et al. 1994; Kurniawan and Altinakar 2002). The ADVP model used in the present study was a Nortek Vectrino II. It includes a 4-beam down-looking probe and a fixed cable as shown in Figure 3-10(a). The ‘Vectrino II’ is suitable for high resolution boundary layer observations and for estimation of turbulence parameters. It can profile the water column over a 30 mm range (see Figure 3-10(b)) and provide three-component velocity observations with a resolution as fine as 1 mm and sampling rate as fast as 100 Hz. It also includes software which provides enhanced capabilities such as real-time plots of velocity profiles, velocity standard deviation and energy spectra. The accuracy of the water velocity can be as high as ‘($\pm 0.5\%$ of measured value) ± 1 mm/s’. The technical specifications are summarized in Table 3-9.

Figure 3-10 (a) Dimensions of ADVP; (b) ADVP can profile the water column over a 3 cm range; (c) The ADVP includes a 4-beam down-looking probe and a fixed cable; (d) Installation of ADVP onto the carriage above the flume

The instrument was installed on the carriage and point gauge above the flume as shown in Figure 3-10(c) and (d) (see also Figure 3-1). The carriage can be moved along the flume to measure the velocity at various x-locations, while the point gauge allows the instrument to be moved vertically up and down to measure the velocity at different depths.

Figure 3-11 shows the grids of the extent and coverage of the velocity measurements for the fixed bed model. The grids are spaced 40 mm apart longitudinally and 20 mm vertically in the crucial scoured and ridge regions. Due to the depth limitation of the ADVP set-up, no measurement was done for the area from the water surface to the depth 40 mm below the water surface.

Table 3-9 Technical specifications of the ADVP used in the present study (Nortek-AS 2012)

<p><u>Water Velocity Measurements</u> <i>Range:</i> 0.01 m/s in increments of 0.01 m/s to maximum of 3.0 m/s <i>Accuracy:</i> $\pm 0.5\%$ of measured value ± 1 mm/s <i>Sampling rate (output):</i> 100 Hz</p> <p><u>Sampling Volume</u> <i>Profile Range:</i> 3 cm <i>Location:</i> 4 – 7 cm from probe <i>Diameter:</i> 6 mm <i>Min cell size:</i> 1 mm</p> <p><u>Echo Intensity</u> <i>Acoustic frequency:</i> 10 MHz <i>Resolution:</i> Linear & log scale <i>Dynamic range:</i> 60 dB</p> <p><u>Sensors</u> <i>Temperature:</i> Thermistor embedded in probe <i>Range:</i> -4°C to 40°C <i>Accuracy/Resolution:</i> $1^{\circ}\text{C}/0.1^{\circ}\text{C}$ <i>Time response:</i> 5 min</p> <p><u>Data Communication</u> <i>I/O:</i> RS-485 (comes with high speed RS-485-to-USB converter) <i>Communication Baud rate:</i> Up to 1.25 Mbps <i>User control:</i> Handled via Vectrino II configuration and collection software <i>Analog outputs:</i> None <i>Synchronization:</i> SynchIn and SyncOut</p>	<p><u>Software (“Vectrino II”)</u> <i>I/O:</i> RS 485–USB support for devices with 1, 2, 4, and 8 serial ports. <i>Operating system:</i> Windows XP, Vista and 7 (32 and 64 bit) <i>Functions:</i> Instrument configuration, data collection, data storage. Probe test modes. <i>Multi Unit Operation:</i> Vectrino II software allows multiple Vectrino II to be run within a single instance of the program.</p> <p><u>Power</u> <i>DC Input:</i> 12–48 VDC <i>Peak current:</i> 2.5 A at 12 VDC (user selectable) <i>Max. consumption:</i> 4 W at 100 Hz</p> <p><u>Connectors</u> <i>Bulkhead:</i> Splash proof connector or MCBH-12-FS, bronze (Impulse) <i>Cable:</i> Splash proof or PMCIL-12-MP</p> <p><u>Materials</u> <i>Standard model:</i> Delrin® housing. Stainless steel (316) probe and screws.</p> <p><u>Environmental</u> <i>Operating temperature:</i> -4°C to 40°C <i>Storage temperature:</i> -15°C to 60°C <i>Shock and vibration:</i> IEC 721-3-2</p> <p><u>Dimensions</u> <i>See Figure 3-10(a) for main dimensions</i> <i>Weight in air:</i> 1.2 kg <i>Weight in water:</i> Neutral</p>
<p><u>Options</u></p> <ul style="list-style-type: none"> • 4-beam down-looking probe. Fixed stem or flexible cable • 50 m cable with choice of splashproof or impulse underwater connector • RS 485–USB converter (one-to-one) • Combined transportation and storage case 	

For a complete velocity measurement of the surface or bed jet regime, at least 15 hours are needed to make sure the measured results are correct. For each point, a 1 cm overlap between the adjacent points was measured to make sure the flow field (i.e. jet regime) did not change during the measuring process. For example, consider points P1 (160, 80) and P2 (160, 60) as shown in Figure 3-11. When measuring

point P1, the velocity data are within the water column over a 30 mm range from (160, 50) to (160, 80). For point P2, the data are for (160, 30) to (160, 60). Hence, the results between the overlapped region (160, 50) to (160, 60) are measured twice. The velocity distributions of points P1 and P2 are immediately calculated and plotted. If the velocity distributions of the overlapped area do not agree, the P2 measurements were repeated until the velocity distributions did agree.

Figure 3-11 Grids for velocity measurements

3.2.3 Velocity data acquisition using ADVP

The following procedures were used to extract the velocity data from the ADVP:

1. First, the software 'Vectrino II' was installed and the ADVP was connected to the computer.
2. As shown in Figure 3-12, all the necessary configurations must be set correctly in the software. The range of the velocity is an approximate value. The jet exit velocity of Run 122 is 0.83 m/s. Hence, the velocity range was set as 1 and the system then self-generates the approximate horizontal and vertical velocity range 1.931 and 0.565 m/s. The range of the first cell, last cell and cell sizes were set as 40, 70 and 1 mm respectively. As a result, 31 points with an interval of 1mm can be measured at a time. The measuring time was chosen as 3 minutes and the sampling rate was set as 100Hz, which means 18000 data were collected for each 30 mm water column. Other configurations in Figure 3-12 are

by default or self-generated.

3. The 'Connect' button was clicked to start the acquisition process.
4. The velocity data captured by the ADV were saved in a file with the format of '*.ntk'.
5. The '*.ntk' files were transferred using 'Vectrino II' into another file with the format '*.mat' which could then be read by MATLAB.
6. A MATLAB code was written (see Appendix C) to calculate the turbulence parameters, i.e. time-averaged velocity, and the results were saved in EXCEL for further analysis. Subsequently the software 'Grapher 7.0' was used to draw the velocity distribution figures.

Figure 3-12 Setting configurations of ADV before measurement

3.2.4 Velocity measurements for surface jet regimes

Two surface jet regimes were measured. One is at the start of the first filling phase under bed profile A and the other is at the end of the first filling phase under the bed profile B (see Figure 3-9). The following steps were used to conduct the velocity measurement:

1. First, the ADVP was installed in the flume. A spirit level was used to make sure the ADVP is vertical to the flume. Moreover, one of the four beams which has a red line must face downstream.
2. The pump was turned on. The tailwater depth, apron length and flow rate were adjusted to the same hydraulic conditions previously used to obtain the fixed-bed model. The flow was allowed to be stabilized, which could take a while.
3. Since the fixed-bed model was constructed based on the scour profile at the threshold of the jet-flipping phenomenon, it was necessary to check the water surface to see which type of jet regime was formed. A choppy surface indicated a surface jet regime and the measurements could proceed as described in step 5. However, if the water surface was calm, this indicated a bed jet regime. Then, step 4 should be performed to trigger the jet direction from the bed to the water surface.
4. To change the jet direction, a plate was placed above the sluice gate opening as shown in Figure 3-13(a). This caused the initially calm water surface to become slightly choppy after some time, which indicated the jet was changing flow direction. The plate was then removed slowly to ensure that the water surface continued to be choppy which indicated a surface jet has been formed.
5. The velocity measurements were initiated by activating the software program running on the computer after the flow stabilized. The ADVP was moved to various x-locations, with the point gauge attached to it allowing the ADVP to be moved vertically up and down to measure the velocity at different

depths. In the present study, the measurements were taken in the sequence of up to down and left to right. During the measuring process, the overlapped method was used to make sure the flow regime did not change (see Section 3.2.2)

6. Seeding such as kaolin clay was added to the approach section upstream of the sluice gate to enhance the measuring results.

Figure 3-13 (a) To induce the jet transfer from a bed jet to surface jet, (b) or transfer from a surface jet to bed jet with a plate

3.2.5 Velocity measurements for bed jet regimes

Two bed jet regimes were measured. One was at the end of the first digging phase under profile A and another was at the start of the second digging phase under profile B. The procedures were similar to the 6 steps described above, except for some differences in steps 3 and 4.

For step 3, if the water surface was calm, this signified a bed jet regime and the velocity measurements could proceed as in Step 5. However, if the water surface was choppy, a plate was placed in the scour hole, as shown in Figure 3-13(b), and the initially choppy water surface would become calm and the jet could be observed to be attaching to the plate after some time. The plate was then removed slowly to ensure that the water surface continued to be relatively calm which indicated a bed jet had been formed in the digging phase.

The velocity data obtained from the measurements were analysed, tabulated and are discussed in Chapter 5.

CHAPTER 4 OBSERVATIONS AND ANALYSIS OF JET-FLIPPING CHARACTERISTICS

The chapter presents studies of the scouring process with jet-flipping, the flow patterns and the evolution of the scour hole, the ridges and the scour volume. Some defining terms describing the jet-flipping phenomenon such as digging phase, filling phase, flipping cycles, time durations and frequencies are discussed.

4.1 Dimensional Analysis

Generally, the jet-flipping phenomenon involves two cyclical phases: a digging phase where the jet erodes the bed and forms a scour hole; and a filling phase where sediments are deposited in the scour hole due to the surface jet motion. Figure 4-1 shows definition sketches of the geometrical dimensions at the end of the digging and filling phases, respectively, and their corresponding photos taken from Run 13, ($F_0 = 6.5$, $H_t/d_0 = 12.7$, $L/d_0 = 21$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.71$ m/s, run time = 7 days). In the figure, x denotes horizontal distance from the edge of the apron, y is the vertical distance from the flat bed, y_s is the maximum scour depth at any instant of time, x_s is the horizontal distance of the location of the maximum scour depth, y_{ws} is the depth of the water surface above the maximum scour location, x_e is the horizontal distance of the downstream extreme end of the sand ridge, x_r is the horizontal distance of the sand ridge from the edge of the apron, y_r is the height of the sand ridge and y_b is the brink depth at any instant of time.

The maximum scour depth at any instant of time, y_s , which is the main characteristic parameter of the scour hole formed, may be written in a functional form as

$$y_s = f_1(u_0, d_0, L, H_t, \rho, \mu, d_{50}, \rho_s, \sigma_g, g, t) \quad (4-1)$$

Figure 4-1 Photos of bed profile during (a) digging phase and (b) filling phase;
Definition sketch of (c) digging phase and (d) filling phase

where u_0 is the jet exit velocity, d_0 is the jet opening size, L is the apron length, H_t is the tailwater depth, ρ is the water density, μ is the dynamic viscosity of water, d_{50} is median sediment diameter, ρ_s is the sediment density, g is the gravitational

acceleration and t is the scour time. The other related geometrical dimensions, x_s , y_{ws} , x_e , x_r , y_r and the volume of the scour hole, V_s may also be analysed in terms of the parameters on the right hand side of Eq.(4-1).

Using dimensional analysis, Eq.(4-1) may be expressed as,

$$\frac{y_s}{d_0} = f_2\left(Fr, \frac{L}{d_0}, \frac{H_t}{d_0}, \frac{d_{50}}{d_0}, Re, S, \sigma_g, \frac{d_0}{u_0 t}\right) \quad (4-2)$$

where $Fr = \frac{u_0}{\sqrt{gd_0}}$ is the flow Froude number, $Re = \frac{\rho u_0 d_0}{\mu}$ is the Reynolds number and $S = \frac{\rho_s}{\rho}$ is the specific gravity of sediment. Since the jet velocity used is high, Re will be large enough such that the effect of the viscosity on the jet hydraulics and its scouring should be insignificant (Rajaratnam 1976).

In the present study, the frequencies of the cyclical jet-flipping phenomenon are investigated, (see Section 6.6). The Strouhal number, $St = \frac{d_0}{u_0 T}$ is a useful dimensionless parameter to describe oscillating flow phenomena, where T is the period of the jet-flipping.

As introduced in Section 2.1.4.1, for local scour, Fr , d_{50}/d_0 and S may be combined to form a physically more meaningful term called the sediment densimetric Froude number, $F_0 = \frac{u_0}{\sqrt{(S-1)gd_{50}}}$. Hence, Eq.(4-2) becomes

$$\frac{y_s}{d_0} = f_3\left(F_0, \frac{L}{d_0}, \frac{H_t}{d_0}, \frac{d_{50}}{d_0}, \sigma_g, \frac{d_0}{u_0 t}\right) \quad (4-3)$$

Eq.(4-3) is the general functional relationship for the analysis and discussions in the

subsequent sections. For example, d_{se-dig} which is defined as the maximum value of y_s throughout each experiment and is usually reached at the end of the digging phase, and $d_{se-fill}$, which is defined as the minimum value of y_s throughout each experiment and is usually reached at the end of the filling phase, can be written as:

$$\frac{d_{se-dig}}{d_0} = f_4 \left(F_0, \frac{L}{d_0}, \frac{H_t}{d_0}, \frac{d_{50}}{d_0}, \sigma_g, \frac{d_0}{u_{0t}} \right) \quad (4-3b)$$

$$\frac{d_{se-fill}}{d_0} = f_5 \left(F_0, \frac{L}{d_0}, \frac{H_t}{d_0}, \frac{d_{50}}{d_0}, \sigma_g, \frac{d_0}{u_{0t}} \right) \quad (4-3c)$$

In Chapter 6, the effects of the six parameters on the right hand side of Eqs.(4-3) will be analysed individually to explain the characteristics of the local scour with and without jet-flipping downstream of a sluice gate.

4.2 Time development of bed profiles with jet-flipping

4.2.1 Jet-flipping, digging phase and filling phase

Figure 4-2 Centreline scour profiles with no jet-flipping for Run 2 ($F_0 = 6.19$, $H_t/d_0 = 7.7$, $L/d_0 = 0$, $d_0 = 9$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.67$ m/s, run time = 5 days, $d_{se}/d_0 = 16.4$)

Figure 4-2 shows a typical scouring process downstream of a sluice gate from the beginning of the test. The jet-flipping was not observed throughout this Run. Generally, it can be seen that the scour depth increases with time, and eventually attains an equilibrium state after a long scouring time. The figure shows that the scour profiles during the 40.6 hours scouring period from the 69 hr (hour) 53min (minute) to the 110 hr 27min remains almost the same. In many of the previous jet scour studies(Iwagaki et al. 1965; Rajaratnam 1981; Chatterjee et al. 1994; Lim and Yu 2002; Dey and Sarkar 2006), this would have been regarded as reaching the equilibrium scour condition. Additional figures for the experiments without jet-flipping are presented in Appendix D.

However, under certain hydraulic conditions, this study has found that a jet-flipping phenomenon would occur during the scouring process. The intermittent shifting of jet direction, from the bed to the water surface and vice versa, is called the jet-flipping phenomenon. With jet-flipping, there is no equilibrium scour condition being observed. Figure 4-3 shows snapshots of the evolution of the scour profiles with the jet-flipping from the beginning of the test for Run 209 ($F_0 = 10.4$, $H_t/d_0 = 10.0$, $L/d_0 = 9$, $d_0 = 10$ mm, $d_{50} = 0.29$ mm, $u_0 = 0.71$ m/s, run time = 4 days).

The photos from Figure 4-3(a) to (f) show that the jet, upon being released from the gate and flowing over the apron, begins to dig at the flat bed and soon a scour hole forms. The hole continues to deepen as the scour progresses until a stage is reached with no significant change in the scour depth, seemingly indicating an equilibrium state has been reached. This period is called the digging phase of the scour development. The water surface remained calm throughout the digging phase as shown in Figure 4-3(d) and (e). The arrows in these two photos show the bed jet direction. A clearer visualization photo using dye injection during the digging phase is shown in Figure 4-4. The photo shows that a cloud of blue dye is observed near the bed, suggesting that a bed jet is actively scouring the bed. The jet travels to the maximum scour depth location and subsequently flows up again (red line). This shows that the jet attaches itself closely to the bed and follows the curves of the scour

hole. A small loop (yellow line) that re-circulates back to the bottom of the sluice gate is also observed. In Figure 4-4(b), the jet splits into two portions as it travels to the water surface. A part of it backflows to the sluice gate forming a large recirculation loop (blue line). The other part of it continues to flow over the sand ridge and further downstream (purple line). This particular flow transports sand particles and deposits them further downstream. The accumulation of sand particles forms a sand ridge downstream of the scour hole.

Figure 4-3(g) shows the filling phase in progress with a surface jet, shown by two green arrow lines. A clearer photo using the dye injection, during the filling phase with a surface jet is shown in Figure 4-5. It can be seen that the jet flows towards the water surface and spreads into two opposite directions. A portion of it flows back to the upper part of the sluice gate forming an anticlockwise recirculation loop (red). The other portion continues to flow downstream and forms a large clockwise recirculation loop (blue). This particular flow causes sediments on the sand ridge to roll down and re-fill the scour hole. There is also a portion that flows horizontally downstream to the sand ridge (yellow). The filling takes place until there is no significant change in depth of the filled scour hole and at a point in time (Figure 4-3(i)), the surface jet is again transformed into a bed jet and the subsequent digging phase commences. Then the jet suddenly scours the bed rapidly (Figure 4-3(j)).

Figure 4-6 shows the time development of the scour profiles extracted from the recording for Run 79 ($F_0 = 5.6$, $H_t/d_0 = 12.7$, $L/d_0 = 9$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.61$ m/s, run time = 28 days). The figure shows three complete cycles of digging and filling phases. In Figure 4-6(a), the scour profiles from 61s to 409,203s (113.7hr) are the digging phase, at the end of which the digging action stops and the filling phase commences. The subsequent profiles of 412,108s (114.5hr) and 462,557s (128.5hr) showed that the scour hole became shallower because the jet flips to the water surface and causes sediments from the ridge region to roll down and back-fill into the scour hole. This is the filling phase.

Figure 4-3 Snapshots of jet-flipping for Run 209 ($F_0 = 10.4$, $H_t/d_0 = 9.8$, $L/d_0 = 9$, $d_0 = 10$ mm, $d_{50} = 0.29$ mm, $u_0 = 0.71$ m/s, run time = 4 days)

Figure 4-4 Flow directions in scour hole region during the digging phase

Figure 4-5 Flow directions in scour hole region during the filling phase

After the scour hole attains a minimum scour depth at the end of the filling phase, the second digging phase commences at 462,557s (128.5hr). After scouring for another 187 seconds (462,744s in Figure 4-6(b)), it can be seen that the bed has been eroded quickly to a depth of 6.2 cm. This is about 70% of the maximum scour depth achieved at 622,357s (172.9hr) at the end of the second digging phase which is also the start of the second filling phase. At this point in time, the jet flips to the water surface and the surface jet causes the sediments to back-fill into the hole again. 19.0 hours later at the profile 690,660s (191.9hr) in Figure 4-6(c), the scour hole reaches a minimum scour depth of about 7.2 cm which is almost the same as

the profile at the end of the first filling phase (profile for 462,557s). It is also the start of the third digging phase which ends at 891,030s (247.5hr) with a scour depth of 9.2 cm, which is almost the same as the first and second digging phases (462,557s and 622,357s profiles).

The digging and filling phases are periodic and the sequence continues alternately with nearly similar characteristics in the evolution of the bed profiles. The period from the start of a digging phase to the end of its corresponding filling phase is called “one cycle”. For Run 209, the time recorded for the first cycle is 2.4 hours (Figure 4-3(a) to (i)), and 128.5 hours for Run 79 (Figure 4-6(a)). This illustrates that the frequency of flipping will be different depending on the hydraulic conditions. This aspect is discussed in a later section.

Figure 4-6 Centreline scour profiles of Run 79 at different times; (a) A complete dig-fill cycle; (b) 2nd digging phase; (c) 2nd filling phase; (d) 3rd digging phase, ($F_0 = 5.6$, $H_t/d_0 = 12.7$, $L/d_0 = 9$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.61$ m/s, run time = 28 days)

Figure 4-7 and Figure 4-8 show that the bed profiles at the end of each digging/filling phase remained almost the same. Generally, the bed attains a sinusoidal shape with regular scour hole and ridge outlines at the end of each digging phase, and a sharper scour hole and ridge profile at the end of each filling phase. The only difference is that the ridges in the first few cycles are slightly higher compared to subsequent cycles. The evolution of the ridge profile is discussed further in Section 4.4.3.

One more case showing the evolution of the scour hole for the experiments with jet-flipping is presented in Appendix D.

Figure 4-7 Centreline scour profiles of Run 79 at (a) the end of digging phases; and (b) the end of filling phases for the first 4 cycles

Figure 4-8 Centreline scour profiles of Run 122 at the end of different (a) digging phases and (b) filling phases ($F_0 = 7.7$, $H_t/d_0 = 16$, $L/d_0 = 15$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.83$ m/s, run time = 18 days)

The characteristics of the slopes of the scour bed are investigated. Four slopes were recorded for both digging and filling phases as shown in Figure 4-9, where S_{hu} and S_{hd} are the slopes upstream and downstream of the scour hole, respectively; S_{ru} and S_{rd} are the slopes upstream and downstream of the ridge, respectively, and θ is the corresponding angle. These slopes of Run 79 were recorded in Table 4-1. And by

referring to Figure 4-6, conclusions can be drawn that S_{hu} , S_{hd} and S_{rd} are nearly constants for both digging and filling phases. S_{ru} is equal to S_{hd} for digging phase and therefore also constant. For filling phase, S_{ru} is decreasing with time, because the sediments on the ridge roll back into the scour hole.

Figure 4-9 Definition sketches of slopes of the scour bed during (a) digging phase and (b) filling phase

Table 4-1 The angles and slopes of the scour bed of Run 79 at different time

t (s)	θ_{hu} (°)	θ_{hd} (°)	θ_{ru} (°)	θ_{rd} (°)	S_{hu}	S_{hd}	S_{ru}	S_{rd}
61	-32	31	31	-32	-0.62	0.60	0.60	-0.62
266	-28	32	32	-29	-0.53	0.62	0.62	-0.55
19707	-28	33	33	-34	-0.53	0.65	0.65	-0.67
409203	-33	32	32	-33	-0.65	0.62	0.62	-0.65
409741	-32	40	35	-32	-0.62	0.84	0.70	-0.62
412108	-33	43	33	-33	-0.65	0.93	0.65	-0.65
462557	-33	41	24	-32	-0.65	0.87	0.45	-0.62
462744	-32	33	33	-32	-0.62	0.65	0.65	-0.62
463751	-31	35	35	-32	-0.60	0.70	0.70	-0.62
476907	-28	34	34	-32	-0.53	0.67	0.67	-0.62
622357	-34	34	34	-32	-0.67	0.67	0.67	-0.62
623782	-32	45	34	-34	-0.62	1.00	0.67	-0.67
627947	-32	45	30	-33	-0.62	1.00	0.58	-0.65
638891	-31	45	27	-33	-0.60	1.00	0.51	-0.65
690660	-27	41	24	-32	-0.51	0.87	0.45	-0.62
690882	-30	36	36	-33	-0.58	0.73	0.73	-0.65
692908	-33	34	34	-33	-0.65	0.67	0.67	-0.65
772107	-33	34	34	-33	-0.65	0.67	0.67	-0.65
891030	-35	34	34	-35	-0.70	0.67	0.67	-0.70

Because the bed profiles are almost the same at the end of each digging and filling phase, their averaged slopes S_{hu0} , S_{hd0} , S_{ru0} and S_{rd0} and their corresponding angles θ are recorded in Table 4-2. It can be found that $\theta_{hu0} \approx \theta_{rd0}$ for both digging and filling phases and $\theta_{ru0\text{-fill}} < \theta_{hd0\text{-dig}} < \theta_{hd0\text{-fill}}$. Migniot (1968) found that the angle of repose, ϕ for the gravel and sand in static water is in the range of 31° to 40° as shown in Figure 4-10, and $\phi \approx 34.7^\circ$ for $d_{50} = 0.73\text{mm}$ used in the present study. Hence, for Run 79, 122 and 21, $\theta_{ru0\text{-fill}}$ is usually much lower than ϕ , while $\theta_{hd0\text{-fill}}$ is sometimes greater than ϕ . Most of the other angles are slightly lower than ϕ for both the digging and filling phases.

Figure 4-10 Relationship between size of the non-cohesive sediment and angle of repose in the static water, redraw from Migniot (1968)

Table 4-2 The average angles and slopes of the scour bed at the critical conditions of Run 79, Run 122 and Run 21

	Run 79	Run 122	Run 21		Run 79	Run 122	Run 21
$S_{hu0-dig}$	-0.62	-0.65	-0.73	$\theta_{hu0-dig}$	-31.82°	-33.00°	-36.00°
$S_{hd0-dig}$	0.60	0.61	0.55	$\theta_{hd0-dig}$	31.00°	31.38°	29.00°
$S_{ru0-dig}$				$\theta_{ru0-dig}$			
$S_{rd0-dig}$	-0.62	-0.65	-0.73	$\theta_{rd0-dig}$	-31.83°	-33.00°	-36.00°
$S_{hu0-fill}$	-0.58	-0.51	-0.62	$\theta_{hu0-fill}$	-30.13°	-27.00°	-32.00°
$S_{hd0-fill}$	0.88	0.67	1.07	$\theta_{hd0-fill}$	41.45°	34.00°	47.00°
$S_{ru0-fill}$	0.36	0.45	0.42	$\theta_{ru0-fill}$	20.05°	24.00°	23.00°
$S_{rd0-fill}$	-0.59	-0.65	-0.60	$\theta_{rd0-fill}$	-30.44°	-33.00°	-31.00°
Angle of repose $\phi \approx 34.7^\circ$							

4.2.2 Dynamic equilibrium scour state

In jet scour without flipping, there are three distinct stages during the local scour process (Breusers 1965; Rajaratnam 1981; Nik Hassan and Narayanan 1985; Sarkar and Dey 2005): an initial stage with a rapid rate of scouring; a development stage with a relatively slower rate of scouring; and an equilibrium stage where there is no observable scouring activity and the scour geometry achieves a stabilized shape. Also, at the equilibrium phase, the scour hole attains its maximum depth. For runs with jet-flipping, the scour process also consists of the same three stages as above. However, there is no equilibrium scour condition but a dynamic equilibrium scour condition is observed. The dynamic equilibrium scour condition is a state observed during the experiment with jet-flipping where there is no obvious scouring activity and the scour geometry achieves a stabilized shape. This is illustrated by the following three runs, using snapshots of the dynamic equilibrium conditions for Runs 20 and 21, and detailed plots of the transitional profiles from the digging to the filling phases for Run 122.

Figure 4-11 shows the scour profiles during the dynamic equilibrium state for Runs 20 and 21. For Run 20 (Figure 4-11(a) and (b)), the scour profile for the first digging phase remains almost the same for a period of 4.6 hours (from 2010/10/27 17:00 to 2010/10/27 21:36). For Run 21, it is 11.9 hours (from 2010/11/13 02:00 to 2010/11/13 13:55). After this period, the jet flips to the surface and the filling phase begins. This observation shows that it is important to run tests long enough to be able to see whether jet-flipping occurs. This may be a reason why many previous studies did not report on the jet-flipping phenomenon in local scour.

Figure 4-11 Dynamic equilibrium scour state at end of first digging phase for: (a) and (b) Run 20, lasting 4.6 hr ($L/d_0 = 9$, run time = 7 days,); and (c) and (d) Run 21, lasting 11.9 hr ($L/d_0 = 3$, run time = 22 days,) (Both Runs: $F_0 = 6.5$, $H_t/d_0 = 12.7$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.71$ m/s)

Figure 4-12 clearly shows the 3 scouring stages for Run 122. The dotted lines represent the first half of the digging/filling phase and the solid lines represent the second half of it. The scouring or refilling process progresses rapidly initially (0-1688min, 3377-3639min, 3901-4559min and 5216-5478min) and slows down subsequently until the dynamic equilibrium state is reached, and thereby a new phase starts again. In Figure 4-12(a), the scour depth y_s increases and the position of the maximum scour depth x_s shifts downstream. At time 3377min, the scour hole reaches a maximum scour depth at the end of the digging phase d_{se-dig} . At that time, the first filling phase starts and the scour depth y_s decreases quickly, x_s shifts upstream, the ridge height y_r lowers and its position x_r shifts downstream (Figure 4-12(b)). At the end of the filling phase (3901 min), the scour hole reaches $d_{se-fill}$. At that point in time, the second digging phase commences, and the rate of scour is rapid which is similar to the first digging phase, and a secondary ridge soon forms (Figure 4-12(c)). At the end of the second digging phase (5216 min), the scour hole

attains the d_{se-dig} which is similar to the value of d_{se-dig} at the end of the first digging phase. Then the next filling phase starts. In Figure 4-12(d), the $d_{se-fill}$ is achieved at 5740 min at the end of the second filling phase which is similar to the value of $d_{se-fill}$ at the end of the first filling phase.

In this manner, the values of d_{se-dig} and $d_{se-fill}$ are extracted from the video recording. The analysis of the data is discussed in Section 4.4.2.

Figure 4-12 Centreline scour profiles of Run 122 during the (a) first digging phase, (b) first filling phase, (c) second digging phase, and (d) second filling phase

4.3 Definitions of frequency parameters of jet-flipping

The above discussions show that the jet-flipping phenomenon is a periodic process. Hence, the time sequences of the many cycles can be extracted from the video recordings for further investigation (see Appendix B). As an example, the first 11 dig-fill cycles of the time sequence of Run 79 are shown in Table 4-3. T_{fi} and T_{di} are the duration of the filling and digging phases in the i_{th} cycle, respectively. For the first cycle, $T_{d1} = 113.7hr$ and $T_{f1} = 14.8hr$. Figure 4-13 shows a 3-D plot of the centreline scour profile for the first 4 cycles. The time axis in this plot shows the time interval in each digging and filling phase. The durations of the digging and filling phases are quite consistent except for the first digging cycle. The evolutions of the scour profile at any instant of time are shown clearly in this figure. The shifting of the scour hole and sand ridge are similar in each filling phase. This also applies to the digging phases except for the first digging cycle.

It is noted that the duration of the first digging phase, T_{d1} is much longer than the subsequent digging phases for all the runs (see Appendix B). This can be explained by the fact that T_{d1} begins from an original flat bed condition whereas in the second cycle, T_{d2} starts from a lower bed, i.e. the $d_{se-fill}$ level achieved at the end of the first filling phase. Hence, T_{d2} would be shorter than T_{d1} to scour to the level of d_{se-dig} . In the analysis, T_{d1} is considered separately. It is worth noting that data on T_{d1} will be useful to guide how long it needs for a laboratory test in order not to miss the chance of observing the jet-flipping phenomenon. In this study the longest t_{d1} is 10 days, and the shortest is 30 seconds (see Appendix A). To this end, all the runs in this study were conducted for a sufficiently long period to ascertain whether jet-flipping occurred. The T_{d1} parameter is used to compare if the scouring time used by previous researchers is sufficiently long to be able to observe the jet-flipping phenomenon. This is discussed in Section 6.6.

Figure 4-13 3-D plot of the centreline scour profiles of Run 79 for the first 4 cycles

Table 4-3 Digging and filling durations of the first 11 cycles for Run 79

Cycle No.	Phase	Start Time		End Time		T _{di} (hr)	T _{fi} (hr)
1	Digging	7/3/2011	15:32	12/3/2011	9:12	113.7	14.8
	Filling	12/3/2011	9:12	13/3/2011	0:01		
2	Digging	13/3/2011	0:01	14/3/2011	20:24	44.4	19.0
	Filling	14/3/2011	20:24	15/3/2011	15:23		
3	Digging	15/3/2011	15:23	17/3/2011	23:02	55.7	17.5
	Filling	17/3/2011	23:02	18/3/2011	16:31		
4	Digging	18/3/2011	16:31	20/3/2011	10:12	41.7	18.8
	Filling	20/3/2011	10:12	21/3/2011	5:00		
5	Digging	21/3/2011	5:46	21/3/2011	15:06	9.3*	10.6
	Filling	21/3/2011	15:06	22/3/2011	1:42		
6	Digging	22/3/2011	1:42	24/3/2011	18:21	64.7	17.0
	Filling	24/3/2011	18:21	25/3/2011	11:22		
7	Digging	25/3/2011	11:22	26/3/2011	10:54	23.5	14.8
	Filling	26/3/2011	10:54	27/3/2011	1:44		
8	Digging	27/3/2011	1:44	29/3/2011	3:20	49.6	18.6
	Filling	29/3/2011	3:20	29/3/2011	21:58		
9	Digging	29/3/2011	21:58	31/3/2011	0:05	26.1	16.9
	Filling	31/3/2011	0:05	31/3/2011	17:00		
10	Digging	31/3/2011	17:00	3/4/2011	4:55	59.9	22.0
	Filling	3/4/2011	4:55	4/4/2011	2:55		
11	Digging	4/4/2011	2:55	5/4/2011	3:43	24.8	17.5
	Filling	5/4/2011	3:43	5/4/2011	21:10		
Note:* Pump stops accidently for 4.5 hours from 2011-3-21, 10:30 to 15:00							

Other important parameters used to describe the cyclical process are the average digging time (T_{d0}), the average filling time (T_{f0}) and the average time to complete one cycle of the digging-filling phase (T_0). These time parameters are defined as follows,

$$T_{d0} = \frac{\sum_{i=1}^{n-1} (T_{d_{i+1}})}{n-1} \quad (4-4)$$

$$T_{f0} = \frac{\sum_{i=1}^{n-1} (T_{f_i})}{n-1} \quad (4-5)$$

$$T_0 = T_{d0} + T_{f0} \quad (4-6)$$

$$\text{or } T_0 = \frac{\sum_{i=1}^{n-1} (T_{f_i} + T_{d_{i+1}})}{n-1} \quad (4-7)$$

where n is the total number of digging-filling cycles recorded for a run. In Eqs.(4-4) to (4-7), T_{d1} is excluded because it is the time taken in the first digging stage from a flat bed condition, as opposed to the subsequent digging duration which starts from the end of the filling stage. The characteristics of T_{d1} are analysed separately in a later section. Eqs.(4-4) to(4-7) and T_{d1} can also be non-dimensionalized in terms of the jet velocity, u_0 and jet opening, d_0 to form a Strouhal number, St , as follows,

$$St_{T0} = d_0/u_0T_0 \quad (4-8)$$

$$St_{T_{d0}} = d_0/u_0T_{d0} \quad (4-9)$$

$$St_{T_{f0}} = d_0/u_0T_{f0} \quad (4-10)$$

$$St_{T_{d1}} = d_0/u_0T_{d1} \quad (4-11)$$

The St is used to analyze the characteristics of jet-flipping frequency with respect to the hydraulics conditions. It is noted that this is also a key parameter in (Lin et al. 2008)'s investigation on the periodic oscillation caused by jet flow over a vertical drop pool.

4.4 Characteristic geometries of the scour hole

4.4.1 Periodic properties of the geometrical dimensions

In order to show the cyclical trend of the characteristic geometrical dimensions, Figure 4-13 is re-orientated as shown in Figure 4-14. It shows that y_s (indicated by the dark blue colour), x_s , y_r (dark red) and x_r change cyclically in accordance with the digging and filling phases. They increase during the digging phases and decrease in the filling phases. The length x_e (indicated by the light green colour on the right edge of Figure 4-14) increasing continuously throughout the scouring process, initially increases quickly and then slowing down. Figure 4-15 shows the maximum scour depth at any instant of time (y_s) change cyclically with an m-shaped trend in accordance with the digging and filling phases. Figure 4-16 shows that the water depths (y_{ws}) are also periodic, higher during the filling phases and lower during the

digging phases.

Figure 4-14 Trend of characteristic geometries of Run 79

Figure 4-15 Time variation of the maximum scour depth of Run 21 ($F_0 = 6.5$, $H_t/d_0 = 12.7$, $L/d_0 = 3$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.71$ m/s, run time = 22 days)

Figure 4-16 Time variation of the water surface height above the maximum scour location of Run13 with jet-flipping ($F_0 = 6.5$, $H_t/d_0 = 12.7$, $L/d_0 = 21$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.71$ m/s, run time = 7 days)

4.4.2 Scour depth during digging and filling phases

In jet scour studies, most researchers are mainly concerned with the dimension of the maximum scour depth. This parameter is important for design. The recording shows

that for most of the experiments with jet-flipping, the scour depth usually reaches its maximum value (d_{se-dig}) in the first few digging phases and remains relatively unchanged throughout the other cycles of jet-flipping (see Figure 4-12). Similarly, the minimum value of y_s recorded during each filling phase ($d_{se-fill}$) was also almost the same, even though the duration of the filling phase may be different.

Table 4-4 Maximum and minimum scour depths of Run 19

Jet-flipping cycle no.	End time of digging phase		d_{se-dig} (cm)	End time of filling phase		$d_{se-fill}$ (cm)
1	14-10-2010	14:32	8.4	14-10-2010	20:52	6.4
2	15-10-2010	11:46	8.0	15-10-2010	19:44	6.4
3	16-10-2010	2:41	8.0	16-10-2010	12:27	6.0
4	16-10-2010	21:16	8.4	17-10-2010	6:14	6.4
5	17-10-2010	15:34	8.4	18-10-2010	1:17	6.4
6	18-10-2010	5:57	8.0	18-10-2010	15:05	6.4
7	19-10-2010	0:46	8.4	19-10-2010	12:25	6.4
8	19-10-2010	23:41	8.8	20-10-2010	13:25	6.4
9	20-10-2010	21:01	8.8	21-10-2010	11:30	6.4
10	21-10-2010	19:05	8.4	22-10-2010	6:04	6.8
11	22-10-2010	12:21	8.0	23-10-2010	3:46	6.0
12	23-10-2010	11:21	8.0	24-10-2010	4:10	6.0
13	24-10-2010	12:29	8.4	25-10-2010	4:46	6.4
14	25-10-2010	16:05	8.4	26-10-2010	10:05	6.0

Table 4-4 lists the scour depths for 14 cycles in Run 19 ($F_0 = 6.4$, $H_t/d_0 = 12.7$, $L/d_0 = 15$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.69$ m/s, run time = 13 days). It can be seen that the d_{se-dig} varies between 8.0 to 8.8 cm for the 14 cycles. The $d_{se-fill}$ ranges from 6.0 to 6.8 cm. The maximum 8.8 cm (d_{se-dig}) and minimum 6.0 cm ($d_{se-fill}$) are recorded as the scour depths for Run 19. The percentage difference in scour depth between the two phases (Δd) is defined in Eq.(4-12).

$$\Delta d(\%) = \frac{(d_{se-dig} - d_{se-fill})}{d_{se-dig}} \times 100 \quad (4-12)$$

Based on the data collected in the present study (see Appendix A), the average Δd for

all the runs with jet-flipping is 30% and the maximum value is 60%. The upper bound of Δd is significant and should be considered in laboratory studies and field applications.

Table 2-1 lists some of the more recent prediction equations proposed for 2-D jet scour below a sluice gate with an apron (Lim and Yu 2002; Dey and Sarkar 2006; Melville and Lim 2013). These equations were developed based on a database that covers a wide range of flow conditions and sediment sizes. Jet-flipping either did not occur or was not clearly mentioned in these previous experiments. In the present study, there are 40 experiments (out of 72 runs) with jet-flipping (Appendix A). A comparison is made to see how well the prediction equations for no-flip conditions perform with the measured d_{se-dig}/d_0 with jet-flipping. The results are plotted in Figure 4-17.

The comparison shows that under the same hydraulic conditions, scour is more severe if jet-flipping occurs compared to the no-flip scour conditions. The under prediction using Eqs.(2-7) to (2-10) are 80%, 83%, 76% and 68%, respectively. In practice, this implies that it is important to check whether jet-flipping would occur given a particular hydraulic condition. Otherwise, the design may under-estimate the scour depth when using a prediction equation with no consideration for jet-flipping. To this end, a criterion is proposed in this study for the threshold of jet-flipping in local scour and a time scale to check if sufficient scouring time has been provided in a test to allow jet-flipping to be observed. This is discussed in Chapter 6.

Figure 4-17 Comparison of the maximum scour depths computed using Lim and Yu (2002), Dey and Sarkar (2006) and Melville and Lim (2013)'s equations (Eqs.(2-7) to (2-10)) for no-flip conditions with measured maximum scour depths with jet-flipping from the present study

4.4.3 Ridge profile during digging and filling phases

The sand ridge profile experienced transitional changes during the dig-fill flipping cycles. Figure 4-18 shows 3 snapshots of the change to the shape of the sand ridge and its extreme end, x_e (Figure 4-1) for Run 13. This run has 41 recorded flipping cycles (see Appendix B) and the photos were taken at the end of the digging phases for 3 different cycles to show the change of the shape of the ridge over the 6.5 days of run time. It can be clearly seen that the scour hole part remains almost the same, but

the ridge height decreases and its shape changed considerably after 41 flipping cycles.

Figure 4-18 Transition of the scour profiles. The photos were extracted from Run13 (a) 24/8/2010, 05:32, (b) 25/8/2010, 04:37, (c) 30/8/2010, 16:25. The dashed line refers to the ridge profile from photo (a).

The ridge profiles in Figure 4-18(b) and (c) can be seen being flattened and lengthened compared to Figure 4-18(a), resulting in a reduced ridge height. Figure 4-18(c) shows that the ridge materials in the shaded region were deposited further downstream, giving an elongated and flattened bed profile downstream of the crest after about 6.5 days of scouring action. The change in ridge profile is usually not so significant during the first few cycles, (see Figure 4-7(a)). But in some experiments, and Run 13 is one such example, the ridge profile is significantly altered (Figure 4-18(c)) as more digging-filling cycles occurred. This is because more sand particles have ‘escaped’ to the downstream as the scouring time and flipping cycle increases

and there are relatively fewer particles in the hole-ridge region compared to earlier cycles. The net effect is that back-filling of sediments from the ridge to the scour hole takes a longer time to fill the hole to the same level ($d_{se-fill}$) to trigger the next digging phase. This also means the filling time T_{fi} will increase as more flipping cycles occurred. This is best illustrated with an example. Figure 4-19 shows the time sequence of Run 14 which registered 70 cycles in 2 days (see Appendix B). It can be seen that while the digging duration remains relatively unchanged, the filling duration generally increases with the number of cycles. This is because the jet digs to almost the same depth to trigger the next filling phase.

Figure 4-19 Time-sequence of each digging and filling phase of Run 14 ($F_0 = 6.5$, $H_t/d_0 = 12.7$, $L/d_0 = 30$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.71$ m/s, run time = 2 days)

Observations also showed that more than one ridge was formed during the digging/filling phases. Figure 4-20 shows visually the profiles of multiple ridges formation during the digging phase (photos a and b, two ridges), during the filling phase (photo c, two ridges) and during the subsequent digging phase (photo d, three ridges).

Figure 4-20 Snapshots showing multiple ridges formation during (a) and (b) digging phase and (c) filling phase (d) subsequent digging phase (Run166: $F_0 = 7.5$, $H_t/d_0 = 16.0$, $L/d_0 = 9$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.82$ m/s, run time = 8 days)

Some figures shown in earlier sections are worth noting here to highlight the process of ridge formation during the digging phase. Two good examples are Figure 4-6 and Figure 4-12. The two ridges formation can be seen clearly during the second digging phase in the former (Figure 4-6(b)) and again during the start of the third digging phase (Figure 4-6(d)). The latter (Figure 4-12(c)) shows how a new ridge formed in

the scour zone at the beginning of a digging phase progressively merges to form a single ridge with the original one towards the end of the digging phase.

On the other hand, during the filling phase, the progression of the multiple ridges formation is different and may have influence on the frequency of flipping duration. Run 13 is a good example for further discussion. Figure 4-21 and Figure 4-22 show visually the time development of the formation of the sand ridge during the second and third filling phases for Run 13, respectively. In these photos, 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 a previous cycle or the 1st cycle. Figure 4-21 shows the sequence of the current d_{h2} ridge progressively overtopping on the ridge d_{h1} formed from the previous cycle, whereas Figure 4-22 shows that of the current d_{h2} progressively merging below the d_{h1} formed from the previous cycle.

Overall, it can be seen that with jet-flipping, the ridges are quite different from the previous studies. The observations of the ridges can help to judge whether jet-flipping occurs or not. To this end, if similar types of experiments are conducted but without the video recording setup as in the present study, then the appearance of multiple ridges during the scour process probably indicates that jet-flipping has occurred.

(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 4-21 Sequence of the current d_{h2} formation overtopping on d_{h1} formed from previous cycle for Run 13

(a) Third filling phase (time: 22:39:16)

(b) Third filling phase (time: 22:52:54)

(b) Third filling phase (time: 23:25:51)

Figure 4-22 Sequence of the current d_{h2} formation merging below d_{h1} formed from previous cycle for Run 13

4.4.4 Scour volume

The volume of the scour hole per unit transverse width at any time, V_s was computed from the photo extracted from the video recording. As shown in Figure 4-23, the area of the scour hole is divided into small rectangular columns. As introduced in Section 3.1.5, the coordinates of the points on the scour profile can be obtained by WinDIG. Hence, the shaded area $A_i = (x_{i+1} - x_i)y_i$ and $V_s \approx |\sum_{i=1}^n A_i|$ can be calculated. The more points used, the more precise is the estimation of V_s . For Run 79, about 20 points were extracted from the scour hole for each screenshot.

Figure 4-23 Method used to calculate the volume of scour

Figure 4-24 Variation of scour volume with time for Run 79

Figure 4-24 shows the variation of V_s with time over 4 cycles for Run 79. It can be seen that in each digging or filling phase, there is an initial stage with a rapid rate of scouring or refilling; a development stage with a relatively slower rate of scouring or

refilling; and then the scour volume attains a maximum value (V_{s-max}) at the end of each digging phase or a minimum value at the end of each filling phases (V_{s-min}). Meanwhile, the maximum scour depth reaches the maximum value (d_{se-dig}) or the minimum value ($d_{se-fill}$). For various cycles, the dimensionless volume of scour (V_s/d_0^2) during the digging, and filling phases are plotted with dimensionless time (u_0t/d_0) as shown in Figure 4-25(a) and (b), respectively. The figures show that the evolution of the scour volume with time is similar in each cycle. In Figure 4-25(a), it can be seen that the data points for the volume of the first digging phase (indicated as ‘cycle 1-dig from flat bed’) deviate from the other cycles. As explained in Section 4.3, this is because in cycle 1, the scouring action begins from the original flat bed condition; hence the duration of the first digging period is longer than the following cycles. After subtracting T_0 from T_{d1} , the data points for cycle 1 (‘cycle1-dig from $d_{se-fill}$ ’) agree well with the rest of the cycles and the trend of Eq.(4-13).

The following equations can be fitted for the digging Eq.(4-13) and filling Eq.(4-14) phases respectively, where R is the correlation coefficient, and the subscript ‘dig’ and ‘fill’ indicates during the digging and filling phases respectively. For the digging or filling phases, the scouring or filling rate is very rapid at the beginning, and it is difficult to record the scour volume precisely. Therefore, the data used for fitting these equations are for $t > 0$. Eq.(4-13) is valid for $t \geq 29s$ and Eq.(4-14) for $t \geq 69s$.

$$\frac{V_{s-dig}}{d_0^2} = 98435 \ln\left(\frac{u_0t}{d_0}\right) + 54068, \quad R^2 = 0.795 \quad (t \geq 29s) \quad (4-13)$$

$$\frac{V_{s-fill}}{d_0^2} = -8555 \ln\left(\frac{u_0t}{d_0}\right) + 3 \times 10^6, \quad R^2 = 0.841 \quad (t \geq 69s) \quad (4-14)$$

The corresponding sediment bed load transport rate $q_b(t) = \frac{d(V_s)}{d(t)}$ can be estimated as,

$$q_{b-dig}(t) = \frac{d(V_{s-dig})}{d(t)} = 98435 \frac{d_0^2}{t} \quad (4-15)$$

$$q_{b-fill}(t) = \frac{d(V_{s-fill})}{d(t)} = -8555 \frac{d_0^2}{t} \quad (4-16)$$

In Figure 4-26, the scour volume V_s/d_0^2 shows a clear trend with the scour depth y_s/d_0 during the digging and filling phases, especially for the digging phases. The relationship between the volume of scour and scour depth is given by Eqs. (4-17) and (4-18). The data used in the correlation starts from 61 seconds for Eq. (4-17) and 409,367 seconds for Eq. (4-18). As a result, the volume of the scour hole can be easily estimated from the scour depth.

$$\frac{V_{s-dig}}{d_0^2} = 26.9 \frac{y_s}{d_0} - 72.0, \quad R^2 = 0.97 \quad (4-17)$$

$$\frac{V_{s-fill}}{d_0^2} = 19.8 \frac{y_s}{d_0} - 26.3, \quad R^2 = 0.71 \quad (4-18)$$

Figure 4-25 Variation of the scour volume during (a) digging phase, and (b) filling phase with time for Run 79

Figure 4-26 Correlation of dimensionless maximum scour depth at any instant of time versus volume of the scour hole per unit transverse width during (a) digging and (b) filling phases for Run 79

4.4.5 Brink depth

Lim and Yu (2002) indicate that the localized scour region at the interface between

the solid apron and sand bed, i.e., at the brink of the apron (y_b in Figure 4-1), is also of concern to the engineers. The reverse flow in the toe region immediately downstream of the apron is the cause of the brink erosion. They found the maximum brink or backwater scour depth, y_{bmax} at the downstream end of the apron is linearly related to the maximum scour depth d_{se} given by Eq.(2-4) and Figure 2-9.

In the present study, the brink depths at any instant of time y_b of Run 79 were extracted for analysis. Results show that only in the first digging phase, the brink depth developed from the flat bed. However, in the following filling or digging phases, the brink depth does not change much, i.e. y_b/d_0 varying from 2.9 to 4.5 for the 2nd to 4th digging phases and, and 3.1 to 4.9 for the 1st to 4th filling phases as shown in Figure 4-27. The reason is that y_b in the following digging or filling phase is almost equal to y_b at the end of the first digging phase, and it is not much affected by the dig-fill process. Therefore, when considering the brink depth with jet-flipping, it is only necessary to consider the brink depth at the end of the first digging phase.

The data of y_b/d_0 in the first digging phase recorded from 61seconds can be linearly related to y_s/d_0 as follows,

$$\frac{y_{b-dig}}{d_0} = 0.29 \frac{y_s}{d_0} + 1.39, \quad R^2 = 0.80 \quad (4-19)$$

For comparison, Lim and Yu (2002)'s Eq.(2-4) is also plotted in Figure 4-27(a). It can be seen that 77% of the data with jet-flipping are higher than the no jet flip values predicted using Eq.(2-4). This implies that it is important to check whether jet-flipping would occur or the design may under-estimate the brink depth when using a prediction equation with no consideration for jet-flipping.

Figure 4-27 Correlation of dimensionless maximum scour depth at any instant of time versus brink depth during (a) digging and (b) filling phases for Run 79

4.5 Importance of the apron downstream of a sluice gate

In this study, it was observed that without an apron (i.e. $L = 0$) downstream of the sluice gate, jet-flipping was not observed throughout the entire experiment. It is noted

that previous researchers who discovered jet-flipping downstream of a sluice gate did their experiments with an apron (Balachandar and Kells 1997; Balachandar et al. 2000; Lim and Yu 2002; Gautam 2008). Experiments (Series L6 in Appendix A, $F_0 = 5.6$, $L/d_0 = 0$ and $H_t/d_0 = 3.0$ to 17.8) were done to confirm whether the existence of an apron is important for the occurrence of jet-flipping. Series L6 were designed according to the hydraulic conditions of Run 79 ($F_0 = 5.6$, $L/d_0 = 9$ and $H_t/d_0 = 12.7$). Flipping was observed in run 79. With the same F_0 , and adjusting L/d_0 to 0, the tailwater depths were varied from $H_t/d_0 = 3.0$ to 17.8 , and no flipping was observed. The discharge was increased to $F_0 = 6.5$ (Run 16, $F_0 = 6.5$, $L = 0$ and $H_t/d_0 = 12.7$) and again, no flipping was observed. However, after adding an apron to Run 16, i.e. $L/d_0 = 1$ to 30 , flipping occurs (refer to Series L1 in Appendix A). This suggests that installing an apron downstream of the sluice gate is an important criterion to trigger the flipping phenomenon. The apron somehow acts like a ‘springboard’ and with the right hydraulic conditions, jet-flipping occurs during the scouring process.

However, the jet-flipping may be observed without an apron downstream of other hydraulic structures. Mazurek et al. (2009) and Ahsan (2003) found jet-flipping downstream of a rectangle nozzle without an apron. The experimental setup is shown in Figure 4-28. It is a box-like nozzle, which is like a 3-D jet but spanning the whole channel width and therefore it is called a 2-D jet. This type of set up has 3-D flow characteristics downstream of the nozzle (Ali and Lim 1986) and is different from the present study.

Figure 4-28 Experimental setup with an rectangle nozzle in Ahsan (2003)'s work

CHAPTER 5 VELOCITY DISTRIBUTIONS OF THE FLOW FIELD AND THE TRIGGER MECHANISM OF JET-FLIPPING

For a better understanding of the jet-flipping mechanism, the flow fields in the threshold scour hole profile were measured, separately, for the instant when the jet was attached to the bed, and on another instant when it was flowing towards the water surface. The former is under a bed-jet regime and the latter is a surface jet regime. The velocities were measured using an ADV in two specially constructed fixed-bed models, one with the scoured bed profile at the end of the digging phase, and the other at the end of the filling phase. The details of the set-up are given in Chapter 3. The velocity vectors and their magnitudes, velocity components in the x and y directions are investigated in this chapter. This chapter also examines the possible trigger mechanism of the jet-flipping in two parts. One is the region downstream of the scour hole, to examine whether the transportation of the sediments downstream of the scour hole causes the jet to flip. The second is the region upstream of the scour hole, to examine whether the interactions of the free surface, bed boundary and the jet location trigger the jet-flipping.

5.1 Velocity distributions of the flow field

5.1.1 Velocity vectors in x-y plane

As discussed in Section 4.2.1, the visualisation of the flow pattern using dye injection (Figure 4-4 and Figure 4-5) shows that there are two recirculation regions during the digging and filling phases. The flow directions in the scour hole region are in exact opposite direction during the digging and filling phases, and have resulted in the alternating erosion and deposition of sediments in the scour hole. It is therefore clear that the sediment transport mechanism depends on the flow patterns, and that there is a critical point in time that the flow will suddenly switch from a bed jet to a surface jet and vice versa.

The velocity measurements were carried out in two fixed-bed scoured bed profiles. One (Profile A) is extracted at the end of the digging phase in cycle 1 of Run 122 ($F_0 = 7.67$, $H_t/d_0 = 16$, $L/d_0 = 15$ and $u_0 = 0.833$ m/s). The other (Profile B) is at the end of filling phase in cycle 1. From the recording, it was observed that it takes 6.4 hours for the end-of-digging bed profile to evolve into the end-of-filling bed profile. Due to the limitation of the ADV, the flow fields were measured only for depth with $y \leq 10$ cm.

Figure 5-1(a) shows that the sediment bed attained a sinusoidal shape at the end of the digging phase (Profile A) and reached a dynamic equilibrium state (see also Section 4.2.2). In this figure, the velocity vectors represent the resultant of the streamwise u and vertical w velocity components. It is clear that the jet dives and impinges on the bed after leaving the apron. Above the jet there is a large anticlockwise recirculation region that extends to $x = 35$ cm. The centre of this region is located at about $(x, y) = (20, 5)$. The recirculation region provides a significant downward velocity component near the edge of the apron, which contributes to the scouring action.

As shown in Figure 4-12(a), the flow pattern suddenly transferred from the bed jet into a surface jet at the end of digging phase. This signifies the start of the subsequent filling phase. The change of phase occurs almost instantaneously every time, accompanied by a sudden flick in jet direction. During the velocity measurement with the fixed profiles, the transformation of the jet regimes was done manually (see Section 3.2.3). For the surface jet regime as shown in Figure 5-1(b), the jet approaches the water surface immediately after leaving the apron. It splits into upstream and downstream directions at about $x = 15$ cm, forming two recirculation regions with centres at about $(8, 7)$ and $(28, 5)$. The clockwise recirculation provides a significant downward velocity component near the slope of the ridge, causing sediments on it to slide down and back-filling of the scour hole. The anticlockwise recirculation makes the water surface rise between $x = 5$ to 20 cm, the zone looking like ‘boiling’. Hence, Figure 5-1(a) and (b) clearly show the velocity distribution patterns at the threshold end-of-digging bed profiles whence the jet flips from a bed jet to a surface jet. The latter is the flow pattern responsible for the start of a subsequent filling phase.

As shown in Figure 4-12(b), at the end of the filling phase, the bed would attain a new profile (Profile B) with comparatively sharper ridge and scour hole, as shown in Figure 5-1(c). This figure shows the velocity distributions of the surface jet and looks similar to that in Figure 5-1(b). It has two recirculation zones with centres at about the (x,y) coordinates (8, 7) and (30, 6), (unit: cm). Again, under the same bed Profile B, the flow pattern transfers as shown in Figure 5-1(d). It represents the start of a subsequent digging phase. This figure shows the bed jet flow pattern which is similar to Figure 5-1(a) where the jet is seen to attach itself to the bed after leaving the apron. A large anticlockwise recirculation region is formed above the bed jet but extends further downstream to $x = 45\text{cm}$ due to the change in bed profile. The centre of recirculation is at about (28, 7). A small clockwise recirculation is also observed in the scour hole. The flow fields shown in Figure 5-1(a) to (d) repeat cyclically over many cycles of the jet-flipping phenomenon.

Figure 5-1 Velocity vectors of Run 122 with (a) bed jet at Profile A(end of 1st digging phase), (b) surface jet at Profile A(start of 2nd filling phase), (c) surface jet at Profile B (end of 2nd filling phase), and (d) bed jet at Profile B(start of a 3rd digging phase)

5.1.2 Distributions of streamwise velocity components (u) along x-direction

Figure 5-2(a) shows the streamwise u velocity components of the bed jet and surface jet at various x-locations around the scour region (i.e. $x = -10$ to 60 cm) with Profile A. Each individual graph in the figure shows the vertical distribution of u components at the same x-location.

The velocity profiles for the bed jet in the scour hole region (around $x = 5$ to 35 cm) are practically self-preserving (Dey and Sarkar 2008). The bed jet's u components are positive near the bed and negative near the water surface, indicating downstream movement near the bed and upstream movement near the water surface. These flow movements are represented by the anticlockwise recirculation region as shown in Figure 5-1(a). Also, it can be seen that the u components are highly positive (approximately 0.8 m/s) near the apron, less positive (approximately 0.4 m/s) at the scour bed and become almost uniform when the jet exits the scour hole region. This suggests that the flow velocities are close to mean jet velocity u_0 (0.833 m/s) when released from the sluice gate opening but generally decrease in the vicinity of the scour hole due to the energy loss. The near-zero u velocities at about $x = 50$ cm suggest a change in sign from positive to negative since the jet bends and returns upstream to form recirculation in the scour hole region. Contrary to the bed jet, the surface jet's u components are positive near the water surface and negative near the bed from $x = 12$ to 45 cm. This is represented by the clockwise recirculation region in Figure 5-1(b). Near the apron (from $x = -7$ to 12 cm), the surface jet's u components are represented by an anticlockwise recirculation region as shown in Figure 5-1(b).

5.1.3 Distribution of vertical velocity components (w) along x-direction

Figure 5-2(b) shows the vertical w velocity components of bed jet and surface jet at various x-locations around the scour region with Profile A. Each individual graph in the figure shows the vertical distribution of w components at the same x-location.

For the bed jet, w velocity components are negative from the sluice gate to the centre

of the scour hole, and positive from the centre of the scour hole to the end of the scour region. This suggests a change in the vertical direction of the jet, from downwards to upwards, at the section of maximum erosion. It relates to a digging action. For the surface jet, the most prominent feature is between $x = 0$ to 16 cm, where the jet is observed to be directed up to the water surface at an angle. Also, a ‘bulge’ is observed on the water surface around $x = 16$ cm. Since the upward velocity of the jet is not high enough to cause it to pierce the water surface, the jet spreads into two directions and forms two recirculation regions as shown in Figure 5-1(b). In addition, the presence of downward velocity components near the ridge induced sediments from the slope to roll down and back-fill the scour hole.

Figure 5-2(c) and (d) show the streamwise u and vertical w velocity components of the bed jet and surface jet at various x -locations around the scour region (i.e. $x = -10$ to 65 cm) with Profile B. The velocity components are similar to Figure 5-2(a) and (b). The bed profile interacts closely with the flow. Referring to section $x = 8$ cm and comparing Figure 5-2(a) and (c), the maximum u for the bed jet is at about (8, -3) and (8, 1) respectively, while for the surface jet it is at about (8, 0) and (8, 4). This indicates that the location of the maximum u was higher because of the change of the bed profile.

Figure 5-2 Velocity components of Run 122; (a) Streamwise u at Profile A, (b) vertical w at Profile A, (c) streamwise u at Profile B, and (d) vertical w at Profile B

5.1.4 Magnitude of velocity vectors in x-y plane

Figure 5-3 shows contour lines of the magnitude of velocity vectors in the x-y plane. The contour lines between $y = 10$ cm to 15 cm in Figure 5-3 were extrapolated as the ADVP is not able to measure in this region. The magnitude is normalized by the mean jet velocity, and expressed as $\frac{\sqrt{u^2+w^2}}{u_o}$. During the digging phase, high velocities are observed near the bed from $x = 0$ to 40 cm in Figure 5-3(a) and from $x = 0$ to 50 cm in Figure 5-3(c) because of the change in bed profile. The jet hits the bed at high velocity but loses some of its kinetic energy as it moves upwards at about $x = 45$ cm (Figure 5-3(a)). During the filling phase, high velocities are observed near the apron and the path to the water surface (indicated by the blue region) as shown in Figure 5-3(b) and (d). Velocities in the vicinity of the bed are apparently low. Moreover, the centres of recirculation are evident in the plots. They are indicated by the red circles at about $(28, 7)$ in Figure 5-3(a), and $(8, 7)$ and $(30, 6)$ in Figure 5-3(b).

Figure 5-3 Magnitude of velocity vectors in x-y plane of Run 122 with (a) bed jet at Profile A(end of 1stdigging phase), (b) surface jet at Profile A(start of 2ndfilling phase), (c) surface jet at Profile B (end of 2ndfilling phase), and (d) bed jet at Profile B(start of a 3rddigging phase)

5.2 Discussions on the possible trigger mechanism of jet-flipping

5.2.1 Partial sediment ridge removal test

As introduced in Section 4.4.3, the evolution of the sediment ridges is influenced by the flipping process, and the ridge profiles are different from the usual no-flipping jet scour studies. In order to determine whether the evolution of the ridge plays an important role in jet-flipping, sediment ridge removal tests were conducted. In these experiments, the sediment ridge formation was removed manually at the dynamic equilibrium state during the digging phase. The process was done quickly by taking the sediments of the ridge out of the flume using a flat dustpan. This inevitably caused some disturbance to the flow, but the disturbance was short compared to the subsequently long observation period subsequently. The qualitative assessment on whether jet-flipping continues to occur without a ridge was conducted in Runs 20 and 79.

In Run 20, jet-flipping was observed before the ridge removal, and the ridges were partially removed in the 9th digging phase (Figure 5-4(a)) after a scouring duration of 194.2 hours from the start of the experiment. According to Table 5-1, the scour dimensions in Figure 5-4(a) in the 9th digging phase are almost the same as those at the end of the 8th digging phase. Therefore the scour in Figure 5-4(a) is regarded to have reached the dynamic equilibrium state. Several minutes later, the shaded area was removed as shown in Figure 5-4(a) and (b). Figure 5-4(b) shows several minutes after the ridge removal. The red dashed lines in Figure 5-4(b) and (c) are the scour profile in (a). It can be seen that, during the ridge removal process, some of the sediments rolled back into the scour hole and the ridge moved upstream slightly because of the manual disturbance. Figure 5-4(c) shows the profile 4.4 hours after the ridge was removed. Some sediments had been eroded and deposited on the ridge region compared to Figure 5-4(b). The scour hole and the ridge become similar to the profile in Figure 5-4(a) (red dashed line). One minute later (Figure 5-4(d)), the jet flips up (note the wavy water surface) and the filling phase begins. Figure 5-4(e) and (f) show the refilling is in progress. The digging and filling phases continue

after the ridge removal test.

Figure 5-4 (a) scour hole and ridge formation at the dynamic equilibrium state in 9th digging phase; (b) Photo showing scour profile after the ridge in (a) was removed (the red dashed line was the previous profile in (a)); (c)-(f) After partially removing the ridges, it started to fill from the moment at (c), (the black dashed lines in (c) and (d) is the water surface profiles) of Run 20 ($F_0 = 6.5$, $H_t/d_0 = 12.7$, $L/d_0 = 9$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.71$ m/s, run time = 14 days)

Figure 5-5 shows 4 photos to compare the bed profiles at the end of 2 typical filling or digging cycles before and after the ridge removal. The aim of these photos is to show that the scour hole region remains relatively unchanged although the ridge was different because of its removal. Comparing the scour dimensions in the second row and last row in Table 5-1, it can be seen that the ridge height at the end of digging decreases 21.3% because of ridge removal, but the scour depth at the end of digging decreases only 6.8%. From Figure 5-4 and Figure 5-5, it can be seen that the jet starts to flip only as the scour hole reaches a similar scour depth, 13cm ($\pm 3\%$). In other words, the depth of scour is an important factor controlling whether

jet flip occurs.

Table 5-1 Dimensions of scour hole and ridge before and after ridge removal for Run 20

Cycle	Time	x_s (cm)	y_s (cm)	x_r (cm)	y_r (cm)
8 th digging ended	02/11/2010 5:35	13.55	9.56	46.32	7.52
Figure 5-4(a): 9 th dig, dynamic equilibrium state, (several minutes before ridge removal)	03/11/2010 16:14	13.52	9.55	46.32	7.52
Figure 5-4(b): 9 th dig, dynamic equilibrium state, (several minutes after ridge removal)	03/11/2010 16:34	11.48	8.94	38.15	5.83
Figure 5-4(c): 9 th digging ended (4.8 hrs after ridge removal)	03/11/2010 20:51	12.66	9.46	41.77	6.67
Figure 5-6(d): 15 th digging ended (121.7 hrs after ridge removal)	08/11/2010 18:15	12.62	9.73	42.45	5.92

Figure 5-5 Comparison of scour depths $d_{se-fill}$ and d_{se-dig} before and after ridge removal for Run 20 (the red dashed lines in (b) and (d) are the previous profiles of (a) and (c), respectively)

There were two reasons for only partially removing the ridge. One was to find out whether the ridge downstream is important to jet-flipping compared to the ridge facing the approaching flow. The second was to investigate whether expanding the distance between the ridge to the water surface can affect jet-flipping. A conclusion can be drawn that the ridge downstream is less important to jet-flipping compared to the ridge facing the approaching flow. Also the distance between the ridge to the water surface is less important than the distance between the water surface to the scour hole.

5.2.2 Complete sediment ridge removal test

For Run 79, the complete ridge sediment downstream of the scour hole was removed to the original flat-bed level during the dynamic equilibrium state of the 12th digging phase, as shown in Figure 5-6. After ridge removal, Run 79 shows similar characteristics to those of Run 20 as shown in Figure 5-7. The scour dimensions were recorded before and after removal as shown in Table 5-2.

Figure 5-6 (a) Two ridges were formed; (b) Photo showing scour profiles immediately after removing the ridges (The red dashed line was the previous profile in (a)) of Run 79 ($F_0 = 5.6$, $H_t/d_0 = 12.7$, $L/d_0 = 9$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.61$ m/s, run time = 38 days)

Figure 5-7 Snapshots of the scour and ridge profiles after ridge removal for Run 79 ($F_0 = 5.6$, $H_t/d_0 = 12.7$, $L/d_0 = 9$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.61$ m/s, run time = 38 days)

The jet-flipping was observed immediately after the ridge removal (Figure 5-7(b)). Figure 5-7(b) to (d) are the filling phase, and the sediments in the downstream steep slope of the scour hole are rolling back. After the scour hole is refilled to a certain scour depth of y_s , the subsequent digging phase starts (Figure 5-7(e)). The scouring process continues until the scour hole reaches a certain maximum depth y_s as shown in Figure 5-7(g). A small ridge forms which is much lower than that before ridge removal. The red dashed lines are outline of the scour hole regions. In Figure 5-7(g) and (l), it can be seen that the scour holes at the end of the digging phases after the ridge removal, are slightly deeper compared to those before removal (Figure 5-7(a)). Figure 5-7(h) to (j) are the subsequent filling phase. In Figure 5-7(d) and (j), the scour holes at the end of filling in these two cycles are almost the same after ridge removal, and there remains no ridge downstream of the scour hole regions.

Table 5-2 Dimensions of scour hole and ridge before and after ridge removal for Run 79

Cycle No.	Digging phases					Filling phases				
	End Time	x _s (cm)	y _s (cm)	x _r (cm)	y _r (cm)	End Time	x _s (cm)	y _s (cm)	x _r (cm)	y _r (cm)
8	-					29/3, 21:58	6.6	7.4	53.7	5.8
9	31/3, 0:05	12.2	9.4	44.3	7.5	31/3, 17:00	6.6	7.5	55.1	5.2
10	3/4, 4:55	12.7	9.5	47.7	8.0	4/4, 2:55	6.4	7.5	55.4	5.9
11	5/4, 3:43	11.7	9.0	44.2	7.2	5/4, 21:10	6.6	7.4	56.2	5.6
12	Before ridge removal 6/4, 12:45	11.6	8.2	42.5	7.0	9/4, 16:31 Figure 5-7(d)	5.8	6.7	-	0
	6/4, 12:57* Figure 5-7(a)	11.4	8.0	-	0					
13	9/4, 22:20 Figure 5-7(g)**	12.2	9.0	38.8	4.8	12/4, 11:26 Figure 5-7(j)	6.1	7.1	-	0
14	12/4, 21:46 Figure 5-7(l)**	13.1	9.2	40.7	5.3	-				

* All ridges were removed at 12:46 to 12:56 during the 12th digging phase.

** Figure 5-7(g) and (l) were captured at the dynamic equilibrium states while other snapshots were captured at the end of digging or filling phases.

Table 5-2 shows the scour hole dimensions before and after ridge removal. In Table 5-2, the scour depths (y_s) during the digging/filling phases before and after ridge removal are almost the same (9.0 to 9.5 cm for digging, 7.1 to 7.5 cm for filling) except the 12th cycle because of the manual disturbance during the removal operation. This means that during each digging phase, the jet digs the scour hole to more or less a similar scour depth, 9.3 cm (±3%) to trigger the jet to flip. Similarly,

during each filling phase, the scour hole needs to be refilled to a more or less similar shallow depth, 7.3cm ($\pm 3\%$) to trigger a change of the jet direction from the water surface to attach to the sediment bed. It seems that the water depth between the water surface and the scour hole is much more important than the ridges in the occurrence of jet-flipping.

5.2.3 Time sequence after sediment ridge removal

The above discussion shows that the occurrence of jet-flipping and the shapes of the scour hole are not much affected after ridge removal. However, results show the ridge removal affects the time durations of jet-flipping. For Run 20, the time-sequence records are divided into two parts: the 1st to 8th cycles before ridge removal and 10th to 15th cycles after the ridge was removed (see Appendix B). The 9th cycle was ignored as this is the time when the ridge removal operation was conducted. Figure 5-8 and Table 5-3 show the digging and filling time for each jet-flipping cycle T_0 (Eq. (4-6)) for the first 8 cycles is 1097 min, while from the 10th to 15th cycles, T_0 is 1201 min.

Table 5-3 Digging and filling time over 15 cycles for Run 20 before and after removing the ridge

i th Cycle	Dig(min)	Fill(min)	i th Cycle	Dig(min)	Fill(min)
1	1888	299	9	1804	535
2	377	357			
3	1134	371	10	463	660
4	502	368	11	359	473
5	978	463	12	770	703
6	667	381	13	266	689
7	396	463	14	814	878
8	923	551	15	434	827
av(2 to 8)	711	406	av(10 to 15)	517	705

After removing the ridge downstream, Table 5-3 shows the average digging time decreases from 711 min to 517 min, while the average filling time increases from 406 min to 705 min. Figure 5-8 shows that during 1st to 8th cycles, most of the digging

time is distinctly longer than the filling time, which is contrary to those after the 9th cycle. From the 10th to 15th cycles, most of the digging time is shorter than the filling time.

Figure 5-8 Time-sequence of digging and filling durations of Run20

Figure 5-9 Time-sequence of digging and filling durations of Run 79

For Run 79, Figure 5-9 shows the ridge removal caused the digging time (except 12th cycle) to be shorter than the filling time. The results show that the availability of sediment particles affects the dig and fill durations. The ridge removal process means fewer particles are available for back filling, hence longer fill times are

needed to reach the minimum scour depth ($d_{se-fill}$) before the next digging phase is triggered. Similarly, the digging time is shorter because the ridge formation starts from a levelled bed surface in the ridge region. Thus it seems that the sediment availability affects the time durations of dig-fill cycles but it is not the sole cause of the jet-flipping mechanism.

5.2.4 Coanda effect

The ridge removal tests show that the depth of the scour hole is an important factor to jet-flipping. Hence, the possible cause may lie in the region above and upstream of the scour hole, i.e., the interactions of the free surface, the scour bed, the jet locations and the apron bed.

Figure 5-10(a)-(f) are snapshots of the jet-flipping process in progress for Run 122. In Figure 5-10(a), a bed jet is scouring near the bed (see also the typical velocity vectors of a bed jet in Figure 5-1(a)). It is observed that jet-flipping only occurs after the scour hole reaches its maximum depth. At the maximum scour depth, the jet takes a longer path to reach the lowest point of the bed. For example, Figure 5-3(d) in Section 5.1.4 shows clearly that the region with large velocity magnitude (dark blue colour) closely attaches to the sediment bed. The bed jet flow pattern occurs until the scour hole attains the maximum scour depth at the end of the digging phase. In Figure 5-3(a), the scour hole reaches a maximum depth at the end of the digging phase, and it can be seen that the region with large velocity magnitude (dark blue colour) is further from the sediment bed compared to Figure 5-3(d). Hence, at a point in time, it suddenly flips up and attaches itself to the relatively nearer water surface.

The shift in surface attachment is signified by the ‘boiling’ water surface, as shown in Figure 5-10(b). The jet attempts to attach to the water surface by sweeping itself across the water body; in other words, the jet deflects more and more towards the water surface. It can be seen from the ‘bulge’ on the water surface which becomes nearer to the sluice gate in Figure 5-10(c). An imaginary line is drawn in Figure

5-10(c) from the point the jet leaves the apron to the maximum point of bulge on the water surface (see also the velocity distribution in Figure 5-1(b)). The left portion would represent a backflow region, with a strong vortex, that creates a pressure difference and a resultant lifting force for the jet to remain attached to the water surface. The right portion would form a larger recirculation region that causes sediments on the slope to roll down and back-filling of the scour hole.

Figure 5-10 Observations of jet-flipping phenomenon in Run 122 (a) Initially a bed jet; (b) 1s later, flip to become a surface jet; (c) 10s later, surface jet; (d) 1 hour later, surface jet; (e) 8 hours later, surface jet; (f) 9s after photo (e), jet flips to become a bed jet and start of subsequent digging phase

As mentioned in Section 2.2.2, the jets can deflects to a parallel or inclined boundary due to the Coanda effect. Tritton (1977) mentioned that when a jet is released in the vicinity of a solid boundary, differential entrainment on both sides of

the jet causes it to deflect towards one side and consequently the jet attaches to the boundary surface. This is also known as the Coanda effect which is described as the tendency of a jet to attach to a nearby surface. This effect either arises due to the pressure gradient perpendicular to a surface, or asymmetric entrainment of fluid near a boundary surface (Schlichting 1968). The former can be explained using the Bernoulli's principle. When a jet of higher velocity than the surrounding fluid flows over a boundary surface, the pressure near the surface is reduced. The pressure difference results in a resultant lift force on the surface. In a system, that force will move the surface upwards. However, as each force has an equal and opposite force, there is a corresponding force attracting the flow towards the surface. If the surface can be regarded as immovable, the only noticeable effect is the bending of the flow towards the surface.

Coates (1976) studied bed-surface jets in open channels without a sediment bed and concluded that the formation of bed and surface jet is due to the Coanda effect. The situation is more complex with the presence of a sediment bed. Johnston (1990) investigated the bed-surface jet by offset jet with a sediment bed and observed that the flipping is most likely to occur when the tailwater depth is approximately equal to the offset ratio.

Hence, in the present study, one possible reason for the abrupt change in jet attachment to bed or water surface is the preference of the jet to attach to the nearest boundary, i.e. the effect of 'relative nearness'. It can also be described as the tendency of a jet to take the shortest path to reach a boundary.

Figure 5-10(d) and (e) show the surface jets filling the scour hole 1 and 8 hours after the filling phase started (from Figure 5-10(b)), respectively. It can be seen that the filling causes the scour bed to be shallower as time progresses, and 9 seconds later, the jet suddenly reattaches itself to the bed when the scour hole is filled to a certain depth. This is because the bed is now relatively nearer to the jet, as shown in Figure 5-10(f). Therefore, it can be concluded that the Coanda effect is the most significant factor that triggers the jet-flipping phenomenon.

CHAPTER 6 EFFECTS OF JET-FLIPPING ON LOCAL SCOUR DOWNSTREAM OF A SLUICE GATE

This chapter presents the effects of the tailwater depth, densimetric Froude number and apron on jet-flipping frequencies and the scour depth during the local scour process downstream of the sluice gate. Altogether 72 runs were conducted in this study and the hydraulic conditions and results are listed in Appendix A. A threshold criterion for the occurrence of the jet-flipping phenomenon is proposed. Moreover, the prediction formulas of jet-flipping frequencies and maximum scour depth during the digging and filling phases are suggested.

6.1 Effects of tailwater depth (H_t/d_0)

6.1.1 Observations on jet flow regimes with change in tailwater depth

The experiments for Series H1 to H5 focused on the effects of the relative tailwater depths, H_t/d_0 . Observations reveal there are three jet flow regimes at different tailwater depths. For relatively high F_0 for the smaller yellow sand (Series H1 to H3, $d_{50} = 0.29$ mm) and under relatively high submergence, i.e. $H_t/d_0 > 20$, the jet is observed to be attached to the bed for the entire run. This is the bed jet regime and the jet digs into the sediment bed to form a scour hole. The scouring process eventually reaches an equilibrium scour condition with no visible changes of the bed profile. Under low submergence, i.e. $H_t/d_0 \leq 5$, the jet is observed to flow towards the water surface immediately after release from the sluice opening. This is the surface jet regime. At any submergence level between the two extremes, i.e. $5 < H_t/d_0 \leq 20$, jet-flipping occurs. The jet direction alternates between the bed and surface jet regimes and a permanent equilibrium stage was never reached (see Section 4.2.1). Similarly, for Series H4 and H5 with the larger green sand ($d_{50} = 0.73$ mm) and for a lower F_0 , it is observed that bed jet dominates for $H_t/d_0 > 13$, and jet-flipping happens when $H_t/d_0 \leq 13$. The results show that the jet-flipping depends on H_t/d_0 and F_0 . It is clear that a critical range of tailwater depths exist, at which jet-flipping would occur and beyond which no flipping would be induced.

6.1.2 Effects of H_t/d_0 on scour depth

Figure 6-1 shows the dimensionless scour depth at the end of digging, d_{se-dig}/d_0 and filling, $d_{se-fill}/d_0$ phases plotted against the tailwater depth, H_t/d_0 . Different symbols are used to denote the runs without jet-flipping, i.e. BJ for runs with bed jet only and SJ for surface jet only, and for these 2 jet regimes, the dimensionless maximum scour depth at the equilibrium state (d_{se}/d_0) are used in the figure. The symbols under JF are runs with jet-flipping and the figure shows that for tailwater in the range i.e. $5 < H_t/d_0 \leq 20$, both d_{se-dig}/d_0 and $d_{se-fill}/d_0$ increase with an increase in tailwater depth. In Figure 6-1(a), there is a downward sloping trend when $H_t/d_0 \leq 5$ which indicates that d_{se}/d_0 decreases as H_t/d_0 increases up to $H_t/d_0 = 5$. Ali and Lim (1986) mentioned that a critical tailwater depth exists beyond which an increase in tailwater causes the scour depth to increase. For series H1, $H_t/d_0 = 5$ and for H2 and H3, $H_t/d_0 = 6$ seem to be the critical tailwater depth and it also defines a lower boundary that determines whether jet-flipping would occur or not. There is also an upper boundary beyond which jet-flipping does not occur. It is $H_t/d_0 = 20$ for H1 and H2, and $H_t/d_0 = 21.5$ for H3. As discussed in Section 5.2.4, the change of the jet regimes is probably due to the Coanda effect whereby the jet has a tendency to attach to a nearby surface.

Series H5 was specially designed to determine the sensitivity of jet-flipping. The values of H_t/d_0 were chosen in small intervals. In order to narrow the range, this process was repeated a few times until the range is lower to a 0.5cm interval. It was found that the jet-flipping phenomenon is very sensitive to the change in tailwater. For example, for Series H5, jet-flipping occurred when $H_t/d_0 = 13.0$, but when H_t/d_0 was increased slightly to 13.5, the jet-flipping disappeared. This shows that there is a threshold tailwater depth for flipping to occur.

Figure 6-1 Effects of tailwater depth on scour depth at the end of (a) digging and (b) filling phases (SN = Series No., JF = jet-flipping, BJ = bed jet and SJ = surface jet)

Figure 6.2 shows a comparison of the present study data with the data from Iwagaki et al. (1965), Basmaci (1971), Dey and Sarkar (2006) and Mazurek et al. (2009). It can be seen that the trend of d_{se-dig}/d_0 and d_{se}/d_0 increasing with increase in tailwater depth agrees with that of the present study.

Figure 6-2 Effects of tailwater depth on maximum scour depth with data from previous studies

6.1.3 Effects of H_t/d_0 on frequency of jet-flipping

Figure 6-3 Effects of tailwater depth on (a) average cycle frequency, St_{T0} , (b) average digging frequency, St_{Td0} , (c) average filling frequency, St_{Tf0} , (d) first digging frequency St_{Td1} , and (e) ratio of average digging to filling frequency St_{Td0}/St_{Tf0}

Figure 6-3 (a) to (d) show that as the tailwater depth increases, the flipping frequencies decrease and finally disappear (no jet-flipping). It suggests that it is better to conduct experiments under higher tailwater submergence (i.e. $H_t/d_0 > 20$) to avoid the occurrence of the complex jet-flipping phenomenon. According to the trend in Figure 6-1, for a given F_0 and L/d_0 , the maximum scour hole is deeper with a higher

tailwater depth for the experiments with jet-flipping. Therefore it takes more time to dig the scour hole to a certain depth, a depth that is ‘relatively far’ from the jet compared to the water surface.

The ratio of the frequency of the digging and filling phases is shown in Figure 6-3(e). The ratio, St_{Td0}/St_{Tf0} ($= T_{f0}/T_{d0}$) > 1 indicates the average filling duration is longer than the average digging duration. As the tailwater depth increases, St_{Td0}/St_{Tf0} decreases. This implies that with an increase in tailwater depth, the rate of decrease of the filling frequency as can be seen by the slope of the data trend in Figure 6-3(c), is slower than that of the digging frequency (see the slope in Figure 6-3(b)).

6.2 Effects of Densimetric Froude numbers (F_0)

6.2.1 Effects of F_0 on maximum scour depth

Three series of experiments, SeriesF1 to F3 (Appendix A) were done to study the effects of F_0 on jet-flipping. The F_0 ranges from 5.4 to 16.2, with constant $L/d_0 = 9$, $H_t/d_0 = 10$ and 16, and $d_{50} = 0.29$ mm and 0.73 mm. The results of maximum scour depth versus F_0 are shown in Figure 6-4. For the digging phases, d_{se-dig}/d_0 (or d_{se}/d_0 for no-jet flip data) increases with increase in F_0 . This is similar to previous studies that the maximum scour depth increases with increase in F_0 (Dey and Sarkar 2006). In Figure 6-4(b), $d_{se-fill}/d_0$ generally increases with increase in F_0 except for a few points. As $F_0 \propto u_0$ and $F_0 \propto d_{50}^{0.5}$, for a given d_{50} , Series F1 and F2 in Figure 6-4 reveal that both d_{se-dig}/d_0 and $d_{se-fill}/d_0$ increase with increase in u_0 since an increase in the flow energy causes more erosion.

For Series F3, F_0 is tested with small increment to test the sensitivity of jet-flipping with F_0 . It was found that the jet-flipping phenomenon is also very sensitive to the change in F_0 . For example, for $F_0 = 7.1$ ($u_0 = 0.77$ m/s), there was jet-flipping but no flip when F_0 was lowered to 6.7 ($u_0 = 0.73$ m/s). This shows that there is a threshold F_0 for the occurrence of flipping.

Figure 6-4 Effects of F_0 on maximum scour depth in (a) digging and (b) filling phases

Figure 6-5 Effects of F_0 on maximum scour depth with data from previous studies

Figure 6-5 shows d_{se-dig}/d_0 or d_{se}/d_0 against F_0 with data from Mazurek et al. (2009), Dey and Sarkar (2006) and Iwagaki et al. (1965) together with those from the present study. It can be seen that both d_{se}/d_0 and d_{se-dig}/d_0 increase with an increase in F_0 . This trend is in line with the data from the previous studies.

6.2.2 Effects of F_0 on frequency of jet-flipping

Figure 6-6 Effects of F_0 on (a) average cycle frequency, St_{T0} , (b) average digging frequency, St_{Td0} , (c) average filling frequency, St_{Tf0} , (d) first digging frequency St_{Td1} , and (e) ratio of average digging to filling frequency St_{Td0}/St_{Tf0}

Figure 6-6(a) to (d) show the variation of the frequencies of the jet-flipping with F_0 . As F_0 decreases, the jet-flipping frequencies decrease and finally disappear (no jet-flipping). With smaller F_0 , the flow energy is not high enough to trigger the jet oscillation. At constant H_t/d_0 and L/d_0 , the flow impinging on the sediment bed has more erosion potential with a higher F_0 , and therefore the jet requires a shorter time to dig to a certain critical scour depth. Under this critical scour depth, the jet flow is relatively near the water surface, and at a point of time it flips to the water surface. For Series F3, the points are clustered because the tests were undertaken with a small increment in F_0 .

In Figure 6-6(e), the ratios (St_{Td0}/St_{Tf0}) increase with increase in F_0 for lower F_0 . However, for higher F_0 , the ratio seems to be relatively unaffected by F_0 .

6.3 Effects of apron lengths (L/d_0)

6.3.1 Effects of L/d_0 on maximum scour depth

Five series of experiments, Series L1 to L5 (Appendix A) were conducted to study the effects of the apron length, L on the scour depth and frequencies of jet-flipping, with L/d_0 ranging from 0 to 45.

There were 3 regimes with a change of apron length (Series L1). First, with a very long apron, the effect of erosion is weak and no jet-flipping was observed when $L/d_0 > 30$. Second, with an intermediate apron length, jet-flipping was observed for $1 \leq L/d_0 \leq 30$. Third, without an apron, i.e. $L/d_0 = 0$, jet-flipping was not observed throughout the entire run (see also Section 4.5).

Figure 6-7 Effects of apron length on maximum scour depth in (a) digging and (b) filling phases

Figure 6-7 shows that the maximum scour depths generally decrease with increase in L/d_0 for both digging and filling phases. One reason is that the erosive energy of the flow is dissipated over the apron before impinging on the sediment bed. This is also the reason why the river bed is usually armoured with an apron or other protection to

avoid excessive erosion. Another reason is that the recirculation region downstream of the sluice gate is affected as the apron length changes. According to the velocity measurement results in Figure 5-1 in Section 5.1.1, during the digging phase, there is a large anticlockwise recirculation region above the jet. The recirculation provides a significant downward velocity component near the edge of the apron, which contributes to the scouring action (Figure 5-1(a)). During the filling phase, the jet approaches the water surface immediately after leaving the apron. It splits into upstream and downstream directions, forming two recirculation regions (Figure 5-1(b)). The clockwise recirculation provides a significant downward velocity component near the slope of the ridge, causing sediments on it to slide down and back-filling of the scour hole. The anticlockwise recirculation causes the water surface to rise, which looks like ‘boiling’. With a longer apron, the recirculation region is expanded and its position is changed. Hence, the effects on the sediment bed change.

The maximum scour depth, d_{se}/d_0 data from (Lim and Yu 2002; Dey and Sarkar 2006) are plotted in Figure 6-8 together with the d_{se-dig}/d_0 or d_{se}/d_0 data from the present study. It can be seen the data trend coincides well with the present study.

Figure 6-8 Effects of apron length on maximum scour depth with data from previous studies

6.3.2 Effects of L/d_0 on frequency of jet-flipping

Figure 6-9 Effects of apron length on (a) average cycle frequency, St_{T_0} , (b) average digging frequency, $St_{T_{d0}}$, (c) average filling frequency, $St_{T_{f0}}$, (d) first digging frequency $St_{T_{d1}}$, and (e) ratio of average digging to filling frequency $St_{T_{d0}}/St_{T_{f0}}$

The jet-flipping frequencies of Series L1 to L5 are shown in Figure 6-9. With an increase in apron length, the jet-flipping frequencies generally increase. According to Figure 6-7, the scour hole downstream of a longer apron is shallower, and it requires less time to refill and dig the scour hole. Hence, the frequencies are higher with a longer apron.

Figure 6-10 Time-sequence of each digging and filling phase for different apron lengths

Figure 6-9(e) shows that the ratio of the frequency of digging and filling phases, St_{Td0}/St_{Tf0} ($= T_{f0}/T_{d0}$) generally increases with an increase in apron length. This implies that for a longer apron, the digging frequency increases at a higher rate than the filling frequency over the recording period (see Figure 6-9(b) and (c)). The detailed sequence of the cycles versus the digging and filling durations of each run in

Series L1 is shown in Figure 6-10 (also see Appendix B). It can be seen that the digging time in the first cycle is much longer than the others in each run. The digging and filling durations show small scale variation over the recording period. For Runs 20, 21, and 22, where the apron is relatively short ($L/d_0 = 1$ to 9), the digging durations in each cycle are quite long, in the order of thousands of minutes. The filling duration is shorter than the digging duration. As the apron length increases in Runs 13, 14 and 15 ($L/d_0 = 15$ to 30), the digging duration in each cycle decreases sharply from thousands to several minutes, and becomes shorter than the filling phase. It could be as high as 35 cycles per day for Run 14 ($L/d_0 = 30$), while only 1.3 cycles per day for Run 22 ($L/d_0 = 1$), which explains the trend in Figure 6-9(e).

6.4 Threshold of jet-flipping

It is clear from the above discussion that there is a critical range in terms of the tailwater depth, flow intensity and apron length for jet-flipping to occur. Figure 6-11 shows a threshold of jet-flipping diagram in terms of H_t/d_0 versus F_0 . There is no clear trend in terms of L/d_0 , because the data investigating L/d_0 is not varied wide enough. However, the zone confined by the upper and lower boundaries of H_t/d_0 , and within $5.6 \leq F_0 \leq 16.2$ is valid for $1 \leq L/d_0 \leq 30$. These two boundaries are fitted by the following equations,

$$\frac{H_t}{d_0} = 70.9 (1 - e^{-0.4F_0}) + 2.7 (1 - e^{-3.0F_0}) - 51.2 \quad 5.6 \leq F_0 \leq 16.2 \quad (6-1)$$

$$\frac{H_t}{d_0} = 0.36F_0 + 1.5 \quad 5.6 \leq F_0 \leq 16.2 \quad (6-2)$$

Figure 6-11 Threshold diagram of jet-flipping occurrence in local scour

In Figure 6-12, some relevant data with jet-flipping from previous studies are plotted together with the present data from Figure 6-11. These data were mostly tested with much lower F_0 than the present study. By extrapolating Eqs. (6-1) and (6-2) to the lower range of F_0 , as shown by the purple dashed lines, it can be seen that the threshold diagram agrees reasonably well with their experimental data. Hence, the threshold criteria for jet-flipping as shown in Figure 6-11 bounded by Eqs. (6-1) and (6-2) are recommended as a practical guideline to assess and if necessary, avoid the occurrence of the complex jet-flipping phenomenon in local scour downstream of a sluice gate.

Figure 6-12 Threshold diagram of jet-flipping occurrence including other researchers' data

6.5 Maximum scour depth prediction

Based on the dimensional analysis in Section 4.1, the non-dimensional maximum scour depth at the end of the digging and filling phases can be given in functional form as

$$\frac{d_{se-dig}}{d_0} = f_6 \left(F_0, \frac{L}{d_0}, \frac{H_t}{d_0} \right) \quad (6-3)$$

$$\frac{d_{se-fill}}{d_0} = f_7 \left(F_0, \frac{L}{d_0}, \frac{H_t}{d_0} \right) \quad (6-4)$$

The sediment terms σ_g and $\frac{d_{50}}{d_0}$ are not included, because the effects of sediment size and gradation are not investigated thoroughly as only two sediment sizes were used in the present study. It should be noted that the scour depth functions given by Eqs. (6-3) and (6-4) are for scour attained at the dynamic equilibrium state as there is no equilibrium scour condition with jet-flipping. However, as discussed in Section 4.2.2, the dynamic equilibrium state is usually very long, and therefore the time scale term $\frac{d_0}{u_0 t}$ is also ignored.

Using regression analysis for the 40 experiments with jet-flipping (Appendix A), the following equations are obtained,

$$\frac{d_{se-dig}}{d_0} = 0.407 F_0^{0.546} \left(\frac{L}{d_0} \right)^{-0.443} \left(\frac{H_t}{d_0} \right)^{1.145}, R^2 = 0.91 \quad (6-5)$$

$$\frac{d_{se-fill}}{d_0} = 0.388 F_0^{0.373} \left(\frac{L}{d_0} \right)^{-0.451} \left(\frac{H_t}{d_0} \right)^{1.173}, R^2 = 0.85 \quad (6-6)$$

where R = regression correlation coefficient. Eqs. (6-5) and (6-6) are valid for the range of $5.6 \leq F_0 \leq 16.2$, $1 \leq L/d_0 \leq 30$ and $5 \leq H_t/d_0 \leq 21.5$. The comparisons of the experimental data with the computed results using Eqs. (6-5) and (6-6) are shown in Figure 6-13, and the predictions for most of the data are within the $\pm 20\%$ error lines.

Figure 6-13 Comparison of the experimental data with the maximum scour depths
(a) computed using Eq. (6-3) and (b) Eq. (6-4)

Figure 6-14 Comparison of the maximum scour depths computed using Eq. (6-5) with the experimental data from previous studies and present study (without jet-flipping)

Eq. (6-5) may be used to compare to relevant published scour data without jet-flipping. Figure 6-14 shows a comparison between the measured maximum scour depth (d_{sc}/d_0) from previous studies and the present study without jet-flipping with the predictions using Eq. (6-5). The purpose of this plot is to compare the difference in the scour depth for experiments with and without jet-flipping. For data shown in Figure 6-14 (a), (b), (c) and (d), 36%, 88%, 88% and 62%, respectively of the maximum scour depth with jet-flipping are much deeper than the maximum scour depth without jet-flipping. These results agree with the earlier discussion in Section 4.4.2. Under the same hydraulic conditions, scour depths with jet-flipping are deeper

than that without jet-flipping in many cases.

6.6 Jet-flipping frequency prediction

Using dimensional analysis, the jet-flipping frequencies, in terms of the Strouhal number, St , can be expressed as follows:

$$St_{T0} = f_8 \left(F_0, \frac{L}{d_0}, \frac{H_t}{d_0} \right) \quad (6-7)$$

$$St_{Td0} = f_9 \left(F_0, \frac{L}{d_0}, \frac{H_t}{d_0} \right) \quad (6-8)$$

$$St_{Tf0} = f_{10} \left(F_0, \frac{L}{d_0}, \frac{H_t}{d_0} \right) \quad (6-9)$$

$$St_{Td1} = f_{11} \left(F_0, \frac{L}{d_0}, \frac{H_t}{d_0} \right) \quad (6-10)$$

Using regression analysis for the 40 experiments with jet-flipping (Appendix A) yields the following equations,

$$St_{T0} = 2.584 \times 10^{-4} F_0^{1.370} \left(\frac{L}{d_0} \right)^{1.613} \left(\frac{H_t}{d_0} \right)^{-5.048}, R^2 = 0.82 \quad (6-11)$$

$$St_{Td0} = 4.857 \times 10^{-4} F_0^{2.860} \left(\frac{L}{d_0} \right)^{2.423} \left(\frac{H_t}{d_0} \right)^{-6.677}, R^2 = 0.85 \quad (6-12)$$

$$St_{Tf0} = 3.746 \times 10^{-3} F_0^{0.297} \left(\frac{L}{d_0} \right)^{1.016} \left(\frac{H_t}{d_0} \right)^{-4.440}, R^2 = 0.74 \quad (6-13)$$

$$St_{Td1} = 8.460 \times 10^{-4} F_0^{3.276} \left(\frac{L}{d_0} \right)^{2.104} \left(\frac{H_t}{d_0} \right)^{-7.342}, R^2 = 0.91 \quad (6-14)$$

Eqs. (6-11) to (6-14) are valid for the range of $5.6 \leq F_0 \leq 16.2$, $1 \leq L/d_0 \leq 30$ and $5 \leq H_t/d_0 \leq 21.5$. A comparison of the experimental data with the computed results is shown in Figure 6-15.

Figure 6-15 Comparison of the computed results using Eqs. (6-10) to (6-14) with the experimental data of frequencies of (a) jet-flipping cycles, St_{T0} , (b) digging phases, St_{Td0} , (c) filling phases, St_{Tf0} and (d) first digging phases, St_{Td1}

As a guide, Eqs. (6-11) to (6-13) can be used to predict the approximate time when the filling or digging starts. However, the present study found that it may take a very long scour duration to observe the first cycle of jet-flipping. For example, it requires 113.7 hours of scouring in Run 79 to be able to observe the first jet-flipping. Hence, it is crucial to conduct experiments with sufficiently long scour time so that the jet-flipping phenomenon is not missed. To this end, Eq. (6-14) can be used to predict the minimum scour time required to assess whether jet-flipping occurs under particular hydraulic conditions. Data from past studies are used to illustrate the

application of Eq. (6-14).

Figure 6-16 Comparison of the first digging frequencies, St_{Td1} computed using Eq. (6-14) with the experimental data from the present study (without jet-flip) and previous studies

Figure 6-16 shows a comparison between the measured d_0/u_0t based on the scour time reported in the past works with the prediction using Eq. (6-14) of the time required before the first flipping cycle can be observed. In Figure 6-16(a), Balachandar et al. (2000) observed jet-flipping in 18 runs, and Eq. (6-14) predicted 15 runs (81%). The data in Figure 6-16(b) to (d) did not report any jet-flipping occurrence. Eq. (6-14) can be used to check whether the scouring time used in these works is sufficiently long to observe the flipping, if it happens. It can be seen that Lim and Yu (2002), Dey and Sarkar (2006) and the present study conducted the experiments long enough to make

sure there was no jet-flipping. However, Nik Hassan and Narayanan (1985) and Gautam (2008) experimental durations are insufficient.

The necessary time for the jet-flipping to occur in the field can be estimated based on similitude. When the model and prototype have the same Froude number, the relationship between time scale (λ_t) and the length scale (λ_l) should be $\lambda_t = \lambda_l^{0.5}$, where $\lambda_t = \frac{t_p}{t_m}$, t_p and t_m are the time of prototype and model respectively; $\lambda_l = \frac{l_p}{l_m}$, l_p and l_m are the characteristic length of prototype and model respectively.

CHAPTER 7 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The study investigates a unique jet-flipping phenomenon during the local scour process caused by 2-D wall jets downstream of a sluice gate with a launching apron. This chapter summarizes the conclusions drawn from the study and suggests some recommendations for future works.

7.1 Webcam recording method

A novel webcam recording method was used to record the scouring process continuously for a long period of time. The video recording used 3.6GB of hard-disk storage for every 24 hours recording at a frame rate of 25 fps and a resolution of 640*480pixels, which is clear enough to measure the scour dimensions. The recordings are saved hourly and automatically into hard-disk using the software of Video Camera Monitor. This method enables subsequent viewing of the entire scouring processes in detail, and accurate data extraction on the occurrence of jet-flipping, its frequencies, and close-up analysis of the scour hole characteristics.

7.2 Characteristics of the scouring process with jet-flipping

Jet-flipping phenomenon consists of two cyclical phases: a digging phase with an attached bed jet scouring the bed, and a filling phase with a surface jet after the scour has reached a certain maximum value. While the bed jet has a relatively calm water surface, the surface jet causes the water surface to become choppy and the sediments on the ridge roll back to fill up the hole until it reaches a certain minimum scour depth. The cycle repeats itself and there is no equilibrium scour state with jet-flipping.

The data show that the maximum scour depth at the digging phase can be as high as 60% more than the filling phase. Compared to the no jet flip scour conditions in the previous studies, it was found under the same hydraulic conditions, scour is more

severe if jet-flipping occurs.

It was found that the digging process consists of three stages: an initial stage with a rapid rate of scouring; a development stage with a relatively slower rate of scouring; and a dynamic equilibrium state with a stabilized scour profile. The latter may last up to 10 days after which the jet flips to the surface to start the next filling phase. A similar dynamic equilibrium state is formed at the end of the refilling phase. To this end, it is concluded that experiments must be observed for a sufficiently long period to ascertain whether jet-flipping had occurred. The study found that many previous studies may have hydraulic conditions that can cause the jet-flipping phenomenon but the scour duration used was too short for the phenomenon to be observed.

The scour dimensions were found to change cyclically in accordance with the digging and filling phases. At the end of the digging phases over many cycles, the scour profiles were found to be similar. This also applies to the filling phases.

It was also found that more than one ridge was formed during the digging-filling process. The formation and change to the ridge profiles are indications to judge whether jet-flipping had occurred. Hence, for studies without a continuous video recording setup as in the present study, the appearance of multiple ridges during the scour process probably indicates that jet-flipping had occurred.

7.3 Velocity distributions of the flow field in scour holes

The flow fields were measured using an ADVP in two specially constructed fixed-bed models at the threshold of jet-flipping: One with a deep scour hole at the end of the digging phase, and the other with a shallow scour hole at the end of the filling phase.

The results showed that, for the digging phase, the jet dives and impinges on the bed after leaving the apron, which contributes to the scouring action. For the filling phase, the jet approaches the water surface immediately after leaving the apron causing

sediments on the ridge to slide down and back-filling of the scour hole.

It was found that the velocity magnitudes are high near the bed during the digging phases for both of the two bed profiles. However, during the filling phases, high velocities are near the apron and the path to the water surface. Velocities in the vicinity of the bed are relatively low.

7.4 Possible trigger mechanism

The possible trigger mechanism of the jet-flipping was examined in two parts. The first was the ridge removal tests which examine the region downstream of the scour hole, and it was found that both the complete and partial removal of the ridge did not stop the jet-flipping process. It was concluded that the relative distance between the ridge to the water surface is not a factor to cause jet-flipping.

The second is the region upstream of the scour hole, and it was found that the relative distance between the jet axis to the maximum scour depth location and its distance to the water surface is a crucial factor. This suggests that jet-flipping could be triggered by the Coanda effect due to the jet's preference to attach to a relatively nearer boundary which could be either the bed or the water surface, i.e. the effect of 'relative nearness'.

7.5 Effects of jet-flipping on local scour downstream of a sluice gate

The results showed that there are three distinctive jet flow regimes associated with the change in tailwater depth. Under relatively high submergence, the jet dived downwards as a bed jet digging a deep scour hole. With low submergence, it behaves as a surface jet; and in between these two submergences, jet-flipping occurs, the bed and surface jet regimes happened cyclically.

The results showed that the maximum scour depth for both digging and filling phases

increase as the tailwater depth becomes deeper, decrease as the apron length becomes longer, and increase as the densimetric Froude number becomes larger.

It was found that the Strouhal number is useful to analyse the frequencies of the jet-flipping phenomenon. The frequencies increase as the densimetric Froude number increases, increase as the apron length increases and decrease as the tailwater increases. These results suggest that no jet-flipping will be observed if the tailwater is sufficiently deep.

The results also showed that an apron needs to be present downstream of a sluice gate outlet for jet-flipping to occur. On the other hand, if the apron is relatively long, jet-flipping does not occur.

Based on the present results with jet-flipping, prediction equations are proposed for the maximum scour depth at the end of the digging and filling phases. Using data from the present work and past studies, it was found that under the same hydraulic conditions, the maximum scour depths computed with jet-flipping in many cases are deeper than those without jet-flipping. This suggests that jet-flipping is an important factor to consider for local scour below a sluice gate.

Similarly, equations to predict the jet-flipping frequencies, in terms of the Strouhal number were proposed. The equations can be used to predict the approximate time when the filling or digging begins, especially the one to predict the minimum scour time required to assess whether jet-flipping has occurred under particular hydraulic conditions. To this end, it was found that for many cases in the previous studies, the scour time used were not long enough to observe the first cycle of the jet-flipping phenomenon.

Based on the present results, a threshold diagram to predict the occurrence of jet-flipping is presented and can be used as a practical guideline if it is needed to avoid the complex jet-flipping phenomenon in local scour downstream of a sluice gate.

7.6 Recommendations

The present study used two types of sediment sizes. Other types should be used in future works, including larger sizes in the gravel range and non-uniform sediments. In addition, the effects of the apron length in the proposed threshold criteria for jet-flipping need more scour data with jet-flipping occurrence to generalize the trend lines of the diagram. The flow patterns in the scour hole should be investigated further to understand better the triggering mechanism of the jet-flipping phenomenon.

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APPENDIX A: LISTS OF EXPERIMENTS

Experiments are listed in the following tables. 72 experiments were conducted and 40 of them with jet-flipping occurrence. The letters, BJ indicates the flow pattern observed was bed jet throughout the experiment. SJ indicates the flow pattern was surface jet. And JF refers to jet-flipping was observed during the experiment. The prefixes H, F and L before the run numbers indicates the experiments are designed to study the effects of tailwater depth (H_t), densimetric Froude number (F_0) and apron length (L), respectively. Some of the experiments are listed also in different series. The sluice gate opening size is $d_0 = 10$ mm for all the experiments.

Table A-1 Hydraulic conditions and the effect of tailwater depth on the scour depth

Run No.	Time (day)	Flow pattern	H_t/d_0	d_{se-dig}/d_0	$d_{se-fill}/d_0$	Δd (%)
Series H1 ($L/d_0 = 9$, $u_0 = 0.61$ m/s, $F_0 = 8.8$, $Fr = 1.9$, $d_{50} = 0.29$ mm, $\sigma_g = 1.64$)						
H1-204	20	BJ	23.0	14.07	NA	NA
H1-229	12	BJ	21.5	12.96	NA	NA
H1-203	14	JF	20.0	13.90	9.40	32
H1-212	7	JF	16.0	11.37	8.33	27
H1-221	6	JF	10.0	7.08	5.00	29
H1-230	2	JF	8.0	5.83	3.75	36
H1-231	2	JF	7.0	4.20	2.70	36
H1-232	2	JF	6.0	3.33	2.50	25
H1-211	2	JF	5.0	3.24	2.08	36
H1-213	5	SJ	4.0	4.50	NA	NA
H1-214	2	SJ	3.0	4.40	NA	NA
H1-215	4	SJ	2.0	8.10	NA	NA
Series H2 ($L/d_0 = 9$, $u_0 = 0.71$ m/s, $F_0 = 10.4$, $Fr = 2.3$, $d_{50} = 0.29$ mm, $\sigma_g = 1.64$)						
H2-205	18	BJ	23.0	15.90	NA	NA
H2-233	8	BJ	21.5	15.00	NA	NA
H2-207	13	JF	20.0	16.42	11.10	32
H2-206	14	JF	16.0	12.50	8.60	31
H2-209	4	JF	9.8	8.33	5.83	30
H2-234	4	JF	8.0	6.40	4.17	35
H2-235	4	JF	7.0	5.00	3.75	25
H2-236	12	JF	6.0	3.75	3.33	11
H2-210	4	SJ	5.0	6.10	NA	NA
Series H3 ($L/d_0 = 9$, $u_0 = 0.83$ m/s, $F_0 = 12.2$, $Fr = 2.6$, $d_{50} = 0.29$ mm, $\sigma_g = 1.64$)						
H3-222	15	JF	21.5	18.80	12.80	32
H3-202	6	JF	20.0	17.20	12.08	30
H3-201	5	JF	16.0	12.60	6.90	45

Run No.	Time (day)	Flow pattern	H_t/d_0	d_{se-dig}/d_0	$d_{se-fill}/d_0$	Δd (%)
H3-223	6	JF	10.0	9.50	6.87	28
H3-239	4	JF	7.0	5.83	3.33	43
H3-240	6	JF	6.0	4.17	1.67	60
H3-224	5	SJ	5.0	5.00	NA	NA
Series H4 ($L/d_0 = 30$, $u_0 = 0.71$ m/s, $F_0 = 6.5$, $Fr = 2.3$, $d_{50} = 0.73$ mm, $\sigma_g = 1.12$)						
H4-52	4	JF	16.0	4.4	3.0	31.1
H4-14	2	JF	12.7	3.9	2.8	28.0
Series H5 ($L/d_0 = 9$, $u_0 = 0.61$ m/s, $F_0 = 5.6$, $Fr = 1.9$, $d_{50} = 0.73$ mm, $\sigma_g = 1.12$)						
H5-85	15	BJ	16.0	8.9	NA	NA
H5-165	8	BJ	13.5	8.6	NA	NA
H5-164	9	JF	13.0	8.9	7.8	12.0
H5-79	28	JF	12.7	8.7	7.1	16.2

Table A-2 Effects of tailwater depth on the time durations and frequencies of jet-flipping

Run No.	T_0 (min)	T_{d0} (min)	T_{f0} (min)	T_{f0}/T_{d0}	T_{d1} (min)	St_{T0} (10^{-8})	St_{Td0} (10^{-8})	St_{Tf0} (10^{-8})	St_{Td1} (10^{-8})
Series H1									
H1-204	NA	NA	NA	NA	NA	NA	NA	NA	NA
H1-229	NA	NA	NA	NA	NA	NA	NA	NA	NA
H1-203	18688.0	6368.0	12320.0	1.9	7162.0	1.5	4.3	2.2	3.8
H1-212	3383.0	830.0	2553.0	3.1	3907.0	8.1	33.1	10.8	7.0
H1-221	668.0	45.0	623.0	13.8	60.0	41.2	611.2	44.1	458.4
H1-230	103.0	9.0	94.0	10.4	10.0	267.0	3055.9	292.6	2750.3
H1-231	29.0	2.0	27.0	13.5	4.0	948.4	13751.4	1018.6	6875.7
H1-232	18.0	1.0	17.0	17.0	2.0	1527.9	27502.8	1617.8	13751.4
H1-211	15.0	1.0	14.0	14.0	1.0	1833.5	27502.8	1964.5	27502.8
H1-213	NA	NA	NA	NA	NA	NA	NA	NA	NA
H1-214	NA	NA	NA	NA	NA	NA	NA	NA	NA
H1-215	NA	NA	NA	NA	NA	NA	NA	NA	NA
Series H2									
H2-205	NA	NA	NA	NA	NA	NA	NA	NA	NA
H2-233	NA	NA	NA	NA	NA	NA	NA	NA	NA
H2-207	5847.0	3486.0	2361.0	0.7	2816.0	4.0	6.7	10.0	8.3
H2-206	1712.0	223.0	1489.0	6.7	596.0	13.7	105.4	15.8	39.4
H2-209	177.0	12.0	165.0	13.8	30.0	132.7	1958.0	142.4	783.2
H2-234	29.0	3.0	26.0	8.7	5.0	810.2	7832.1	903.7	4699.2
H2-235	18.0	1.0	17.0	17.0	1.0	1305.3	23496.2	1382.1	23496.2
H2-236	5.8	0.4	5.4	13.6	0.8	4037.2	58740.6	4335.1	29370.3
H2-210	NA	NA	NA	NA	NA	NA	NA	NA	NA
Series H3									
H3-222	5688.0	2261.0	3427.0	1.5	14190.0	3.5	8.8	5.8	1.4
H3-202	4571.0	2381.0	2190.0	0.9	2496.0	4.4	8.4	9.1	8.0
H3-201	1050.0	107.0	943.0	8.8	350.0	19.0	186.9	21.2	57.1
H3-223	81.0	5.0	76.0	15.2	15.0	246.9	4000.0	263.2	1333.3
H3-239	9.0	1.1	7.9	7.1	1.0	2232.1	18018.0	2547.8	20000.0
H3-240	4.4	0.4	4.1	11.0	0.5	4504.5	54054.1	4914.0	42553.2
H3-224	NA	NA	NA	NA	NA	NA	NA	NA	NA
Series H4									

Run No.	T ₀ (min)	T _{d0} (min)	T _{f0} (min)	T _{f0} /T _{d0}	T _{d1} (min)	St _{T0} (10 ⁻⁸)	St _{Td0} (10 ⁻⁸)	St _{Tf0} (10 ⁻⁸)	St _{Td1} (10 ⁻⁸)
H4-52	27.0	3.0	24.0	8.0	54.0	869.4	7824.7	978.1	434.7
H4-14	23.0	2.0	21.0	10.5	14.0	1020.6	11737.1	1117.8	1676.7
Series H5									
H5-85	NA	NA	NA	NA	NA	NA	NA	NA	NA
H5-165	NA	NA	NA	NA	NA	NA	NA	NA	NA
H5-164	3528.0	2845.0	680.0	0.2	4076.0	7.7	9.6	40.2	6.7
H5-79	3524.0	2498.0	1026.0	0.4	6701.0	7.8	10.9	26.6	4.1

Table A-3 Hydraulic conditions and the effect of densimetric Froude number (F_0) on the scour depth ($L/d_0 = 9$)

Run No.	Time (day)	Flow pattern	u_0 (m/s)	F_0	Fr	d_{se-dig}/d_0	$d_{se-fill}/d_0$	Δd (%)
Series F1 ($H_t/d_0 = 10$, $d_{50} = 0.29$ mm, $\sigma_g = 1.64$)								
F1-251	4	JF	1.11	16.2	3.5	10.78	8.14	24
F1-252	4	JF	0.98	14.3	3.1	10.13	6.44	36
F1-223	4	JF	0.83	12.2	2.7	9.50	6.87	28
F1-209	4	JF	0.71	10.4	2.3	8.33	5.83	30
F1-221	6	JF	0.61	8.8	1.9	7.08	5.00	29
F1-253	6	JF	0.47	6.8	1.5	6.67	4.58	31
F1-254	9	BJ	0.37	5.4	1.2	5.83	NA	NA
Series F2 ($H_t/d_0 = 16$, $d_{50} = 0.29$ mm, $\sigma_g = 1.64$)								
F2-255	7	JF	1.11	16.2	3.5	17.08	11.00	36
F2-256	3	JF	0.98	14.3	3.1	15.15	10.20	33
F2-201	5	JF	0.83	12.2	2.7	12.60	6.90	45
F2-206	14	JF	0.71	10.4	2.3	12.50	8.60	31
F2-212	14	JF	0.61	8.8	1.9	11.37	8.33	27
F2-257	4	BJ	0.47	6.8	1.5	8.10	NA	NA
Series F3 ($H_t/d_0 = 16$, $d_{50} = 0.73$ mm, $\sigma_g = 1.12$)								
F3-121	12	JF	0.83	7.7	2.7	13.6	7.9	42.0
F3-166	8	JF	0.82	7.5	2.6	12.4	10.6	15.0
F3-167	7	JF	0.80	7.4	2.6	12.2	10.0	18.0
F3-168	15	JF	0.77	7.1	2.4	11.8	9.5	20.0
F3-169	8	BJ	0.73	6.7	2.3	11.1	NA	NA

Table A-4 Effects of densimetric Froude number (F_0) on the time durations and frequencies of jet-flipping

Run No.	T_0 (min)	T_{d0} (min)	T_{f0} (min)	T_{f0}/T_d	T_{d1} (min)	St_{T0} (10^{-8})	St_{Td0} (10^{-8})	St_{Tf0} (10^{-8})	St_{Td1} (10^{-8})
Series F1									
F1-251	14.2	1.3	12.9	9.7	2.0	1058.1	11289.5	1167.6	7507.5
F1-252	26.9	2.0	24.9	12.4	4.0	633.2	8503.4	684.1	4251.7
F1-223	81.0	5.0	76.0	15.2	15.0	246.9	4000.0	263.2	1333.3
F1-209	177.0	12.0	165.0	13.8	30.0	132.7	1958.0	142.4	783.2
F1-221	668.0	45.0	623.0	13.8	60.0	41.2	611.2	44.1	458.4
F1-253	2203.5	519.0	1684.5	3.3	663.0	16.2	68.8	21.2	53.9
F1-254	NA	NA	NA	NA	NA	NA	NA	NA	NA
Series F2									
F2-255	185.1	30.8	154.3	5.0	104.0	81.1	487.0	97.3	144.4
F2-256	306.7	63.0	243.7	12.4	180.0	55.4	269.9	69.8	94.5
F2-201	1050.0	107.0	943.0	8.8	350.0	19.0	186.9	21.2	57.1
F2-206	1712.0	223.0	1489.0	6.7	596.0	13.7	105.4	15.8	39.4
F2-212	3383.0	830.0	2553.0	3.1	3907.0	8.1	33.1	10.8	7.0
F2-257	NA	NA	NA	NA	NA	NA	NA	NA	NA
Series F3									
F3-121	1158.0	568.0	590.0	1.0	4276.0	17.3	35.4	34.0	4.7
F3-166	1076.0	809.0	267.0	0.3	3794.0	18.9	25.1	76.1	5.4
F3-167	3792.0	3433.0	359.0	0.1	4666.0	5.5	6.1	58.0	4.5
F3-168	2746.0	2537.0	509.0	0.2	3143.0	7.9	8.5	42.5	6.9
F3-169	NA	NA	NA	NA	NA	NA	NA	NA	NA

Table A-5 Hydraulic conditions and the effect of the apron length (L) on the scour depth ($d_{50} = 0.73$ mm, $\sigma_g = 1.12$)

Run No.	Time (day)	Flow pattern	L/d_0	u_0 (m/s)	F_0	Fr	H_t/d_0	d_{se-dig}/d_0	$d_{se-fill}/d_0$	Δd (%)
Series L1										
L1-16	7	BJ	0	0.71	6.5	2.3	12.7	14.7	NA	NA
L1-22	18	JF	1	0.71	6.5	2.3	12.7	13.8	10.4	25.0
L1-21	22	JF	3	0.71	6.5	2.3	12.7	12.0	8.0	33.0
L1-20	7	JF	9	0.71	6.5	2.3	12.7	9.6	5.2	46.0

Run No.	Time (day)	Flow pattern	L/d_0	u_0 (m/s)	F_0	Fr	H_t/d_0	d_{se-dig}/d_0	$d_{se-fill}/d_0$	Δd (%)
L1-15	7	JF	15	0.71	6.5	2.3	12.7	8.1	5.1	37.0
L1-13	7	JF	21	0.71	6.5	2.3	12.7	6.5	4.6	29.0
L1-14	2	JF	30	0.71	6.5	2.3	12.7	3.9	2.8	28.0
L1-161	12	BJ	35	0.71	6.5	2.3	12.7	2.2	NA	NA
L1-162	7	BJ	40	0.71	6.5	2.3	12.7	2.1	NA	NA
L1-163	10	BJ	45	0.71	6.5	2.3	12.7	2.0	NA	NA
Series L2										
L2-77	7	BJ	0	0.61	5.6	1.9	12.7	12.7	NA	NA
L2-176	7	BJ	1	0.61	5.6	1.9	12.7	12.0	NA	NA
L2-79	28	JF	9	0.61	5.6	1.9	12.7	8.5	7.1	16.2
L2-81	4	JF	21	0.61	5.6	1.9	12.7	4.0	3.3	17.0
L2-82	1	JF	30	0.61	5.6	1.9	12.7	3.0	2.3	21.0
Series L3										
L3-170	8	BJ	1	0.61	5.6	1.9	13.5	9.2	NA	NA
L3-171	7	BJ	3	0.61	5.6	1.9	13.5	9.0	NA	NA
L3-165	8	BJ	9	0.61	5.6	1.9	13.5	8.6	NA	NA
L3-172	6	BJ	15	0.61	5.6	1.9	13.5	6.2	NA	NA
Series L4										
L4-85	15	BJ	9	0.61	5.6	1.9	16.0	8.9	NA	NA
L4-88	3	JF*	30	0.61	5.6	1.9	16.0	3.9	NA	NA
Series L5										
L5-121	12	JF	9	0.83	7.7	2.7	16.0	13.6	7.9	41.9
L5-122	18	JF	15	0.83	7.7	2.7	16.0	11.2	7.6	32.0
Series L6 Observation on whether jet-flipping occurs without an apron										
L6-B10	11	BJ	0	0.61	5.6	1.9	17.8	11.3	NA	NA
L6-B9	6	BJ	0	0.61	5.6	1.9	16.0	11.1	NA	NA
L6-B8	11	BJ	0	0.61	5.6	1.9	14.0	11.3	NA	NA
L6-B15	8	BJ	0	0.61	5.6	1.9	11.0	12.9	NA	NA
L6-B14	8	BJ	0	0.61	5.6	1.9	9.0	13.6	NA	NA
L6-B7	6	BJ	0	0.61	5.6	1.9	7.0	14.1	NA	NA
L6-B12	6	BJ	0	0.61	5.6	1.9	4.5	16.3	NA	NA
L6-B5	15	BJ	0	0.61	5.6	1.9	3.0	18.1	NA	NA

Note: *Run 88 with observation on the periodic changes of the water surface.

Table A-6 Effects of apron length (L) on the time durations and frequencies of jet-flipping

Run No.	T ₀ (min)	T _{d0} (min)	T _{f0} (min)	T _{f0} /T _{d0}	T _{d1} (min)	St _{T0} (10 ⁻⁸)	St _{Td0} (10 ⁻⁸)	St _{Tf0} (10 ⁻⁸)	St _{Td1} (10 ⁻⁸)
Series L1									
L1-16	NA	NA	NA	NA	NA	NA	NA	NA	NA
L1-22	1149.0	990.0	158.0	0.2	3157.0	20.4	23.7	148.6	7.4
L1-21	2349.0	1612.0	737.0	0.5	4220.0	10.0	14.6	31.9	5.6
L1-20	1097.0	711.0	386.0	0.5	1888.0	21.4	33.0	60.8	12.4
L1-15	936.0	332.0	604.0	1.8	1217.0	25.1	70.7	38.9	19.3
L1-13	257.0	40.0	217.0	5.4	91.0	91.3	586.9	108.2	258.0
L1-14	23.0	2.0	21.0	10.5	14.0	1020.6	11737.1	1117.8	1676.7
L1-161	NA	NA	NA	NA	NA	NA	NA	NA	NA
L1-162	NA	NA	NA	NA	NA	NA	NA	NA	NA
L1-163	NA	NA	NA	NA	NA	NA	NA	NA	NA
Series L2									
L2-77	NA	NA	NA	NA	NA	NA	NA	NA	NA
L2-176	NA	NA	NA	NA	NA	NA	NA	NA	NA
L2-79	3524.0	2498.0	1026.0	0.4	6820.0	7.8	10.9	26.6	4.1
L2-81	119.0	29.0	90.0	3.1	149.0	229.6	942.2	303.6	183.4
L2-82	52.0	3.0	49.0	16.3	10.0	525.4	9107.5	557.6	2732.2
Series L5									
L5-121	1158.0	568.0	590.0	1.0	4274.0	17.3	35.4	34.0	4.7
L5-122	1839.0	1315.0	524.0	0.4	3377.0	10.9	15.3	38.3	5.9

APPENDIX B: LISTS OF TIME-SEQUENCE OF EACH DIGGING AND FILLING PHASE

The appendix summarizes the time-sequence of each digging and filling phase for the experiments with jet-flipping. Part 1 shows the tables of the data and part 2 shows some of the corresponding figures. They are arranged in the sequence of run number.

Table B-1 Time-sequence of each digging and filling phase of Run 13

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	23/8/2010	15:36	23/8/2010	17:07	91
	Filling	23/8/2010	17:07	23/8/2010	18:58	111
2	Digging	23/8/2010	18:58	23/8/2010	19:57	59
	Filling	23/8/2010	19:57	23/8/2010	22:05	128
3	Digging	23/8/2010	22:05	23/8/2010	22:39	34
	Filling	23/8/2010	22:39	24/8/2010	0:40	121
4	Digging	24/8/2010	0:40	24/8/2010	1:22	42
	Filling	24/8/2010	1:22	24/8/2010	4:35	193
5	Digging	24/8/2010	4:35	24/8/2010	5:35	60
	Filling	24/8/2010	5:35	24/8/2010	8:53	198
6	Digging	24/8/2010	8:53	24/8/2010	9:53	60
	Filling	24/8/2010	9:53	24/8/2010	13:31	217
7	Digging	24/8/2010	13:31	24/8/2010	13:50	19
	Filling	24/8/2010	13:50	24/8/2010	15:33	103
8	Digging	24/8/2010	15:33	24/8/2010	16:18	45
	Filling	24/8/2010	16:18	24/8/2010	19:32	194
9	Digging	24/8/2010	19:32	24/8/2010	20:17	45
	Filling	24/8/2010	20:17	24/8/2010	22:49	152
10	Digging	24/8/2010	22:49	24/8/2010	23:33	44
	Filling	24/8/2010	23:33	25/8/2010	4:08	275
11	Digging	25/8/2010	4:08	25/8/2010	4:38	30
	Filling	25/8/2010	4:38	25/8/2010	8:06	208
12	Digging	25/8/2010	8:06	25/8/2010	8:56	50
	Filling	25/8/2010	8:56	25/8/2010	12:35	219
13	Digging	25/8/2010	12:35	25/8/2010	13:00	25
	Filling	25/8/2010	13:00	25/8/2010	15:50	170
14	Digging	25/8/2010	15:50	25/8/2010	16:50	60
	Filling	25/8/2010	16:50	25/8/2010	20:35	225
15	Digging	25/8/2010	20:35	25/8/2010	21:02	27
	Filling	25/8/2010	21:02	26/8/2010	0:55	233
16	Digging	26/8/2010	0:55	26/8/2010	1:33	38
	Filling	26/8/2010	1:33	26/8/2010	4:53	200
17	Digging	26/8/2010	4:53	26/8/2010	5:42	49
	Filling	26/8/2010	5:42	26/8/2010	10:19	277
18	Digging	26/8/2010	10:19	26/8/2010	11:06	47

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
	Filling	26/8/2010	11:06	26/8/2010	14:52	226
19	Digging	26/8/2010	14:52	26/8/2010	15:38	46
	Filling	26/8/2010	15:38	26/8/2010	19:14	216
20	Digging	26/8/2010	19:14	26/8/2010	19:38	24
	Filling	26/8/2010	19:38	26/8/2010	22:30	172
21	Digging	26/8/2010	22:30	26/8/2010	23:01	31
	Filling	26/8/2010	23:01	27/8/2010	2:39	218
22	Digging	27/8/2010	2:39	27/8/2010	3:17	38
	Filling	27/8/2010	3:17	27/8/2010	7:13	236
23	Digging	27/8/2010	7:13	27/8/2010	7:49	36
	Filling	27/8/2010	7:49	27/8/2010	12:01	252
24	Digging	27/8/2010	12:01	27/8/2010	12:34	33
	Filling	27/8/2010	12:34	27/8/2010	16:06	212
25	Digging	27/8/2010	16:06	27/8/2010	16:42	36
	Filling	27/8/2010	16:42	27/8/2010	20:07	205
26	Digging	27/8/2010	20:07	27/8/2010	20:47	40
	Filling	27/8/2010	20:47	28/8/2010	0:16	209
27	Digging	28/8/2010	0:16	28/8/2010	1:14	58
	Filling	28/8/2010	1:14	28/8/2010	4:30	196
28	Digging	28/8/2010	4:30	28/8/2010	5:03	33
	Filling	28/8/2010	5:03	28/8/2010	9:43	280
29	Digging	28/8/2010	9:43	28/8/2010	10:31	48
	Filling	28/8/2010	10:31	28/8/2010	14:45	254
30	Digging	28/8/2010	14:45	28/8/2010	15:27	42
	Filling	28/8/2010	15:27	28/8/2010	19:30	243
31	Digging	28/8/2010	19:30	28/8/2010	20:23	53
	Filling	28/8/2010	20:23	28/8/2010	23:31	188
32	Digging	28/8/2010	23:31	29/8/2010	0:13	42
	Filling	29/8/2010	0:13	29/8/2010	4:06	233
33	Digging	29/8/2010	4:06	29/8/2010	4:37	31
	Filling	29/8/2010	4:37	29/8/2010	8:49	252
34	Digging	29/8/2010	8:49	29/8/2010	9:33	44
	Filling	29/8/2010	9:33	29/8/2010	14:01	268
35	Digging	29/8/2010	14:01	29/8/2010	14:44	43
	Filling	29/8/2010	14:44	29/8/2010	18:18	214
36	Digging	29/8/2010	18:18	29/8/2010	19:05	47
	Filling	29/8/2010	19:05	29/8/2010	23:50	285
37	Digging	29/8/2010	23:50	30/8/2010	0:27	37
	Filling	30/8/2010	0:27	30/8/2010	5:19	292
38	Digging	30/8/2010	5:19	30/8/2010	6:05	46
	Filling	30/8/2010	6:05	30/8/2010	10:40	275
39	Digging	30/8/2010	10:40	30/8/2010	11:22	42
	Filling	30/8/2010	11:22	30/8/2010	15:43	261
40	Digging	30/8/2010	15:43	30/8/2010	16:27	44
	Filling	30/8/2010	16:27	30/8/2010	20:14	227

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
41	Digging	30/8/2010	20:14	30/8/2010	20:59	45
	Filling	30/8/2010	20:59	31/8/2010	2:10	310
42	Digging	31/8/2010	2:10	31/8/2010	2:34	21
	Filling	31/8/2010	2:34	31/8/2010	5:14	160
43	Digging	31/8/2010	5:14	31/8/2010	5:41	27
	Filling	31/8/2010	5:41	31/8/2010	10:04	263
44	Digging	31/8/2010	10:04	31/8/2010	10:29	25
	Filling	31/8/2010	10:29	31/8/2010	13:19	170
45	Digging	31/8/2010	13:19	31/8/2010	13:52	33

Table B-2 Time-sequence of each digging and filling phase of Run 14

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	14/9/2010	14:46	14/9/2010	15:00	14
	Filling	14/9/2010	15:00	14/9/2010	15:03	3
2	Digging	14/9/2010	15:03	14/9/2010	15:10	7
	Filling	14/9/2010	15:10	14/9/2010	15:18	8
3	Digging	14/9/2010	15:18	14/9/2010	15:21	3
	Filling	14/9/2010	15:21	14/9/2010	15:26	5
4	Digging	14/9/2010	15:26	14/9/2010	15:30	4
	Filling	14/9/2010	15:30	14/9/2010	15:37	7
5	Digging	14/9/2010	15:37	14/9/2010	15:40	3
	Filling	14/9/2010	15:40	14/9/2010	15:51	11
6	Digging	14/9/2010	15:51	14/9/2010	15:55	4
	Filling	14/9/2010	15:55	14/9/2010	16:03	8
7	Digging	14/9/2010	16:03	14/9/2010	16:05	1
	Filling	14/9/2010	16:05	14/9/2010	16:21	16
8	Digging	14/9/2010	16:21	14/9/2010	16:24	3
	Filling	14/9/2010	16:24	14/9/2010	16:38	14
9	Digging	14/9/2010	16:38	14/9/2010	16:41	3
	Filling	14/9/2010	16:41	14/9/2010	16:51	10
10	Digging	14/9/2010	16:51	14/9/2010	16:56	5
	Filling	14/9/2010	16:56	14/9/2010	17:12	16
11	Digging	14/9/2010	17:12	14/9/2010	17:14	2
	Filling	14/9/2010	17:14	14/9/2010	17:21	7
12	Digging	14/9/2010	17:21	14/9/2010	17:25	4
	Filling	14/9/2010	17:25	14/9/2010	17:40	15
13	Digging	14/9/2010	17:40	14/9/2010	17:41	1
	Filling	14/9/2010	17:41	14/9/2010	18:04	23
14	Digging	14/9/2010	18:04	14/9/2010	18:09	5
	Filling	14/9/2010	18:09	14/9/2010	18:37	28
15	Digging	14/9/2010	18:37	14/9/2010	18:40	3
	Filling	14/9/2010	18:40	14/9/2010	18:54	14
16	Digging	14/9/2010	18:54	14/9/2010	18:55	1
	Filling	14/9/2010	18:55	14/9/2010	19:16	21
17	Digging	14/9/2010	19:16	14/9/2010	19:21	5

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
	Filling	14/9/2010	19:21	14/9/2010	19:54	33
18	Digging	14/9/2010	19:54	14/9/2010	19:55	1
	Filling	14/9/2010	19:55	14/9/2010	20:08	13
19	Digging	14/9/2010	20:08	14/9/2010	20:12	4
	Filling	14/9/2010	20:12	14/9/2010	20:37	25
20	Digging	14/9/2010	20:37	14/9/2010	20:39	2
	Filling	14/9/2010	20:39	14/9/2010	20:46	7
21	Digging	14/9/2010	20:46	14/9/2010	20:49	3
	Filling	14/9/2010	20:49	14/9/2010	21:00	11
22	Digging	14/9/2010	21:00	14/9/2010	21:02	2
	Filling	14/9/2010	21:02	14/9/2010	21:32	30
23	Digging	14/9/2010	21:32	14/9/2010	21:34	2
	Filling	14/9/2010	21:34	14/9/2010	22:01	27
24	Digging	14/9/2010	22:01	14/9/2010	22:04	3
	Filling	14/9/2010	22:04	14/9/2010	22:13	9
25	Digging	14/9/2010	22:13	14/9/2010	22:16	3
	Filling	14/9/2010	22:16	14/9/2010	22:38	22
26	Digging	14/9/2010	22:38	14/9/2010	22:40	2
	Filling	14/9/2010	22:40	14/9/2010	23:07	27
27	Digging	14/9/2010	23:07	14/9/2010	23:11	4
	Filling	14/9/2010	23:11	14/9/2010	23:40	29
28	Digging	14/9/2010	23:40	14/9/2010	23:42	2
	Filling	14/9/2010	23:42	15/9/2010	0:03	21
29	Digging	15/9/2010	0:03	15/9/2010	0:05	2
	Filling	15/9/2010	0:05	15/9/2010	0:15	10
30	Digging	15/9/2010	0:15	15/9/2010	0:17	2
	Filling	15/9/2010	0:17	15/9/2010	0:47	30
31	Digging	15/9/2010	0:47	15/9/2010	0:49	2
	Filling	15/9/2010	0:49	15/9/2010	0:58	9
32	Digging	15/9/2010	0:58	15/9/2010	1:01	3
	Filling	15/9/2010	1:01	15/9/2010	1:32	31
33	Digging	15/9/2010	1:32	15/9/2010	1:36	4
	Filling	15/9/2010	1:36	15/9/2010	2:01	25
34	Digging	15/9/2010	2:01	15/9/2010	2:02	1
	Filling	15/9/2010	2:02	15/9/2010	2:36	34
35	Digging	15/9/2010	2:36	15/9/2010	2:39	3
	Filling	15/9/2010	2:39	15/9/2010	2:54	15
36	Digging	15/9/2010	2:54	15/9/2010	2:57	3
	Filling	15/9/2010	2:57	15/9/2010	3:19	22
37	Digging	15/9/2010	3:19	15/9/2010	3:20	1
	Filling	15/9/2010	3:20	15/9/2010	3:34	14
38	Digging	15/9/2010	3:34	15/9/2010	3:35	1
	Filling	15/9/2010	3:35	15/9/2010	3:59	24
39	Digging	15/9/2010	3:59	15/9/2010	4:02	3
	Filling	15/9/2010	4:02	15/9/2010	4:08	6

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
40	Digging	15/9/2010	4:08	15/9/2010	4:10	2
	Filling	15/9/2010	4:10	15/9/2010	4:49	39
41	Digging	15/9/2010	4:49	15/9/2010	4:51	2
	Filling	15/9/2010	4:51	15/9/2010	5:14	23
42	Digging	15/9/2010	5:14	15/9/2010	5:16	2
	Filling	15/9/2010	5:16	15/9/2010	5:53	37
43	Digging	15/9/2010	5:53	15/9/2010	5:55	2
	Filling	15/9/2010	5:55	15/9/2010	6:09	14
44	Digging	15/9/2010	6:09	15/9/2010	6:13	4
	Filling	15/9/2010	6:13	15/9/2010	6:43	30
45	Digging	15/9/2010	6:43	15/9/2010	6:46	3
	Filling	15/9/2010	6:46	15/9/2010	7:26	40
46	Digging	15/9/2010	7:26	15/9/2010	7:27	1
	Filling	15/9/2010	7:27	15/9/2010	7:41	14
47	Digging	15/9/2010	7:41	15/9/2010	7:43	2
	Filling	15/9/2010	7:43	15/9/2010	8:27	44
48	Digging	15/9/2010	8:27	15/9/2010	8:28	1
	Filling	15/9/2010	8:28	15/9/2010	8:50	22
49	Digging	15/9/2010	8:50	15/9/2010	8:52	2
	Filling	15/9/2010	8:52	15/9/2010	9:05	13
50	Digging	15/9/2010	9:05	15/9/2010	9:07	2
	Filling	15/9/2010	9:07	15/9/2010	9:30	23
51	Digging	15/9/2010	9:30	15/9/2010	9:32	2
	Filling	15/9/2010	9:32	15/9/2010	9:52	20
52	Digging	15/9/2010	9:52	15/9/2010	9:54	2
	Filling	15/9/2010	9:54	15/9/2010	10:17	23
53	Digging	15/9/2010	10:17	15/9/2010	10:19	2
	Filling	15/9/2010	10:19	15/9/2010	10:54	35
54	Digging	15/9/2010	10:54	15/9/2010	10:56	2
	Filling	15/9/2010	10:56	15/9/2010	11:12	16
55	Digging	15/9/2010	11:12	15/9/2010	11:14	2
	Filling	15/9/2010	11:14	15/9/2010	11:43	29
56	Digging	15/9/2010	11:43	15/9/2010	11:45	2
	Filling	15/9/2010	11:45	15/9/2010	12:11	26
57	Digging	15/9/2010	12:11	15/9/2010	12:14	3
	Filling	15/9/2010	12:14	15/9/2010	12:48	34
58	Digging	15/9/2010	12:48	15/9/2010	12:49	1
	Filling	15/9/2010	12:49	15/9/2010	13:32	43
59	Digging	15/9/2010	13:32	15/9/2010	13:33	1
	Filling	15/9/2010	13:33	15/9/2010	13:47	14
60	Digging	15/9/2010	13:47	15/9/2010	13:48	1
	Filling	15/9/2010	13:48	15/9/2010	13:59	11
61	Digging	15/9/2010	13:59	15/9/2010	14:01	2
	Filling	15/9/2010	14:01	15/9/2010	14:14	13
62	Digging	15/9/2010	14:14	15/9/2010	14:16	2

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
	Filling	15/9/2010	14:16	15/9/2010	14:48	32
63	Digging	15/9/2010	14:48	15/9/2010	14:49	1
	Filling	15/9/2010	14:49	15/9/2010	15:26	37
64	Digging	15/9/2010	15:26	15/9/2010	15:29	3
	Filling	15/9/2010	15:29	15/9/2010	15:55	26
65	Digging	15/9/2010	15:55	15/9/2010	15:57	2
	Filling	15/9/2010	15:57	15/9/2010	16:08	11
66	Digging	15/9/2010	16:08	15/9/2010	16:10	2
	Filling	15/9/2010	16:10	15/9/2010	16:48	38
67	Digging	15/9/2010	16:48	15/9/2010	16:49	1
	Filling	15/9/2010	16:49	15/9/2010	17:07	18
68	Digging	15/9/2010	17:07	15/9/2010	17:09	2
	Filling	15/9/2010	17:09	15/9/2010	17:25	16
69	Digging	15/9/2010	17:25	15/9/2010	17:26	1
	Filling	15/9/2010	17:26	15/9/2010	17:41	15
70	Digging	15/9/2010	17:41	15/9/2010	17:43	2
	Filling	15/9/2010	17:43	15/9/2010	18:14	31
71	Digging	15/9/2010	18:14	15/9/2010	18:17	3
	Filling	15/9/2010	18:17	15/9/2010	18:38	21
72	Digging	15/9/2010	18:38	15/9/2010	18:40	2
	Filling	15/9/2010	18:40	15/9/2010	19:02	22
73	Digging	15/9/2010	19:02	15/9/2010	19:04	2
	Filling	15/9/2010	19:04	15/9/2010	19:46	42

Table B-3 Time-sequence of each digging and filling phase of Run 15

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	21/9/2010	16:37	22/9/2010	12:54	1217
	Filling	22/9/2010	12:54	22/9/2010	19:29	395
2	Digging	22/9/2010	19:29	23/9/2010	6:40	671
	Filling	23/9/2010	6:40	23/9/2010	15:18	518
3	Digging	23/9/2010	15:18	23/9/2010	21:37	379
	Filling	23/9/2010	21:37	24/9/2010	6:21	524
4	Digging	24/9/2010	6:21	24/9/2010	19:51	810
	Filling	24/9/2010	19:51	25/9/2010	6:30	638
5	Digging	25/9/2010	6:30	25/9/2010	7:39	69
	Filling	25/9/2010	7:39	25/9/2010	16:00	501
6	Digging	25/9/2010	16:00	25/9/2010	20:13	253
	Filling	26/9/2010	20:13	26/9/2010	8:20	727
7	Digging	26/9/2010	8:20	26/9/2010	13:38	318
	Filling	26/9/2010	13:38	27/9/2010	1:55	797
8	Digging	27/9/2010	1:55	27/9/2010	3:32	97
	Filling	27/9/2010	3:32	27/9/2010	15:35	723
9	Digging	27/9/2010	15:35	27/9/2010	20:12	277
	Filling	27/9/2010	20:12	28/9/2010	6:33	621
10	Digging	28/9/2010	6:33	28/9/2010	8:27	114

Table B-4 Time-sequence of each digging and filling phase of Run 20

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	26/10/2010	14:10	27/10/2010	21:38	1888
	Filling	27/10/2010	21:38	28/10/2010	2:37	299
2	Digging	28/10/2010	2:37	28/10/2010	8:54	377
	Filling	28/10/2010	8:54	28/10/2010	14:51	357
3	Digging	28/10/2010	14:51	29/10/2010	9:45	1134
	Filling	29/10/2010	9:45	29/10/2010	15:56	371
4	Digging	29/10/2010	15:56	30/10/2010	0:18	502
	Filling	30/10/2010	0:18	30/10/2010	6:26	368
5	Digging	30/10/2010	6:26	30/10/2010	22:44	978
	Filling	30/10/2010	22:44	31/10/2010	6:27	463
6	Digging	31/10/2010	6:27	31/10/2010	17:34	667
	Filling	31/10/2010	17:34	31/10/2010	23:55	381
7	Digging	31/10/2010	23:55	1/11/2010	6:31	396
	Filling	1/11/2010	6:31	1/11/2010	14:14	463
8	Digging	1/11/2010	14:14	2/11/2010	5:37	923
	Filling	2/11/2010	5:37	2/11/2010	14:48	551
9*	Digging	2/11/2010	14:48	3/11/2010	20:52	1804
	Filling	3/11/2010	20:52	4/11/2010	5:47	535
10	Digging	4/11/2010	5:47	4/11/2010	13:30	463
	Filling	4/11/2010	13:30	5/11/2010	0:30	660
11	Digging	5/11/2010	0:30	5/11/2010	6:29	359
	Filling	5/11/2010	6:29	5/11/2010	14:22	473
12	Digging	5/11/2010	14:22	6/11/2010	3:12	770
	Filling	6/11/2010	3:12	6/11/2010	14:55	703
13	Digging	6/11/2010	14:55	6/11/2010	19:21	266
	Filling	6/11/2010	19:21	7/11/2010	6:50	689
14	Digging	7/11/2010	6:50	7/11/2010	20:24	814
	Filling	7/11/2010	20:24	8/11/2010	11:02	878
15	Digging	8/11/2010	11:02	8/11/2010	18:16	434
	Filling	8/11/2010	18:16	9/11/2010	8:03	827
Note:* Ridge removal test was conducted at 9 th cycle.						

Table B-5 Time-sequence of each digging and filling phase of Run 21

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	10/11/2010	15:35	13/11/2010	13:55	4220
	Filling	13/11/2010	13:55	14/11/2010	0:01	606
2	Digging	14/11/2010	0:01	14/11/2010	19:21	1160
	Filling	14/11/2010	19:21	15/11/2010	5:57	636
3	Digging	15/11/2010	5:57	16/11/2010	6:06	1449
	Filling	16/11/2010	6:06	16/11/2010	16:21	615
4	Digging	16/11/2010	16:21	18/11/2010	17:11	2930
	Filling	18/11/2010	17:11	19/11/2010	7:00	829

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
5	Digging	19/11/2010	7:00	20/11/2010	8:17	1517
	Filling	20/11/2010	8:17	20/11/2010	20:51	754
6	Digging	20/11/2010	20:51	21/11/2010	23:05	1574
	Filling	21/11/2010	23:05	22/11/2010	12:16	791
7	Digging	22/11/2010	12:16	23/11/2010	10:16	1320
	Filling	23/11/2010	10:16	23/11/2010	23:13	777
8	Digging	23/11/2010	23:13	24/11/2010	21:37	1344
	Filling	24/11/2010	21:37	25/11/2010	8:55	678
9	Digging	25/11/2010	8:55	26/11/2010	12:11	1636
	Filling	26/11/2010	12:11	27/11/2010	1:54	823
10	Digging	27/11/2010	1:54	27/11/2010	22:35	1241
	Filling	27/11/2010	22:35	28/11/2010	11:39	784
11	Digging	28/11/2010	11:39	29/11/2010	20:15	1956
	Filling	29/11/2010	20:15	30/11/2010	9:56	821
12	Digging	30/11/2010	9:56	1/12/2010	12:41	1605
	Filling	1/12/2010	12:41	2/12/2010	0:50	729

Table B-6 Time-sequence of each digging and filling phase of Run 22

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	5/1/2011	14:55	7/1/2011	19:32	3157
	Filling	7/1/2011	19:32	7/1/2011	20:47	75
2	Digging	7/1/2011	20:47	9/1/2011	6:16	2009
	Filling	9/1/2011	6:16	9/1/2011	8:41	145
3	Digging	9/1/2011	8:41	10/1/2011	12:57	1696
	Filling	10/1/2011	12:57	10/1/2011	14:37	100
4	Digging	10/1/2011	14:37	11/1/2011	1:39	662
	Filling	11/1/2011	1:39	11/1/2011	2:58	79
5	Digging	11/1/2011	2:58	11/1/2011	6:56	238
	Filling	11/1/2011	6:56	11/1/2011	9:13	137
6	Digging	11/1/2011	9:13	13/1/2011	7:03	2750
	Filling	13/1/2011	7:03	13/1/2011	10:23	200
7	Digging	13/1/2011	10:23	13/1/2011	16:22	359
	Filling	13/1/2011	16:22	13/1/2011	19:25	183
8	Digging	13/1/2011	19:25	14/1/2011	6:43	678
	Filling	14/1/2011	6:43	14/1/2011	9:18	155
9	Digging	14/1/2011	9:18	15/1/2011	6:18	1260
	Filling	15/1/2011	6:18	15/1/2011	8:44	146
10	Digging	15/1/2011	8:44	15/1/2011	14:55	371
	Filling	15/1/2011	14:55	15/1/2011	17:14	139
11	Digging	15/1/2011	17:14	16/1/2011	3:47	633
	Filling	16/1/2011	3:47	16/1/2011	6:43	176
12	Digging	16/1/2011	6:43	16/1/2011	18:00	677
	Filling	16/1/2011	18:00	16/1/2011	21:11	191
13	Digging	16/1/2011	21:11	17/1/2011	22:26	1515
	Filling	17/1/2011	22:26	18/1/2011	1:29	183

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
14	Digging	18/1/2011	1:29	18/1/2011	19:18	1069
	Filling	18/1/2011	19:18	18/1/2011	22:34	196
15	Digging	18/1/2011	22:34	19/1/2011	5:36	422
	Filling	19/1/2011	5:36	19/1/2011	8:52	196
16	Digging	19/1/2011	8:52	19/1/2011	13:47	295
	Filling	19/1/2011	13:47	19/1/2011	16:47	180
17	Digging	19/1/2011	16:47	20/1/2011	2:12	565
	Filling	20/1/2011	2:12	20/1/2011	5:29	197
18	Digging	20/1/2011	5:29	20/1/2011	16:08	639
	Filling	20/1/2011	16:08	20/1/2011	19:01	173
19	Digging	20/1/2011	19:01	21/1/2011	3:57	536
	Filling	21/1/2011	3:57	21/1/2011	6:28	151
20	Digging	21/1/2011	6:28	21/1/2011	22:34	966
	Filling	21/1/2011	22:34	22/1/2011	1:11	157
21	Digging	22/1/2011	1:11	22/1/2011	10:17	546
	Filling	22/1/2011	10:17	22/1/2011	13:46	209
22	Digging	22/1/2011	13:46	23/1/2011	4:05	859
	Filling	23/1/2011	4:05	23/1/2011	6:07	122
23	Digging	23/1/2011	6:07	23/1/2011	8:58	171
	Filling	23/1/2011	8:58	23/1/2011	10:43	105

Table B-7 Time-sequence of each digging and filling phase of Run 52

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	21/4/2011	14:03	21/4/2011	14:57	54
	Filling	21/4/2011	14:57	21/4/2011	14:59	2
2	Digging	21/4/2011	14:59	21/4/2011	15:12	13
	Filling	21/4/2011	15:12	21/4/2011	15:17	5
3	Digging	21/4/2011	15:17	21/4/2011	15:24	7
	Filling	21/4/2011	15:24	21/4/2011	15:32	8
4	Digging	21/4/2011	15:32	21/4/2011	15:41	9
	Filling	21/4/2011	15:41	21/4/2011	15:45	4
5	Digging	21/4/2011	15:45	21/4/2011	15:48	3
	Filling	21/4/2011	15:48	21/4/2011	15:56	8
6	Digging	21/4/2011	15:56	21/4/2011	15:59	3
	Filling	21/4/2011	15:59	21/4/2011	16:06	7
7	Digging	21/4/2011	16:06	21/4/2011	16:10	4
	Filling	21/4/2011	16:10	21/4/2011	16:14	4
8	Digging	21/4/2011	16:14	21/4/2011	16:17	3
	Filling	21/4/2011	16:17	21/4/2011	16:19	2
9	Digging	21/4/2011	16:19	21/4/2011	16:21	2
	Filling	21/4/2011	16:21	21/4/2011	16:33	12
10	Digging	21/4/2011	16:33	21/4/2011	16:38	5
	Filling	21/4/2011	16:38	21/4/2011	16:47	9
11	Digging	21/4/2011	16:47	21/4/2011	16:53	6
	Filling	21/4/2011	16:53	21/4/2011	17:14	21

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
12	Digging	21/4/2011	17:14	21/4/2011	17:21	7
	Filling	21/4/2011	17:21	21/4/2011	17:30	9
13	Digging	21/4/2011	17:30	21/4/2011	17:33	3
	Filling	21/4/2011	17:33	21/4/2011	17:47	14
14	Digging	21/4/2011	17:47	21/4/2011	17:54	7
	Filling	21/4/2011	17:54	21/4/2011	18:08	14
15	Digging	21/4/2011	18:08	21/4/2011	18:15	7
	Filling	21/4/2011	18:15	21/4/2011	18:45	30
16	Digging	21/4/2011	18:45	21/4/2011	18:54	9
	Filling	21/4/2011	18:54	21/4/2011	19:02	8
17	Digging	21/4/2011	19:02	21/4/2011	19:05	3
	Filling	21/4/2011	19:05	21/4/2011	19:16	11
18	Digging	21/4/2011	19:16	21/4/2011	19:23	7
	Filling	21/4/2011	19:23	21/4/2011	19:43	20
19	Digging	21/4/2011	19:43	21/4/2011	19:45	2
	Filling	21/4/2011	19:45	21/4/2011	19:56	11
20	Digging	21/4/2011	19:56	21/4/2011	20:04	8
	Filling	21/4/2011	20:04	21/4/2011	20:23	19
21	Digging	21/4/2011	20:23	21/4/2011	20:30	7
	Filling	21/4/2011	20:30	21/4/2011	21:04	34
22	Digging	21/4/2011	21:04	21/4/2011	21:10	6
	Filling	21/4/2011	21:10	21/4/2011	21:21	11
23	Digging	21/4/2011	21:21	21/4/2011	21:23	2
	Filling	21/4/2011	21:23	21/4/2011	21:42	19
24	Digging	21/4/2011	21:42	21/4/2011	21:45	3
	Filling	21/4/2011	21:45	21/4/2011	21:57	12
25	Digging	21/4/2011	21:57	21/4/2011	22:00	3
	Filling	21/4/2011	22:00	21/4/2011	22:03	3
26	Digging	21/4/2011	22:03	21/4/2011	22:05	2
	Filling	21/4/2011	22:05	21/4/2011	22:23	18
27	Digging	21/4/2011	22:23	21/4/2011	22:29	6
	Filling	21/4/2011	22:29	21/4/2011	23:00	31
28	Digging	21/4/2011	23:00	21/4/2011	23:02	2
	Filling	21/4/2011	23:02	21/4/2011	23:25	23
29	Digging	21/4/2011	23:25	21/4/2011	23:29	4
	Filling	21/4/2011	23:29	21/4/2011	23:44	15
30	Digging	21/4/2011	23:44	21/4/2011	23:50	6
	Filling	21/4/2011	23:50	22/4/2011	0:18	28
31	Digging	22/4/2011	0:18	22/4/2011	0:22	4
	Filling	22/4/2011	0:22	22/4/2011	0:41	19
32	Digging	22/4/2011	0:41	22/4/2011	0:44	3
	Filling	22/4/2011	0:44	22/4/2011	1:11	27
33	Digging	22/4/2011	1:11	22/4/2011	1:16	5
	Filling	22/4/2011	1:16	22/4/2011	1:39	23
34	Digging	22/4/2011	1:39	22/4/2011	1:41	2

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
	Filling	22/4/2011	1:41	22/4/2011	1:54	13
35	Digging	22/4/2011	1:54	22/4/2011	1:58	4
	Filling	22/4/2011	1:58	22/4/2011	2:22	24
36	Digging	22/4/2011	2:22	22/4/2011	2:25	3
	Filling	22/4/2011	2:25	22/4/2011	2:55	30
37	Digging	22/4/2011	2:55	22/4/2011	3:01	6
	Filling	22/4/2011	3:01	22/4/2011	3:40	39
38	Digging	22/4/2011	3:40	22/4/2011	3:42	2
	Filling	22/4/2011	3:42	22/4/2011	4:15	33
39	Digging	22/4/2011	4:15	22/4/2011	4:19	4
	Filling	22/4/2011	4:19	22/4/2011	4:43	24
40	Digging	22/4/2011	4:43	22/4/2011	4:49	6
	Filling	22/4/2011	4:49	22/4/2011	5:31	42
41	Digging	22/4/2011	5:31	22/4/2011	5:33	2
	Filling	22/4/2011	5:33	22/4/2011	5:50	17
42	Digging	22/4/2011	5:50	22/4/2011	5:51	1
	Filling	22/4/2011	5:51	22/4/2011	6:01	10
43	Digging	22/4/2011	6:01	22/4/2011	6:05	4
	Filling	22/4/2011	6:05	22/4/2011	6:26	21
44	Digging	22/4/2011	6:26	22/4/2011	6:32	6
	Filling	22/4/2011	6:32	22/4/2011	7:30	58
45	Digging	22/4/2011	7:30	22/4/2011	7:32	2
	Filling	22/4/2011	7:32	22/4/2011	8:08	36
46	Digging	22/4/2011	8:08	22/4/2011	8:11	3
	Filling	22/4/2011	8:11	22/4/2011	8:38	27
47	Digging	22/4/2011	8:38	22/4/2011	8:40	2
	Filling	22/4/2011	8:40	22/4/2011	9:17	37
48	Digging	22/4/2011	9:17	22/4/2011	9:20	3
	Filling	22/4/2011	9:20	22/4/2011	9:28	8
49	Digging	22/4/2011	9:28	22/4/2011	9:31	3
	Filling	22/4/2011	9:31	22/4/2011	10:09	38
50	Digging	22/4/2011	10:09	22/4/2011	10:12	3
	Filling	22/4/2011	10:12	22/4/2011	10:22	10
51	Digging	22/4/2011	10:22	22/4/2011	10:25	3
	Filling	22/4/2011	10:25	22/4/2011	10:39	14
52	Digging	22/4/2011	10:39	22/4/2011	10:42	3
	Filling	22/4/2011	10:42	22/4/2011	10:55	13
53	Digging	22/4/2011	10:55	22/4/2011	10:57	2
	Filling	22/4/2011	10:57	22/4/2011	11:32	35
54	Digging	22/4/2011	11:32	22/4/2011	11:36	4
	Filling	22/4/2011	11:36	22/4/2011	12:13	37
55	Digging	22/4/2011	12:13	22/4/2011	12:16	3
	Filling	22/4/2011	12:16	22/4/2011	12:32	16
56	Digging	22/4/2011	12:32	22/4/2011	12:33	1
	Filling	22/4/2011	12:33	22/4/2011	12:47	14

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
57	Digging	22/4/2011	12:47	22/4/2011	12:50	3
	Filling	22/4/2011	12:50	22/4/2011	13:07	17
58	Digging	22/4/2011	13:07	22/4/2011	13:12	5
	Filling	22/4/2011	13:12	22/4/2011	13:34	22
59	Digging	22/4/2011	13:34	22/4/2011	13:40	6
	Filling	22/4/2011	13:40	22/4/2011	14:09	29
60	Digging	22/4/2011	14:09	22/4/2011	14:15	6
	Filling	22/4/2011	14:15	22/4/2011	14:25	10
61	Digging	22/4/2011	14:25	22/4/2011	14:27	2
	Filling	22/4/2011	14:27	22/4/2011	15:14	47
62	Digging	22/4/2011	15:14	22/4/2011	15:18	4
	Filling	22/4/2011	15:18	22/4/2011	15:55	37
63	Digging	22/4/2011	15:55	22/4/2011	15:58	3
	Filling	22/4/2011	15:58	22/4/2011	16:08	10
64	Digging	22/4/2011	16:08	22/4/2011	16:11	3
	Filling	22/4/2011	16:11	22/4/2011	16:35	24
65	Digging	22/4/2011	16:35	22/4/2011	16:38	3
	Filling	22/4/2011	16:38	22/4/2011	17:05	27
66	Digging	22/4/2011	17:05	22/4/2011	17:09	4
	Filling	22/4/2011	17:09	22/4/2011	17:29	20
67	Digging	22/4/2011	17:29	22/4/2011	17:34	5
	Filling	22/4/2011	17:34	22/4/2011	18:05	31
68	Digging	22/4/2011	18:05	22/4/2011	18:06	1
	Filling	22/4/2011	18:06	22/4/2011	18:18	12
69	Digging	22/4/2011	18:18	22/4/2011	18:21	3
	Filling	22/4/2011	18:21	22/4/2011	18:50	29
70	Digging	22/4/2011	18:50	22/4/2011	18:53	3
	Filling	22/4/2011	18:53	22/4/2011	19:07	14
71	Digging	22/4/2011	19:07	22/4/2011	19:09	2
	Filling	22/4/2011	19:09	22/4/2011	19:34	25
72	Digging	22/4/2011	19:34	22/4/2011	19:38	4
	Filling	22/4/2011	19:38	22/4/2011	20:15	37
73	Digging	22/4/2011	20:15	22/4/2011	20:18	3
	Filling	22/4/2011	20:18	22/4/2011	20:22	4
74	Digging	22/4/2011	20:22	22/4/2011	20:24	2
	Filling	22/4/2011	20:24	22/4/2011	21:07	43
75	Digging	22/4/2011	21:07	22/4/2011	21:09	2
	Filling	22/4/2011	21:09	22/4/2011	21:18	9
76	Digging	22/4/2011	21:18	22/4/2011	21:22	4
	Filling	22/4/2011	21:22	22/4/2011	21:28	6
77	Digging	22/4/2011	21:28	22/4/2011	21:33	5
	Filling	22/4/2011	21:33	22/4/2011	21:54	21
78	Digging	22/4/2011	21:54	22/4/2011	22:01	7
	Filling	22/4/2011	22:01	22/4/2011	22:23	22
79	Digging	22/4/2011	22:23	22/4/2011	22:28	5

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
	Filling	22/4/2011	22:28	22/4/2011	23:14	46
80	Digging	22/4/2011	23:14	22/4/2011	23:15	1
	Filling	22/4/2011	23:15	22/4/2011	23:32	17
81	Digging	22/4/2011	23:32	22/4/2011	23:35	3
	Filling	22/4/2011	23:35	22/4/2011	23:50	15
82	Digging	22/4/2011	23:50	22/4/2011	23:54	4
	Filling	22/4/2011	23:54	23/4/2011	0:08	14
83	Digging	23/4/2011	0:08	23/4/2011	0:11	3
	Filling	23/4/2011	0:11	23/4/2011	0:47	36
84	Digging	23/4/2011	0:47	23/4/2011	0:48	1
	Filling	23/4/2011	0:48	23/4/2011	1:38	50
85	Digging	23/4/2011	1:38	23/4/2011	1:40	2
	Filling	23/4/2011	1:40	23/4/2011	2:08	28
86	Digging	23/4/2011	2:08	23/4/2011	2:10	2
	Filling	23/4/2011	2:10	23/4/2011	2:30	20
87	Digging	23/4/2011	2:30	23/4/2011	2:33	3
	Filling	23/4/2011	2:33	23/4/2011	2:41	8
88	Digging	23/4/2011	2:41	23/4/2011	2:44	3
	Filling	23/4/2011	2:44	23/4/2011	3:53	69
89	Digging	23/4/2011	3:53	23/4/2011	3:56	3
	Filling	23/4/2011	3:56	23/4/2011	4:46	50
90	Digging	23/4/2011	4:46	23/4/2011	4:48	2
	Filling	23/4/2011	4:48	23/4/2011	4:56	8
91	Digging	23/4/2011	4:56	23/4/2011	4:58	2
	Filling	23/4/2011	4:58	23/4/2011	6:00	62
92	Digging	23/4/2011	6:00	23/4/2011	6:01	1
	Filling	23/4/2011	6:01	23/4/2011	6:31	30
93	Digging	23/4/2011	6:31	23/4/2011	6:37	6
	Filling	23/4/2011	6:37	23/4/2011	7:02	25
94	Digging	23/4/2011	7:02	23/4/2011	7:04	2
	Filling	23/4/2011	7:04	23/4/2011	7:26	22
95	Digging	23/4/2011	7:26	23/4/2011	7:29	3
	Filling	23/4/2011	7:29	23/4/2011	7:54	25
96	Digging	23/4/2011	7:54	23/4/2011	8:00	6
	Filling	23/4/2011	8:00	23/4/2011	8:34	34
97	Digging	23/4/2011	8:34	23/4/2011	8:38	4
	Filling	23/4/2011	8:38	23/4/2011	9:03	25
98	Digging	23/4/2011	9:03	23/4/2011	9:04	1
	Filling	23/4/2011	9:04	23/4/2011	9:29	25
99	Digging	23/4/2011	9:29	23/4/2011	9:30	1
	Filling	23/4/2011	9:30	23/4/2011	9:38	8
100	Digging	23/4/2011	9:38	23/4/2011	9:41	3
	Filling	23/4/2011	9:41	23/4/2011	10:18	37
101	Digging	23/4/2011	10:18	23/4/2011	10:20	2
	Filling	23/4/2011	10:20	23/4/2011	10:33	13

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
102	Digging	23/4/2011	10:33	23/4/2011	10:35	2
	Filling	23/4/2011	10:35	23/4/2011	10:43	8
103	Digging	23/4/2011	10:43	23/4/2011	10:47	4
	Filling	23/4/2011	10:47	23/4/2011	11:00	13
104	Digging	23/4/2011	11:00	23/4/2011	11:02	2
	Filling	23/4/2011	11:02	23/4/2011	11:28	26
105	Digging	23/4/2011	11:28	23/4/2011	11:31	3
	Filling	23/4/2011	11:31	23/4/2011	12:05	34
106	Digging	23/4/2011	12:05	23/4/2011	12:08	3
	Filling	23/4/2011	12:08	23/4/2011	12:20	12
107	Digging	23/4/2011	12:20	23/4/2011	12:22	2
	Filling	23/4/2011	12:22	23/4/2011	12:40	18
108	Digging	23/4/2011	12:40	23/4/2011	12:45	5
	Filling	23/4/2011	12:45	23/4/2011	13:34	49
109	Digging	23/4/2011	13:34	23/4/2011	13:41	7
	Filling	23/4/2011	13:41	23/4/2011	14:23	42
110	Digging	23/4/2011	14:23	23/4/2011	14:29	6
	Filling	23/4/2011	14:29	23/4/2011	15:28	59
111	Digging	23/4/2011	15:28	23/4/2011	15:33	5
	Filling	23/4/2011	15:33	23/4/2011	16:01	28
112	Digging	23/4/2011	16:01	23/4/2011	16:04	3
	Filling	23/4/2011	16:04	23/4/2011	16:43	39
113	Digging	23/4/2011	16:43	23/4/2011	16:48	5
	Filling	23/4/2011	16:48	23/4/2011	17:17	29
114	Digging	23/4/2011	17:17	23/4/2011	17:18	1
	Filling	23/4/2011	17:18	23/4/2011	17:50	32
115	Digging	23/4/2011	17:50	23/4/2011	17:57	7
	Filling	23/4/2011	17:57	23/4/2011	18:34	37
116	Digging	23/4/2011	18:34	23/4/2011	18:36	2
	Filling	23/4/2011	18:36	23/4/2011	19:18	42
117	Digging	23/4/2011	19:18	23/4/2011	19:19	1
	Filling	23/4/2011	19:19	23/4/2011	19:28	9
118	Digging	23/4/2011	19:28	23/4/2011	19:32	4
	Filling	23/4/2011	19:32	23/4/2011	20:22	50
119	Digging	23/4/2011	20:22	23/4/2011	20:25	3
	Filling	23/4/2011	20:25	23/4/2011	20:47	22
120	Digging	23/4/2011	20:47	23/4/2011	20:51	4
	Filling	23/4/2011	20:51	23/4/2011	21:18	27
121	Digging	23/4/2011	21:18	23/4/2011	21:20	2
	Filling	23/4/2011	21:20	23/4/2011	21:39	19
122	Digging	23/4/2011	21:39	23/4/2011	21:46	7
	Filling	23/4/2011	21:46	23/4/2011	22:33	47
123	Digging	23/4/2011	22:33	23/4/2011	22:36	3
	Filling	23/4/2011	22:36	23/4/2011	23:27	51
124	Digging	23/4/2011	23:27	23/4/2011	23:33	6

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
	Filling	23/4/2011	23:33	23/4/2011	23:44	11
125	Digging	23/4/2011	23:44	23/4/2011	23:47	3
	Filling	23/4/2011	23:47	23/4/2011	23:48	1
126	Digging	23/4/2011	23:48	23/4/2011	23:52	4
	Filling	23/4/2011	23:52	24/4/2011	0:04	12
127	Digging	24/4/2011	0:04	24/4/2011	0:05	1
	Filling	24/4/2011	0:05	24/4/2011	0:40	35
128	Digging	24/4/2011	0:40	24/4/2011	0:42	2
	Filling	24/4/2011	0:42	24/4/2011	0:43	1
129	Digging	24/4/2011	0:43	24/4/2011	0:44	1
	Filling	24/4/2011	0:44	24/4/2011	1:00	16
130	Digging	24/4/2011	1:00	24/4/2011	1:04	4
	Filling	24/4/2011	1:04	24/4/2011	1:21	17
131	Digging	24/4/2011	1:21	24/4/2011	1:24	3
	Filling	24/4/2011	1:24	24/4/2011	1:47	23
132	Digging	24/4/2011	1:47	24/4/2011	1:50	3
	Filling	24/4/2011	1:50	24/4/2011	2:34	44
133	Digging	24/4/2011	2:34	24/4/2011	2:36	2
	Filling	24/4/2011	2:36	24/4/2011	3:14	38
134	Digging	24/4/2011	3:14	24/4/2011	3:17	3
	Filling	24/4/2011	3:17	24/4/2011	3:25	8
135	Digging	24/4/2011	3:25	24/4/2011	3:28	3
	Filling	24/4/2011	3:28	24/4/2011	3:57	29
136	Digging	24/4/2011	3:57	24/4/2011	3:59	2
	Filling	24/4/2011	3:59	24/4/2011	4:28	29
137	Digging	24/4/2011	4:28	24/4/2011	4:30	2
	Filling	24/4/2011	4:30	24/4/2011	5:18	48
138	Digging	24/4/2011	5:18	24/4/2011	5:21	3
	Filling	24/4/2011	5:21	24/4/2011	5:23	2
139	Digging	24/4/2011	5:23	24/4/2011	5:24	1
	Filling	24/4/2011	5:24	24/4/2011	5:38	14
140	Digging	24/4/2011	5:38	24/4/2011	5:42	4
	Filling	24/4/2011	5:42	24/4/2011	6:25	43
141	Digging	24/4/2011	6:25	24/4/2011	6:28	3
	Filling	24/4/2011	6:28	24/4/2011	7:12	44
142	Digging	24/4/2011	7:12	24/4/2011	7:13	1
	Filling	24/4/2011	7:13	24/4/2011	7:18	5
143	Digging	24/4/2011	7:18	24/4/2011	7:20	2
	Filling	24/4/2011	7:20	24/4/2011	7:40	20
144	Digging	24/4/2011	7:40	24/4/2011	7:42	2
	Filling	24/4/2011	7:42	24/4/2011	8:18	36
145	Digging	24/4/2011	8:18	24/4/2011	8:22	4
	Filling	24/4/2011	8:22	24/4/2011	8:37	15
146	Digging	24/4/2011	8:37	24/4/2011	8:42	5
	Filling	24/4/2011	8:42	24/4/2011	9:31	49

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
147	Digging	24/4/2011	9:31	24/4/2011	9:33	2
	Filling	24/4/2011	9:33	24/4/2011	10:14	41
148	Digging	24/4/2011	10:14	24/4/2011	10:16	2
	Filling	24/4/2011	10:16	24/4/2011	10:53	37
149	Digging	24/4/2011	10:53	24/4/2011	10:54	1
	Filling	24/4/2011	10:54	24/4/2011	11:17	23
150	Digging	24/4/2011	11:17	24/4/2011	11:18	1
	Filling	24/4/2011	11:18	24/4/2011	11:20	2
151	Digging	24/4/2011	11:20	24/4/2011	11:21	1
	Filling	24/4/2011	11:21	24/4/2011	11:36	15
152	Digging	24/4/2011	11:36	24/4/2011	11:42	6
	Filling	24/4/2011	11:42	24/4/2011	12:20	38
153	Digging	24/4/2011	12:20	24/4/2011	12:21	1
	Filling	24/4/2011	12:21	24/4/2011	12:33	12
154	Digging	24/4/2011	12:33	24/4/2011	12:36	3
	Filling	24/4/2011	12:36	24/4/2011	13:01	25
155	Digging	24/4/2011	13:01	24/4/2011	13:07	6
	Filling	24/4/2011	13:07	24/4/2011	13:43	36
156	Digging	24/4/2011	13:43	24/4/2011	13:46	3
	Filling	24/4/2011	13:46	24/4/2011	13:58	12
157	Digging	24/4/2011	13:58	24/4/2011	14:03	5
	Filling	24/4/2011	14:03	24/4/2011	14:23	20
158	Digging	24/4/2011	14:23	24/4/2011	14:24	1
	Filling	24/4/2011	14:24	24/4/2011	14:44	20
159	Digging	24/4/2011	14:44	24/4/2011	14:48	4
	Filling	24/4/2011	14:48	24/4/2011	15:01	13
160	Digging	24/4/2011	15:01	24/4/2011	15:03	2
	Filling	24/4/2011	15:03	24/4/2011	15:22	19
161	Digging	24/4/2011	15:22	24/4/2011	15:25	3
	Filling	24/4/2011	15:25	24/4/2011	16:12	47
162	Digging	24/4/2011	16:12	24/4/2011	16:14	2
	Filling	24/4/2011	16:14	24/4/2011	16:21	7
163	Digging	24/4/2011	16:21	24/4/2011	16:22	1
	Filling	24/4/2011	16:22	24/4/2011	17:11	49
164	Digging	24/4/2011	17:11	24/4/2011	17:13	2
	Filling	24/4/2011	17:13	24/4/2011	17:30	17
165	Digging	24/4/2011	17:30	24/4/2011	17:33	3
	Filling	24/4/2011	17:33	24/4/2011	18:19	46
166	Digging	24/4/2011	18:19	24/4/2011	18:23	4
	Filling	24/4/2011	18:23	24/4/2011	18:51	28
167	Digging	24/4/2011	18:51	24/4/2011	18:54	3
	Filling	24/4/2011	18:54	24/4/2011	19:25	31
168	Digging	24/4/2011	19:25	24/4/2011	19:27	2
	Filling	24/4/2011	19:27	24/4/2011	20:00	33
169	Digging	24/4/2011	20:00	24/4/2011	20:02	2

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
	Filling	24/4/2011	20:02	24/4/2011	20:32	30
170	Digging	24/4/2011	20:32	24/4/2011	20:34	2
	Filling	24/4/2011	20:34	24/4/2011	21:08	34
171	Digging	24/4/2011	21:08	24/4/2011	21:09	1
	Filling	24/4/2011	21:09	24/4/2011	21:34	25
172	Digging	24/4/2011	21:34	24/4/2011	21:36	2
	Filling	24/4/2011	21:36	24/4/2011	21:40	4
173	Digging	24/4/2011	21:40	24/4/2011	21:41	1
	Filling	24/4/2011	21:41	24/4/2011	22:06	25
174	Digging	24/4/2011	22:06	24/4/2011	22:07	1
	Filling	24/4/2011	22:07	24/4/2011	22:26	19
175	Digging	24/4/2011	22:26	24/4/2011	22:32	6
	Filling	24/4/2011	22:32	24/4/2011	22:55	23
176	Digging	24/4/2011	22:55	24/4/2011	22:57	2
	Filling	24/4/2011	22:57	24/4/2011	23:18	21
177	Digging	24/4/2011	23:18	24/4/2011	23:20	2
	Filling	24/4/2011	23:20	24/4/2011	23:57	37
178	Digging	24/4/2011	23:57	25/4/2011	0:00	3
	Filling	25/4/2011	0:00	25/4/2011	0:22	22
179	Digging	25/4/2011	0:22	25/4/2011	0:23	1
	Filling	25/4/2011	0:23	25/4/2011	0:55	32
180	Digging	25/4/2011	0:55	25/4/2011	0:56	1
	Filling	25/4/2011	0:56	25/4/2011	1:02	6
181	Digging	25/4/2011	1:02	25/4/2011	1:04	2
	Filling	25/4/2011	1:04	25/4/2011	1:49	45
182	Digging	25/4/2011	1:49	25/4/2011	1:51	2
	Filling	25/4/2011	1:51	25/4/2011	2:20	29
183	Digging	25/4/2011	2:20	25/4/2011	2:21	1
	Filling	25/4/2011	2:21	25/4/2011	3:14	53
184	Digging	25/4/2011	3:14	25/4/2011	3:16	2
	Filling	25/4/2011	3:16	25/4/2011	4:03	47
185	Digging	25/4/2011	4:03	25/4/2011	4:05	2
	Filling	25/4/2011	4:05	25/4/2011	4:45	40
186	Digging	25/4/2011	4:45	25/4/2011	4:46	1
	Filling	25/4/2011	4:46	25/4/2011	4:55	9
187	Digging	25/4/2011	4:55	25/4/2011	4:56	1
	Filling	25/4/2011	4:56	25/4/2011	5:31	35
188	Digging	25/4/2011	5:31	25/4/2011	5:37	6
	Filling	25/4/2011	5:37	25/4/2011	5:51	14
189	Digging	25/4/2011	5:51	25/4/2011	5:53	2
	Filling	25/4/2011	5:53	25/4/2011	6:32	39
190	Digging	25/4/2011	6:32	25/4/2011	6:34	2
	Filling	25/4/2011	6:34	25/4/2011	6:57	23
191	Digging	25/4/2011	6:57	25/4/2011	6:59	2
	Filling	25/4/2011	6:59	25/4/2011	7:10	11

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
192	Digging	25/4/2011	7:10	25/4/2011	7:11	1
	Filling	25/4/2011	7:11	25/4/2011	8:03	52
193	Digging	25/4/2011	8:03	25/4/2011	8:05	2
	Filling	25/4/2011	8:05	25/4/2011	8:29	24
194	Digging	25/4/2011	8:29	25/4/2011	8:31	2
	Filling	25/4/2011	8:31	25/4/2011	8:41	10
195	Digging	25/4/2011	8:41	25/4/2011	8:43	2
	Filling	25/4/2011	8:43	25/4/2011	9:14	31
196	Digging	25/4/2011	9:14	25/4/2011	9:16	2
	Filling	25/4/2011	9:16	25/4/2011	9:59	43
197	Digging	25/4/2011	9:59	25/4/2011	10:01	2
	Filling	25/4/2011	10:01	25/4/2011	10:11	10
198	Digging	25/4/2011	10:11	25/4/2011	10:12	1
	Filling	25/4/2011	10:12	25/4/2011	10:49	37
199	Digging	25/4/2011	10:49	25/4/2011	10:50	1
	Filling	25/4/2011	10:50	25/4/2011	10:55	5
200	Digging	25/4/2011	10:55	25/4/2011	10:56	1
	Filling	25/4/2011	10:56	25/4/2011	11:34	38
201	Digging	25/4/2011	11:34	25/4/2011	11:36	2
	Filling	25/4/2011	11:36	25/4/2011	11:49	13
202	Digging	25/4/2011	11:49	25/4/2011	11:50	1
	Filling	25/4/2011	11:50	25/4/2011	12:12	22
203	Digging	25/4/2011	12:12	25/4/2011	12:13	1
	Filling	25/4/2011	12:13	25/4/2011	12:14	1
204	Digging	25/4/2011	12:14	25/4/2011	12:16	2
	Filling	25/4/2011	12:16	25/4/2011	12:56	40
205	Digging	25/4/2011	12:56	25/4/2011	12:57	1
	Filling	25/4/2011	12:57	25/4/2011	13:07	10
206	Digging	25/4/2011	13:07	25/4/2011	13:09	2
	Filling	25/4/2011	13:09	25/4/2011	13:11	2
207	Digging	25/4/2011	13:11	25/4/2011	13:14	3
	Filling	25/4/2011	13:14	25/4/2011	13:35	21

Table B-8 Time-sequence of each digging and filling phase of Run 79

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	7/3/2011	15:33	12/3/2011	9:14	6821
	Filling	12/3/2011	9:14	13/3/2011	0:01	887
2	Digging	13/3/2011	0:01	14/3/2011	20:25	2664
	Filling	14/3/2011	20:25	15/3/2011	15:23	1138
3	Digging	15/3/2011	15:23	17/3/2011	23:02	3339
	Filling	17/3/2011	23:02	18/3/2011	16:39	1057
4	Digging	18/3/2011	16:39	20/3/2011	10:12	2493
	Filling	20/3/2011	10:12	21/3/2011	5:46	1174
5	Digging	21/3/2011	5:46	21/3/2011	15:06*	560
	Filling	21/3/2011	15:06	22/3/2011	1:42	636

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
6	Digging	22/3/2011	1:42	24/3/2011	18:21	3879
	Filling	24/3/2011	18:21	25/3/2011	11:22	1021
7	Digging	25/3/2011	11:22	26/3/2011	10:54	1412
	Filling	26/3/2011	10:54	27/3/2011	1:44	890
8	Digging	27/3/2011	1:44	29/3/2011	3:20	2976
	Filling	29/3/2011	3:20	29/3/2011	21:58	1118
9	Digging	29/3/2011	21:58	31/3/2011	0:05	1567
	Filling	31/3/2011	0:05	31/3/2011	17:00	1015
10	Digging	31/3/2011	17:00	3/4/2011	4:55	3595
	Filling	3/4/2011	4:55	4/4/2011	2:55	1320
11	Digging	4/4/2011	2:55	5/4/2011	3:43	1488
	Filling	5/4/2011	3:43	5/4/2011	21:10	1047
12**	Digging	5/4/2011	21:10	6/4/2011	12:57	947
	Filling	6/4/2011	12:57	9/4/2011	16:31	4534
13	Digging	9/4/2011	16:31	9/4/2011	22:20	349
	Filling	9/4/2011	22:20	12/4/2011	11:26	3666
14	Digging	12/4/2011	11:26	12/4/2011	21:46	620
Note:* Pump stops accidentally for 4.5hours from 2011-3-21, 10:30 to 15:00.						
** Ridge removal test was conducted at 12 th cycle.						

Table B-9 Time-sequence of each digging and filling phase of Run 81

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	28/2/2011	14:37	28/2/2011	17:06	149
	Filling	28/2/2011	17:06	28/2/2011	17:41	35
2	Digging	28/2/2011	17:41	28/2/2011	18:50	69
	Filling	28/2/2011	18:50	28/2/2011	19:30	40
3	Digging	28/2/2011	19:30	28/2/2011	20:11	41
	Filling	28/2/2011	20:11	28/2/2011	21:05	54
4	Digging	28/2/2011	21:05	28/2/2011	22:11	66
	Filling	28/2/2011	22:11	28/2/2011	23:35	84
5	Digging	28/2/2011	23:35	1/3/2011	0:31	56
	Filling	1/3/2011	0:31	1/3/2011	1:40	69
6	Digging	1/3/2011	1:40	1/3/2011	1:51	11
	Filling	1/3/2011	1:51	1/3/2011	2:43	52
7	Digging	1/3/2011	2:43	1/3/2011	3:27	44
	Filling	1/3/2011	3:27	1/3/2011	4:16	49
8	Digging	1/3/2011	4:16	1/3/2011	4:24	8
	Filling	1/3/2011	4:24	1/3/2011	4:59	35
9	Digging	1/3/2011	4:59	1/3/2011	5:40	41
	Filling	1/3/2011	5:40	1/3/2011	7:09	89
10	Digging	1/3/2011	7:09	1/3/2011	7:28	19
	Filling	1/3/2011	7:28	1/3/2011	8:38	70
11	Digging	1/3/2011	8:38	1/3/2011	8:44	6
	Filling	1/3/2011	8:44	1/3/2011	9:42	58
12	Digging	1/3/2011	9:42	1/3/2011	10:22	40
	Filling	1/3/2011	10:22	1/3/2011	10:49	27

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
13	Digging	1/3/2011	10:49	1/3/2011	11:04	15
	Filling	1/3/2011	11:04	1/3/2011	12:38	94
14	Digging	1/3/2011	12:38	1/3/2011	13:03	25
	Filling	1/3/2011	13:03	1/3/2011	13:56	53
15	Digging	1/3/2011	13:56	1/3/2011	14:15	19
	Filling	1/3/2011	14:15	1/3/2011	15:57	102
16	Digging	1/3/2011	15:57	1/3/2011	16:13	16
	Filling	1/3/2011	16:13	1/3/2011	17:17	64
17	Digging	1/3/2011	17:17	1/3/2011	18:00	43
	Filling	1/3/2011	18:00	1/3/2011	19:32	92
18	Digging	1/3/2011	19:32	1/3/2011	19:53	21
	Filling	1/3/2011	19:53	1/3/2011	20:50	57
19	Digging	1/3/2011	20:50	1/3/2011	21:24	34
	Filling	1/3/2011	21:24	1/3/2011	23:10	106
20	Digging	1/3/2011	23:10	1/3/2011	23:42	32
	Filling	1/3/2011	23:42	2/3/2011	0:46	64
21	Digging	2/3/2011	0:46	2/3/2011	1:04	18
	Filling	2/3/2011	1:04	2/3/2011	2:39	95
22	Digging	2/3/2011	2:39	2/3/2011	3:27	48
	Filling	2/3/2011	3:27	2/3/2011	4:47	80
23	Digging	2/3/2011	4:47	2/3/2011	5:09	22
	Filling	2/3/2011	5:09	2/3/2011	7:05	116
24	Digging	2/3/2011	7:05	2/3/2011	7:36	31
	Filling	2/3/2011	7:36	2/3/2011	9:32	116
25	Digging	2/3/2011	9:32	2/3/2011	9:42	10
	Filling	2/3/2011	9:42	2/3/2011	10:53	71
26	Digging	2/3/2011	10:53	2/3/2011	11:19	26
	Filling	2/3/2011	11:19	2/3/2011	12:58	99
27	Digging	2/3/2011	12:58	2/3/2011	13:14	16
	Filling	2/3/2011	13:14	2/3/2011	14:44	90
28	Digging	2/3/2011	14:44	2/3/2011	15:20	36
	Filling	2/3/2011	15:20	2/3/2011	16:46	86
29	Digging	2/3/2011	16:46	2/3/2011	17:06	20
	Filling	2/3/2011	17:06	2/3/2011	19:15	129
30	Digging	2/3/2011	19:15	2/3/2011	19:51	36
	Filling	2/3/2011	19:51	2/3/2011	21:48	117
31	Digging	2/3/2011	21:48	2/3/2011	22:22	34
	Filling	2/3/2011	22:22	2/3/2011	23:57	95
32	Digging	2/3/2011	23:57	3/3/2011	0:19	22
	Filling	3/3/2011	0:19	3/3/2011	1:23	64
33	Digging	3/3/2011	1:23	3/3/2011	1:52	29
	Filling	3/3/2011	1:52	3/3/2011	4:17	145
34	Digging	3/3/2011	4:17	3/3/2011	4:25	8
	Filling	3/3/2011	4:25	3/3/2011	5:37	72
35	Digging	3/3/2011	5:37	3/3/2011	5:58	21

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
	Filling	3/3/2011	5:58	3/3/2011	7:34	96
36	Digging	3/3/2011	7:34	3/3/2011	8:11	37
	Filling	3/3/2011	8:11	3/3/2011	9:33	82
37	Digging	3/3/2011	9:33	3/3/2011	9:52	19
	Filling	3/3/2011	9:52	3/3/2011	11:39	107
38	Digging	3/3/2011	11:39	3/3/2011	12:19	40
	Filling	3/3/2011	12:19	3/3/2011	13:57	98
39	Digging	3/3/2011	13:57	3/3/2011	14:23	26
	Filling	3/3/2011	14:23	3/3/2011	15:45	82
40	Digging	3/3/2011	15:45	3/3/2011	16:15	30
	Filling	3/3/2011	16:15	3/3/2011	18:46	151
41	Digging	3/3/2011	18:46	3/3/2011	19:25	39
	Filling	3/3/2011	19:25	3/3/2011	21:12	107
42	Digging	3/3/2011	21:12	3/3/2011	21:56	44
	Filling	3/3/2011	21:56	4/3/2011	0:13	137
43	Digging	4/3/2011	0:13	4/3/2011	0:38	25
	Filling	4/3/2011	0:38	4/3/2011	3:20	162
44	Digging	4/3/2011	3:20	4/3/2011	3:40	20
	Filling	4/3/2011	3:40	4/3/2011	5:38	118
45	Digging	4/3/2011	5:38	4/3/2011	6:15	37
	Filling	4/3/2011	6:15	4/3/2011	8:40	145
46	Digging	4/3/2011	8:40	4/3/2011	9:13	33
	Filling	4/3/2011	9:13	4/3/2011	11:59	166
47	Digging	4/3/2011	11:59	4/3/2011	12:25	26
	Filling	4/3/2011	12:25	4/3/2011	14:19	114
48	Digging	4/3/2011	14:19	4/3/2011	14:29	10
	Filling	4/3/2011	14:29	4/3/2011	15:37	68
49	Digging	4/3/2011	15:37*	4/3/2011	15:51	14
	Filling	4/3/2011	15:51	4/3/2011	18:22	151
50	Digging	4/3/2011	18:22	4/3/2011	18:41	19
	Filling	4/3/2011	18:41	5/3/2011	1:26	405
51	Digging	5/3/2011	1:26	5/3/2011	1:44	18
	Filling	5/3/2011	1:44	5/3/2011	7:44	360
52	Digging	5/3/2011	7:44	5/3/2011	8:02	18
	Filling	5/3/2011	8:02	5/3/2011	13:09	307
53	Digging	5/3/2011	13:09	5/3/2011	13:25	16
	Filling	5/3/2011	13:25	5/3/2011	17:50	265
54	Digging	5/3/2011	17:50	5/3/2011	18:08	18
	Filling	5/3/2011	18:08	6/3/2011	1:21	433
55	Digging	6/3/2011	1:21	6/3/2011	1:28	7
	Filling	6/3/2011	1:28	6/3/2011	6:16	288
56	Digging	6/3/2011	6:16	6/3/2011	6:32	16
	Filling	6/3/2011	6:32	6/3/2011	14:59	507
57	Digging	6/3/2011	14:59	6/3/2011	15:06	7
	Filling	6/3/2011	15:06	6/3/2011	19:13	247

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
58	Digging	6/3/2011	19:13	6/3/2011	19:31	18
	Filling	6/3/2011	19:31	7/3/2011	2:40	429
59	Digging	7/3/2011	2:40	7/3/2011	2:49	9
	Filling	7/3/2011	2:49	7/3/2011	9:29	400
60	Digging	7/3/2011	9:29	7/3/2011	9:46	17
Note: * Ridge removal test was conducted at 49 th cycle.						

Table B-10 Time-sequence of each digging and filling phase of Run 82

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	15/4/2011	14:00	15/4/2011	14:10	10
	Filling	15/4/2011	14:10	15/4/2011	14:11	1
2	Digging	15/4/2011	14:11	15/4/2011	14:12	1
	Filling	15/4/2011	14:12	15/4/2011	14:13	1
3	Digging	15/4/2011	14:13	15/4/2011	14:15	2
	Filling	15/4/2011	14:15	15/4/2011	14:17	2
4	Digging	15/4/2011	14:17	15/4/2011	14:19	2
	Filling	15/4/2011	14:19	15/4/2011	14:24	5
5	Digging	15/4/2011	14:24	15/4/2011	14:27	3
	Filling	15/4/2011	14:27	15/4/2011	14:29	2
6	Digging	15/4/2011	14:29	15/4/2011	14:32	3
	Filling	15/4/2011	14:32	15/4/2011	14:36	4
7	Digging	15/4/2011	14:36	15/4/2011	14:40	4
	Filling	15/4/2011	14:40	15/4/2011	14:52	12
8	Digging	15/4/2011	14:52	15/4/2011	14:55	3
	Filling	15/4/2011	14:55	15/4/2011	15:03	8
9	Digging	15/4/2011	15:03	15/4/2011	15:06	3
	Filling	15/4/2011	15:06	15/4/2011	15:45	39
10	Digging	15/4/2011	15:45	15/4/2011	15:50	5
	Filling	15/4/2011	15:50	15/4/2011	16:09	19
11	Digging	15/4/2011	16:09	15/4/2011	16:12	3
	Filling	15/4/2011	16:12	15/4/2011	16:28	16
12	Digging	15/4/2011	16:28	15/4/2011	16:30	2
	Filling	15/4/2011	16:30	15/4/2011	16:53	23
13	Digging	15/4/2011	16:53	15/4/2011	16:56	3
	Filling	15/4/2011	16:56	15/4/2011	17:29	33
14	Digging	15/4/2011	17:29	15/4/2011	17:32	3
	Filling	15/4/2011	17:32	15/4/2011	17:59	27
15	Digging	15/4/2011	17:59	15/4/2011	18:03	4
	Filling	15/4/2011	18:03	15/4/2011	18:56	53
16	Digging	15/4/2011	18:56	15/4/2011	18:58	2
	Filling	15/4/2011	18:58	15/4/2011	20:12	74
17	Digging	15/4/2011	20:12	15/4/2011	20:13	1
	Filling	15/4/2011	20:13	15/4/2011	20:25	12
18	Digging	15/4/2011	20:25	15/4/2011	20:28	3
	Filling	15/4/2011	20:28	15/4/2011	22:48	140

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
19	Digging	15/4/2011	22:48	15/4/2011	22:51	3
	Filling	15/4/2011	22:51	16/4/2011	0:18	87
20	Digging	16/4/2011	0:18	16/4/2011	0:20	2
	Filling	16/4/2011	0:20	16/4/2011	1:16	56

Table B-11 Time-sequence of each digging and filling phase of Run 121

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	18/7/2011	15:20	21/7/2011	14:36	4276
	Filling	21/7/2011	14:36	21/7/2011	22:56	500
2	Digging	21/7/2011	22:56	22/7/2011	13:57	901
	Filling	22/7/2011	13:57	22/7/2011	23:39	582
3	Digging	22/7/2011	23:39	23/7/2011	6:39	420
	Filling	23/7/2011	6:39	23/7/2011	16:52	613
4	Digging	23/7/2011	16:52	24/7/2011	0:09	437
	Filling	24/7/2011	0:09	24/7/2011	9:15	546
5	Digging	24/7/2011	9:15	24/7/2011	17:09	474
	Filling	24/7/2011	17:09	25/7/2011	2:41	572
6	Digging	25/7/2011	2:41	25/7/2011	11:43	542
	Filling	25/7/2011	11:43	25/7/2011	22:29	646
7	Digging	25/7/2011	22:29	26/7/2011	4:58	389
	Filling	26/7/2011	4:58	26/7/2011	13:12	494
8	Digging	26/7/2011	13:12	26/7/2011	22:19	547
	Filling	26/7/2011	22:19	27/7/2011	8:57	638
9	Digging	27/7/2011	8:57	28/7/2011	0:01	904
	Filling	28/7/2011	0:01	28/7/2011	12:11	730
10	Digging	28/7/2011	12:11	29/7/2011	0:43	752
	Filling	29/7/2011	0:43	29/7/2011	9:42	539
11	Digging	29/7/2011	9:42	29/7/2011	19:41	599
	Filling	29/7/2011	19:41	30/7/2011	6:13	632
12	Digging	30/7/2011	6:13	30/7/2011	11:00	287

Table B-12 Time-sequence of each digging and filling phase of Run 122

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	1/10/2011	13:30	3/10/2011	21:47	3377
	Filling	3/10/2011	21:47	4/10/2011	4:09	382
2	Digging	4/10/2011	4:09	5/10/2011	18:13	2284
	Filling	5/10/2011	18:13	6/10/2011	3:03	530
3	Digging	6/10/2011	3:03	7/10/2011	10:51	1908
	Filling	7/10/2011	10:51	7/10/2011	19:14	503
4	Digging	7/10/2011	19:14	8/10/2011	0:13	299
	Filling	8/10/2011	0:13	8/10/2011	6:12	359
5	Digging	8/10/2011	6:12	8/10/2011	21:27	915
	Filling	8/10/2011	21:27	9/10/2011	7:00	573
6	Digging	9/10/2011	7:00	10/10/2011	5:18	1338
	Filling	10/10/2011	5:18	10/10/2011	14:57	579
7	Digging	10/10/2011	14:57	11/10/2011	10:32	1175

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
	Filling	11/10/2011	10:32	11/10/2011	20:37	605
8	Digging	11/10/2011	20:37	12/10/2011	9:52	795
	Filling	12/10/2011	9:52	12/10/2011	17:05	433
9	Digging	12/10/2011	17:05	13/10/2011	12:47	1182
	Filling	13/10/2011	12:47	13/10/2011	22:33	586
10	Digging	13/10/2011	22:33	15/10/2011	10:17	2144
	Filling	15/10/2011	10:17	15/10/2011	21:20	663
11	Digging	15/10/2011	21:20	17/10/2011	1:00	1660
	Filling	17/10/2011	1:00	17/10/2011	10:16	556
12	Digging	17/10/2011	10:16	17/10/2011	23:01	765
	Filling	17/10/2011	23:01	18/10/2011	9:03	602

Table B-13 Time-sequence of each digging and filling phase of Run 164

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1*	Digging	-	-	18/11/2011	0:10	-
	Filling	18/11/2011	0:10	18/11/2011	14:20	850
2	Digging	18/11/2011	14:20	21/11/2011	10:16	4076
	Filling	21/11/2011	10:16	21/11/2011	23:50**	814
3	Digging	21/11/2011	23:50	22/11/2011	20:10	1220
	Filling	22/11/2011	20:10	23/11/2011	4:40	510
4	Digging	23/11/2011	4:40	25-11-2011	10:40***	3240
Note:* Data lost for the first digging phase.						
** Estimated. Because webcam software stopped accidentally at 20:30.						
***Estimated. Because pump stopped accidentally at 10:25.						

Table B-14 Time-sequence of each digging and filling phase of Run 166

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	14/12/2011	15:26	17/12/2011	6:40	3794
	Filling	17/12/2011	6:40	17/12/2011	10:42	242
2	Digging	17/12/2011	10:42	17/12/2011	18:28	466
	Filling	17/12/2011	18:28	17/12/2011	23:16	288
3	Digging	17/12/2011	23:16	18/12/2011	17:12	1076
	Filling	18/12/2011	17:12	18/12/2011	21:18	246
4	Digging	18/12/2011	21:18	19/12/2011	9:32	734
	Filling	19/12/2011	9:32	19/12/2011	14:02	270
5	Digging	19/12/2011	14:02	20/12/2011	9:52	1190
	Filling	20/12/2011	9:52	20/12/2011	14:42	290
6	Digging	20/12/2011	14:42	21/12/2011	0:25	583
	Filling	21/12/2011	0:25	21/12/2011	5:28	303

Table B-15 Time-sequence of each digging and filling phase of Run 167

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	21/12/2011	16:36	24/12/2011	22:22	4666
	Filling	24/12/2011	22:22	25/12/2011	4:21	359
2	Digging	25/12/2011	4:21	27/12/2011	13:34	3433

Table B-16 Time-sequence of each digging and filling phase of Run 168

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
2*	Digging	-	-	6/1/2012	10:28	-
	Filling	6/1/2012	10:28	6/1/2012	18:50	502
3	Digging	6/1/2012	18:50	8/1/2012	23:13	3143
	Filling	8/1/2012	23:13	9/1/2012	7:49	516
4	Digging	9/1/2012	7:49	10/1/2012	16:01	1932
Note: *Data lost for the first cycle.						

Table B-17 Time-sequence of each digging and filling phase of Run 201

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	12/4/2012	17:27	13/4/2012	11:47*	<1100
	Filling	13/4/2012	11:47	13/4/2012	13:03	>76
2	Digging	13/4/2012	13:03	13/4/2012	15:52*	169
	Filling	13/4/2012	15:52	14/4/2012	6:22	870
3	Digging	14/4/2012	6:22	14/4/2012	8:21	119
	Filling	14/4/2012	8:21	14/4/2012	20:33	732
4	Digging	14/4/2012	20:33	14/4/2012	22:00	87
	Filling	14/4/2012	22:00	15/4/2012	17:24	1164
5	Digging	15/4/2012	17:24	15/4/2012	18:15	51
	Filling	15/4/2012	18:15	16/4/2012	11:01	1006
Note: * Estimated. Because the data lost. Digging ended earlier than this time.						

Table B-18 Time-sequence of each digging and filling phase of Run 202

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	17/4/2012	10:21	19/4/2012	3:57	2496
	Filling	19/4/2012	3:57	20/4/2012	16:27	2190
2	Digging	20/4/2012	16:27	22/4/2012	8:08	2381

Table B-19 Time-sequence of each digging and filling phase of Run 203

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	23/4/2012	14:20	2012/4/28	13:42	7162
	Filling	2012/4/28	13:42	2012/5/7	3:02	12320
2	Digging	2012/5/7	3:02	2012/5/11	13:10	6368

Table B-20 Time-sequence of each digging and filling phase of Run 206

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2012/6/19	15:27	2012/6/20	1:23	596
	Filling	2012/6/20	1:23	2012/6/20	20:09	1126
2	Digging	2012/6/20	20:09	2012/6/21	3:07	418
	Filling	2012/6/21	3:07	2012/6/22	1:29	1342
3	Digging	2012/6/22	1:29	2012/6/22	5:15	226
	Filling	2012/6/22	5:15	2012/6/23	2:52	1297
4	Digging	2012/6/23	2:52	2012/6/23	6:24	212
	Filling	2012/6/23	6:24	2012/6/24	7:02	1478
5	Digging	2012/6/24	7:02	2012/6/24	8:53	111
	Filling	2012/6/24	8:53	2012/6/25	11:53	1620

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
6	Digging	2012/6/25	11:53	2012/6/25	15:54	241
	Filling	2012/6/25	15:54	2012/6/26	16:05	1451
7	Digging	2012/6/26	16:05	2012/6/26	18:18	133
	Filling	2012/6/26	18:18	2012/6/28	5:32	2114
8	Digging	2012/6/28	5:32	2012/6/28	8:53	201

Table B-21 Time-sequence of each digging and filling phase of Run 207

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2012/7/4	15:55	2012/7/6	14:51	2816
	Filling	2012/7/6	14:51	2012/7/8	1:09	2058
2	Digging	2012/7/8	1:09	2012/7/12	7:03	6114
	Filling	2012/7/12	7:03	2012/7/14	3:28	2665
3	Digging	2012/7/14	3:28	2012/7/15	4:57	1529

Table B-22 Time-sequence of each digging and filling phase of Run 209

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2012/7/23	15:00	2012/7/23	15:30	30
	Filling	2012/7/23	15:30	2012/7/23	17:22	112
2	Digging	2012/7/23	17:22	2012/7/23	17:34	12
	Filling	2012/7/23	17:34	2012/7/23	19:30	116
3	Digging	2012/7/23	19:30	2012/7/23	19:42	12
	Filling	2012/7/23	19:42	2012/7/23	21:55	133
4	Digging	2012/7/23	21:55	2012/7/23	22:11	16
	Filling	2012/7/23	22:11	2012/7/24	1:30	199
5	Digging	2012/7/24	1:30	2012/7/24	1:38	8
	Filling	2012/7/24	1:38	2012/7/24	4:14	156
6	Digging	2012/7/24	4:14	2012/7/24	4:26	12
	Filling	2012/7/24	4:26	2012/7/24	8:13	227
7	Digging	2012/7/24	8:13	2012/7/24	8:26	13
	Filling	2012/7/24	8:26	2012/7/24	11:57	211

Table B-23 Time-sequence of each digging and filling phase of Run 211

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (mm:ss)
1	Digging	2012/8/6	17:10:00	2012/8/6	17:10:50	00:50
	Filling	2012/8/6	17:10:50	2012/8/6	17:13:46	02:56
2	Digging	2012/8/6	17:13:46	2012/8/6	17:14:05	00:19
	Filling	2012/8/6	17:14:05	2012/8/6	17:17:11	03:06
3	Digging	2012/8/6	17:17:11	2012/8/6	17:17:31	00:20
	Filling	2012/8/6	17:17:31	2012/8/6	17:22:30	04:59
4	Digging	2012/8/6	17:22:30	2012/8/6	17:22:49	00:19
	Filling	2012/8/6	17:22:49	2012/8/6	17:26:11	03:22
5	Digging	2012/8/6	17:26:11	2012/8/6	17:26:32	00:21
	Filling	2012/8/6	17:26:32	2012/8/6	17:33:14	06:42
6	Digging	2012/8/6	17:33:14	2012/8/6	17:33:32	00:18
	Filling	2012/8/6	17:33:32	2012/8/6	17:39:26	05:54

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (mm:ss)
7	Digging	2012/8/6	17:39:26	2012/8/6	17:39:50	00:24
	Filling	2012/8/6	17:39:50	2012/8/6	17:47:42	07:52

Table B-24 Time-sequence of each digging and filling phase of Run 212

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2012/8/15	13:34	2012/8/18	6:41	3907
	Filling	2012/8/18	6:41	2012/8/20	1:14	2553
2	Digging	2012/8/20	1:14	2012/8/20	15:04	830

Table B-25 Time-sequence of each digging and filling phase of Run 221

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2012/8/22	14:06	2012/8/22	15:06	60
	Filling	2012/8/22	15:06	2012/8/22	21:14	368
2	Digging	2012/8/22	21:14	2012/8/22	22:04	50
	Filling	2012/8/22	22:04	2012/8/23	7:27	563
3	Digging	2012/8/23	7:27	2012/8/23	8:07	40
	Filling	2012/8/23	8:07	2012/8/23	17:48	581
4	Digging	2012/8/23	17:48	2012/8/23	18:34	46
	Filling	2012/8/23	18:34	2012/8/24	4:55	621
5	Digging	2012/8/24	4:55	2012/8/24	5:44	49
	Filling	2012/8/24	5:44	2012/8/24	15:58	614
6	Digging	2012/8/24	15:58	2012/8/24	16:48	50
	Filling	2012/8/24	16:48	2012/8/25	6:38	830

Table B-26 Time-sequence of each digging and filling phase of Run 222

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2012/11/29	11:45	2012/12/9	8:15	14190
	Filling	2012/12/9	8:15	2012/12/11	17:22	3427
2	Digging	2012/12/11	17:22	2012/12/13	7:03	2261

Table B-27 Time-sequence of each digging and filling phase of Run 223

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2012/11/7	14:36:00	2012/11/7	14:51:00	15
	Filling	2012/11/7	14:51:00	2012/11/7	15:51:00	60
2	Digging	2012/11/7	15:51:00	2012/11/7	15:55:00	4
	Filling	2012/11/7	15:55:00	2012/11/7	16:51:00	56
3	Digging	2012/11/7	16:51:00	2012/11/7	16:56:00	5
	Filling	2012/11/7	16:56:00	2012/11/7	18:12:00	76
4	Digging	2012/11/7	18:12:00	2012/11/7	18:18:00	6
	Filling	2012/11/7	18:18:00	2012/11/7	19:22:00	64
5	Digging	2012/11/7	19:22:00	2012/11/7	19:27:00	5
	Filling	2012/11/7	19:27:00	2012/11/7	20:47:00	80
6	Digging	2012/11/7	20:47:00	2012/11/7	20:55:00	8
	Filling	2012/11/7	20:55:00	2012/11/7	22:32:00	97
7	Digging	2012/11/7	22:32:00	2012/11/7	22:38:00	6

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
	Filling	2012/11/7	22:38:00	2012/11/8	0:18:00	100
8	Digging	2012/11/8	00:18:00	2012/11/8	0:20:00	2
	Filling	2012/11/8	00:20:00	2012/11/8	1:32:00	72

Table B-28 Time-sequence of each digging and filling phase of Run 230

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2012/9/24	15:45	2012/9/24	15:55	10
	Filling	2012/9/24	15:55	2012/9/24	16:32	37
2	Digging	2012/9/24	16:32	2012/9/24	16:38	6
	Filling	2012/9/24	16:38	2012/9/24	17:43	65
3	Digging	2012/9/24	17:43	2012/9/24	17:51	8
	Filling	2012/9/24	17:51	2012/9/24	19:24	93
4	Digging	2012/9/24	19:24	2012/9/24	19:33	9
	Filling	2012/9/24	19:33	2012/9/24	21:13	100
5	Digging	2012/9/24	21:13	2012/9/24	21:24	11
	Filling	2012/9/24	21:24	2012/9/24	23:07	103
6	Digging	2012/9/24	23:07	2012/9/24	23:17	10
	Filling	2012/9/24	23:17	2012/9/25	1:20	123
7	Digging	2012/9/25	1:20	2012/9/25	1:31	11
	Filling	2012/9/25	1:31	2012/9/25	3:51	140
8	Digging	2012/9/25	3:51	2012/9/25	3:57	6

Table B-29 Time-sequence of each digging and filling phase of Run 231

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2012/9/25	15:35:00	2012/9/25	15:39:00	4
	Filling	2012/9/25	15:39:00	2012/9/25	15:51:20	12
2	Digging	2012/9/25	15:51:20	2012/9/25	15:53:00	1
	Filling	2012/9/25	15:53:00	2012/9/25	16:09:16	16
3	Digging	2012/9/25	16:09:16	2012/9/25	16:11:16	2
	Filling	2012/9/25	16:11:16	2012/9/25	16:34:56	23
4	Digging	2012/9/25	16:34:56	2012/9/25	16:36:38	1
	Filling	2012/9/25	16:36:38	2012/9/25	17:01:32	24
5	Digging	2012/9/25	17:01:32	2012/9/25	17:03:50	2
	Filling	2012/9/25	17:03:50	2012/9/25	17:34:45	30
6	Digging	2012/9/25	17:34:45	2012/9/25	17:37:20	2
	Filling	2012/9/25	17:37:20	2012/9/25	18:18:56	41
7	Digging	2012/9/25	18:18:56	2012/9/25	18:20:45	1
	Filling	2012/9/25	18:20:45	2012/9/25	19:00:00	39

Table B-30 Time-sequence of each digging and filling phase of Run 232

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (mm:ss)
1	Digging	2012/9/26	14:50:00	2012/9/26	14:51:47	1:47
	Filling	2012/9/26	14:51:47	2012/9/26	14:59:00	7:13
2	Digging	2012/9/26	14:59:00	2012/9/26	15:00:00	1:00
	Filling	2012/9/26	15:00:00	2012/9/26	15:13:19	13:19
3	Digging	2012/9/26	15:13:19	2012/9/26	15:13:58	0:39

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (mm:ss)
	Filling	2012/9/26	15:13:58	2012/9/26	15:30:47	16:49
4	Digging	2012/9/26	15:30:47	2012/9/26	15:32:00	1:13
	Filling	2012/9/26	15:32:00	2012/9/26	15:52:32	20:32
5	Digging	2012/9/26	15:52:32	2012/9/26	15:53:42	1:10
	Filling	2012/9/26	15:53:42	2012/9/26	16:16:06	22:24
6	Digging	2012/9/26	16:16:06	2012/9/26	16:17:06	1:00
	Filling	2012/9/26	16:17:06	2012/9/26	16:35:21	18:15
7	Digging	2012/9/26	16:35:21	2012/9/26	16:36:23	1:02
	Filling	2012/9/26	16:36:23	2012/9/26	16:53:52	17:29

Table B-31 Time-sequence of each digging and filling phase of Run 234

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2012/10/19	13:45:30	2012/10/19	13:49:55	4
	Filling	2012/10/19	13:49:55	2012/10/19	14:02:00	12
2	Digging	2012/10/19	14:02:00	2012/10/19	14:04:04	2
	Filling	2012/10/19	14:04:04	2012/10/19	14:24:16	20
3	Digging	2012/10/19	14:24:16	2012/10/19	14:27:00	2
	Filling	2012/10/19	14:27:00	2012/10/19	14:47:20	20
4	Digging	2012/10/19	14:47:20	2012/10/19	14:50:45	3
	Filling	2012/10/19	14:50:45	2012/10/19	15:15:00	24
5	Digging	2012/10/19	15:15:00	2012/10/19	15:18:45	3
	Filling	2012/10/19	15:18:45	2012/10/19	15:51:30	32
6	Digging	2012/10/19	15:51:30	2012/10/19	15:54:06	2
	Filling	2012/10/19	15:54:06	2012/10/19	16:26:00	31
7	Digging	2012/10/19	16:26:00	2012/10/19	16:29:58	3
	Filling	2012/10/19	16:29:58	2012/10/19	17:10:55	40

Table B-32 Time-sequence of each digging and filling phase of Run 235

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (mm:ss)
1	Digging	2012/10/16	16:03:00	2012/10/16	16:04:03	1:03
	Filling	2012/10/16	16:04:03	2012/10/16	16:11:03	7:00
2	Digging	2012/10/16	16:11:03	2012/10/16	16:12:06	1:03
	Filling	2012/10/16	16:12:06	2012/10/16	16:25:33	13:27
3	Digging	2012/10/16	16:25:33	2012/10/16	16:26:45	1:12
	Filling	2012/10/16	16:26:45	2012/10/16	16:40:28	13:43
4	Digging	2012/10/16	16:40:28	2012/10/16	16:41:25	0:57
	Filling	2012/10/16	16:41:25	2012/10/16	16:59:50	18:25
5	Digging	2012/10/16	16:59:50	2012/10/16	17:00:45	0:55
	Filling	2012/10/16	17:00:45	2012/10/16	17:20:00	19:15
6	Digging	2012/10/16	17:20:00	2012/10/16	17:20:47	0:47
	Filling	2012/10/16	17:20:47	2012/10/16	17:40:00	19:13
7	Digging	2012/10/16	17:40:00	2012/10/16	17:41:15	1:15
	Filling	2012/10/16	17:41:15	2012/10/16	18:08:34	27:19

Table B-33 Time-sequence of each digging and filling phase of Run 236

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (mm:ss)
1	Digging	2012/10/22	13:40:12	2012/10/22	13:41:00	0:48
	Filling	2012/10/22	13:41:00	2012/10/22	13:42:40	1:40
2	Digging	2012/10/22	13:42:40	2012/10/22	13:43:10	0:30
	Filling	2012/10/22	13:43:10	2012/10/22	13:45:08	1:58
3	Digging	2012/10/22	13:45:08	2012/10/22	13:45:28	0:20
	Filling	2012/10/22	13:45:28	2012/10/22	13:49:23	3:55
4	Digging	2012/10/22	13:49:23	2012/10/22	13:49:46	0:23
	Filling	2012/10/22	13:49:46	2012/10/22	13:55:00	5:14
5	Digging	2012/10/22	13:55:00	2012/10/22	13:55:32	0:32
	Filling	2012/10/22	13:55:32	2012/10/22	14:03:12	7:40
6	Digging	2012/10/22	14:03:12	2012/10/22	14:03:36	0:24
	Filling	2012/10/22	14:03:36	2012/10/22	14:12:05	8:29
7	Digging	2012/10/22	14:12:05	2012/10/22	14:12:25	0:20
	Filling	2012/10/22	14:12:25	2012/10/22	14:21:25	9:00

Table B-34 Time-sequence of each digging and filling phase of Run 239

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (mm:ss)
1	Digging	2012/11/2	15:21:00	2012/11/2	15:22:00	01:00
	Filling	2012/11/2	15:22:00	2012/11/2	15:30:00	08:00
2	Digging	2012/11/2	15:30:00	2012/11/2	15:31:00	01:00
	Filling	2012/11/2	15:31:00	2012/11/2	15:37:00	06:00
3	Digging	2012/11/2	15:37:00	2012/11/2	15:38:00	01:00
	Filling	2012/11/2	15:38:00	2012/11/2	15:44:00	06:00
4	Digging	2012/11/2	15:44:12	2012/11/2	15:44:53	00:41
	Filling	2012/11/2	15:44:00	2012/11/2	15:51:00	07:00
5	Digging	2012/11/2	15:51:00	2012/11/2	15:52:00	01:00
	Filling	2012/11/2	15:51:00	2012/11/2	16:00:00	09:00
6	Digging	2012/11/2	16:00:00	2012/11/2	16:01:00	01:00
	Filling	2012/11/2	16:01:00	2012/11/2	16:09:00	08:00
7	Digging	2012/11/2	16:09:00	2012/11/2	16:11:00	02:00
	Filling	2012/11/2	16:11:00	2012/11/2	16:22:00	11:00
8	Digging	2012/11/2	16:22:20	2012/11/2	16:22:56	00:36
	Filling	2012/11/2	16:22:00	2012/11/2	16:31:00	09:00
9	Digging	2012/11/2	16:31:00	2012/11/2	16:32:00	01:00
	Filling	2012/11/2	16:32:00	2012/11/2	16:43:00	11:00
10	Digging	2012/11/2	16:43:00	2012/11/2	16:44:00	01:00
	Filling	2012/11/2	16:44:00	2012/11/2	16:56:00	12:00
11	Digging	2012/11/2	16:56:00	2012/11/2	16:57:00	01:00
	Filling	2012/11/2	16:57:00	2012/11/2	17:08:00	11:00
12	Digging	2012/11/2	17:08:00	2012/11/2	17:09:00	01:00
	Filling	2012/11/2	17:09:00	2012/11/2	17:24:00	15:00
13	Digging	2012/11/2	17:24:11	2012/11/2	17:24:45	00:34
	Filling	2012/11/2	17:24:00	2012/11/2	17:37:00	13:00
14	Digging	2012/11/2	17:37:47	2012/11/2	17:38:47	01:00
	Filling	2012/11/2	17:38:00	2012/11/2	17:54:00	16:00

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (mm:ss)
15	Digging	2012/11/2	17:54:00	2012/11/2	17:55:00	01:00
	Filling	2012/11/2	17:55:00	2012/11/2	18:11:00	16:00
16	Digging	2012/11/2	18:11:08	2012/11/2	18:11:57	00:49
	Filling	2012/11/2	18:11:00	2012/11/2	18:27:00	16:00
17	Digging	2012/11/2	18:27:00	2012/11/2	18:27:49	00:49
	Filling	2012/11/2	18:27:00	2012/11/2	18:46:00	19:00
18	Digging	2012/11/2	18:46:10	2012/11/2	18:46:55	00:45
	Filling	2012/11/2	18:46:00	2012/11/2	19:04:00	18:00
19	Digging	2012/11/2	19:04:17	2012/11/2	19:05:17	01:00
	Filling	2012/11/2	19:05:00	2012/11/2	19:24:00	19:00
20	Digging	2012/11/2	19:24:22	2012/11/2	19:25:13	00:51
	Filling	2012/11/2	19:25:00	2012/11/2	19:46:00	21:00

Table B-35 Time-sequence of each digging and filling phase of Run 240

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (mm:ss)
1	Digging	2012/11/22	14:25:45	2012/11/22	14:26:13	00:28
	Filling	2012/11/22	14:26:13	2012/11/22	14:27:39	01:26
2	Digging	2012/11/22	14:27:39	2012/11/22	14:27:59	00:20
	Filling	2012/11/22	14:27:59	2012/11/22	14:30:18	02:19
3	Digging	2012/11/22	14:30:18	2012/11/22	14:30:39	00:21
	Filling	2012/11/22	14:30:39	2012/11/22	14:33:52	03:13
4	Digging	2012/11/22	14:33:52	2012/11/22	14:34:02	00:10
	Filling	2012/11/22	14:34:02	2012/11/22	14:37:50	03:48
5	Digging	2012/11/22	14:37:50	2012/11/22	14:38:27	00:37
	Filling	2012/11/22	14:38:27	2012/11/22	14:43:18	04:51
6	Digging	2012/11/22	14:43:18	2012/11/22	14:43:48	00:30
	Filling	2012/11/22	14:43:48	2012/11/22	14:50:39	06:51
7	Digging	2012/11/22	14:50:39	2012/11/22	14:50:51	00:12
	Filling	2012/11/22	14:50:51	2012/11/22	14:56:50	05:59
8	Digging	2012/11/22	14:56:50	2012/11/22	14:57:04	00:14
	Filling	2012/11/22	14:57:04	2012/11/22	15:01:10	04:06
9	Digging	2012/11/22	15:01:10	2012/11/22	15:01:24	00:14
	Filling	2012/11/22	15:01:24	2012/11/22	15:07:19	05:55
10	Digging	2012/11/22	15:07:19	2012/11/22	15:07:35	00:16
	Filling	2012/11/22	15:07:35	2012/11/22	15:16:02	08:27
11	Digging	2012/11/22	15:16:02	2012/11/22	15:16:23	00:21
	Filling	2012/11/22	15:16:23	2012/11/22	15:24:39	08:16
12	Digging	2012/11/22	15:24:39	2012/11/22	15:24:55	00:16
	Filling	2012/11/22	15:24:55	2012/11/22	15:32:07	07:12
13	Digging	2012/11/22	15:32:07	2012/11/22	15:32:33	00:26
	Filling	2012/11/22	15:32:33	2012/11/22	15:44:23	11:50
14	Digging	2012/11/22	15:44:23	2012/11/22	15:44:42	00:19
	Filling	2012/11/22	15:44:42	2012/11/22	15:52:31	07:49
15	Digging	2012/11/22	15:52:31	2012/11/22	15:52:50	00:19
	Filling	2012/11/22	15:52:50	2012/11/22	15:59:37	06:47

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (mm:ss)
16	Digging	2012/11/22	15:59:37	2012/11/22	15:59:59	00:22
	Filling	2012/11/22	15:59:59	2012/11/22	16:11:33	11:34
17	Digging	2012/11/22	16:11:33	2012/11/22	16:11:53	00:20
	Filling	2012/11/22	16:11:53	2012/11/22	16:21:30	09:37
18	Digging	2012/11/22	16:21:30	2012/11/22	16:21:46	00:16
	Filling	2012/11/22	16:21:46	2012/11/22	16:32:49	11:03
19	Digging	2012/11/22	16:32:49	2012/11/22	16:33:09	00:20
	Filling	2012/11/22	16:33:09	2012/11/22	16:50:27	17:18
20	Digging	2012/11/22	16:50:27	2012/11/22	16:50:52	00:25
	Filling	2012/11/22	16:50:52	2012/11/22	17:00:15	09:23

Table B-36 Time-sequence of each digging and filling phase of Run 251

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2013/1/11	12:30	2013/1/11	12:32	2
	Filling	2013/1/11	12:32	2013/1/11	12:35	3
2	Digging	2013/1/11	12:35	2013/1/11	12:37	2
	Filling	2013/1/11	12:37	2013/1/11	12:47	10
3	Digging	2013/1/11	12:47	2013/1/11	12:48	1
	Filling	2013/1/11	12:48	2013/1/11	13:01	13
4	Digging	2013/1/11	13:01	2013/1/11	13:03	2
	Filling	2013/1/11	13:03	2013/1/11	13:17	14
5	Digging	2013/1/11	13:17	2013/1/11	13:18	1
	Filling	2013/1/11	13:18	2013/1/11	13:32	14
6	Digging	2013/1/11	13:32	2013/1/11	13:33	1
	Filling	2013/1/11	13:33	2013/1/11	13:51	18
7	Digging	2013/1/11	13:51	2013/1/11	13:52	1
	Filling	2013/1/11	13:52	2013/1/11	14:10	18

Table B-37 Time-sequence of each digging and filling phase of Run 252

No.	Phase	Start Time		End Time		T _{di} or T _{fi} (min)
1	Digging	2013/1/7	17:19	2013/1/7	17:23	4
	Filling	2013/1/7	17:23	2013/1/7	17:37	14
2	Digging	2013/1/7	17:37	2013/1/7	17:39	2
	Filling	2013/1/7	17:39	2013/1/7	17:58	19
3	Digging	2013/1/7	17:58	2013/1/7	18:00	2
	Filling	2013/1/7	18:00	2013/1/7	18:20	20
4	Digging	2013/1/7	18:20	2013/1/7	18:22	2
	Filling	2013/1/7	18:22	2013/1/7	18:48	26
5	Digging	2013/1/7	18:48	2013/1/7	18:50	2
	Filling	2013/1/7	18:50	2013/1/7	19:17	27
6	Digging	2013/1/7	19:17	2013/1/7	19:19	2
	Filling	2013/1/7	19:19	2013/1/7	19:52	33
7	Digging	2013/1/7	19:52	2013/1/7	19:54	2
	Filling	2013/1/7	19:54	2013/1/7	20:29	35

Table B-38 Time-sequence of each digging and filling phase of Run 253

No.	Phase	Start Time		End Time		T_{di} or T_{fi} (min)
1	Digging	2013/1/16	13:27	2013/1/17	0:30	663
	Filling	2013/1/17	0:30	2013/1/18	1:55	1525
2	Digging	2013/1/18	1:55	2013/1/18	10:38	523
	Filling	2013/1/18	10:38	2013/1/19	17:22	1844
3	Digging	2013/1/19	17:22	2013/1/20	1:57	515

Table B-39 Time-sequence of each digging and filling phase of Run 256

No.	Phase	Start Time		End Time		T_{di} or T_{fi} (min)
1	Digging	2013/3/13	15:44	2013/3/13	18:44	180
	Filling	2013/3/13	18:44	2013/3/13	21:34	170
2	Digging	2013/3/13	21:34	2013/3/13	23:12	98
	Filling	2013/3/13	23:12	2013/3/14	2:57	225
3	Digging	2013/3/14	2:57	2013/3/14	3:28	31
	Filling	2013/3/14	3:28	2013/3/14	7:15	227
4	Digging	2013/3/14	7:15	2013/3/14	8:35	80
	Filling	2013/3/14	8:35	2013/3/14	12:41	246
5	Digging	2013/3/14	12:41	2013/3/14	13:37	56
	Filling	2013/3/14	13:37	2013/3/14	18:18	281
6	Digging	2013/3/14	18:18	2013/3/14	19:20	62
	Filling	2013/3/14	19:20	2013/3/15	0:01	281
7	Digging	2013/3/15	0:01	2013/3/15	0:52	51
	Filling	2013/3/15	0:52	2013/3/15	5:28	276

Figure B-1 Time-sequence of each digging and filling phase of Run 13

Figure B-2 Time-sequence of each digging and filling phase of Run 14

Figure B-3 Time-sequence of each digging and filling phase of Run 15

Figure B-4 Time-sequence of each digging and filling phase of Run 20

Figure B-5 Time-sequence of each digging and filling phase of Run 21

Figure B-6 Time-sequence of each digging and filling phase of Run 22

Figure B-7 Time-sequence of each digging and filling phase of Run 52

Figure B-8 Time-sequence of each digging and filling phase of Run 79

Figure B-9 Time-sequence of each digging and filling phase of Run 81

Figure B-10 Time-sequence of each digging and filling phase of Run 82

Figure B-11 Time-sequence of each digging and filling phase of Run 121

Figure B-12 Time-sequence of each digging and filling phase of Run 122

Figure B-13 Time-sequence of each digging and filling phase of Run 166

Figure B-14 Time-sequence of each digging and filling phase of Run 206

Figure B-15 Time-sequence of each digging and filling phase of Run 209

Figure B-16 Time-sequence of each digging and filling phase of Run 211

Figure B-17 Time-sequence of each digging and filling phase of Run 221

Figure B-18 Time-sequence of each digging and filling phase of Run 223

Figure B-19 Time-sequence of each digging and filling phase of Run 230

Figure B-20 Time-sequence of each digging and filling phase of Run 231

Figure B-21 Time-sequence of each digging and filling phase of Run 232

Figure B-22 Time-sequence of each digging and filling phase of Run 234

Figure B-23 Time-sequence of each digging and filling phase of Run 235

Figure B-24 Time-sequence of each digging and filling phase of Run 236

Figure B-25 Time-sequence of each digging and filling phase of Run 239

Figure B-26 Time-sequence of each digging and filling phase of Run 240

Figure B-27 Time-sequence of each digging and filling phase of Run 251

Figure B-28 Time-sequence of each digging and filling phase of Run 252

Figure B-29 Time-sequence of each digging and filling phase of Run 255

Figure B-30 Time-sequence of each digging and filling phase of Run 256

APPENDIX C: MATLAB CODE TO TRANSFER VELOCITY MEASUREMENT DATA

The MATLAB code to transfer the raw data from Vectrino II is shown below.

```
%*****  
% Norteck Vectrino II, set up  
% 40mm-70mm  
% 31points, 1mm one points  
% The original data from Vectrino II can be exported to matlab  
  
clear all  
  
load('filename.mat','Data');  
  
u=fliplr(Data.Profiles_VelX);  
v=fliplr(Data.Profiles_VelY);  
w=fliplr(Data.Profiles_VelZ1);  
w2=fliplr(Data.Profiles_VelZ2);  
  
u_m=mean(u);    %Time-average horizontal velocity (m/s)  
v_m=mean(v);    %Time-average transversal velocity (m/s)  
w_m=mean(w);    %Time-average vertical velocity (m/s)  
  
u_rms=std(u);  
v_rms=std(v);  
w_rms=std(w);  
  
uv_B1 = u_m.*v_m;  
uw_B1 = u_m.*w_m;  
vw_B1 = v_m.*w_m;
```

```

uv_B=-1000*(mean(uv_B1)-u_m.*v_m);
uw_B=-1000*(mean(uw_B1)-u_m.*w_m);
vw_B=-1000*(mean(vw_B1)-v_m.*w_m);

u_m=u_m';
v_m=v_m';
w_m=w_m';

u_rms=u_rms';
v_rms=v_rms';
w_rms=w_rms';

uv_B=uv_B';
uw_B=uw_B';
vw_B=vw_B';

y=[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
31];
y=y';

N=18001

for j=1:31
    for i=1:N-1
        if abs(u(i,j)-u(i+1,j))/0.01>9.81;

            u(i,j)=NaN;

        end
        if abs(v(i,j)-v(i+1,j))/0.01>9.81;

```

```

        v(i,j)=NaN;

    end

    if abs(w(i,j)-w(i+1,j))/0.01>9.8;

        w(i,j)=NaN;

    end

end

end

u_mf=nanmean(u);
v_mf=nanmean(v);
w_mf=nanmean(w);

u_rmsf=nanstd(u);
v_rmsf=nanstd(v);
w_rmsf=nanstd(w);

uv_B2 = u_mf.*v_mf;
uw_B2 = u_mf.*w_mf;
vw_B2 = v_mf.*w_mf;
uv_Bf=-1000*(nanmean(uv_B2)-u_mf.*v_mf);
uw_Bf=-1000*(nanmean(uw_B2)-u_mf.*w_mf);
vw_Bf=-1000*(nanmean(vw_B2)-v_mf.*w_mf);

u_mf=u_mf';
v_mf=v_mf';
w_mf=w_mf';

u_rmsf=u_rmsf';
v_rmsf=v_rmsf';

```

```
w_rmsf=w_rmsf';
```

```
TKE=0.5*(u_rmsf^2+v_rmsf^2+w_rmsf^2);
```

```
uv_Bf=uv_Bf';
```

```
uw_Bf=uw_Bf';
```

```
vw_Bf=vw_Bf';
```

```
y1=[1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30  
31];
```

```
y1=y1';
```

```
for i=1:31
```

```
    yshift(i)=12-7.1+y1(i)/10 ;
```

```
end
```

```
fout_F=fopen('filename.txt','w');
```

```
fprintf(fout_F,'%s,%s,%s,%s,%s,%s,%s,%s,%s,%s,%s,%s,%s,%s,%s  
\n','ysf(cm)','yf(mm)','uf(m/s)','vf(m/s)','wf(m/s)','urmsf(m/s)','vrmsf(m/s)','wrmsf(  
m/s)','uvf(N/m2)','uwf(N/m2)','vwf(N/m2)','TKEunit(m2/s2)');
```

```
for i=1:31
```

```
fprintf(fout_F,'%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f,%f  
\n',ysf(i),yf(i),u_mf(i),v_mf(i),w_mf(i),u_rmsf(i),v_rmsf(i),w_rmsf(i),uv_Bf(i),u  
w_Bf(i),vw_Bf(i),TKE(i));
```

```
end
```

```
fclose(fout_F);
```


APPENDIX D: FIGURES OF THE EVOLUTION OF THE SCOUR PROFILES

Some more cases showing the evolution of the centerline scour profiles for experiments with or without jet-flipping are shown below.

Figure D-1 Centreline scour profiles of Run 21 (a) during the first digging phase, (b) during the first filling phase ($F_0 = 6.5$, $H_t/d_0 = 12.7$, $L/d_0 = 3$, $d_0 = 10$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.71$ m/s, run time = 22 days)

Figure D-2 Centerline scour profiles for Run 3 ($F_0 = 6.19$, $H_t/d_0 = 7.2$, $L/d_0 = 0$, $d_0 = 9$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.67$ m/s, run time = 5 days, $d_{se}/d_0 = 15.2$)

Figure D-3 Centerline scour profiles for Run 4 ($F_0 = 6.19$, $H_t/d_0 = 9.0$, $L/d_0 = 0$, $d_0 = 9$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.67$ m/s, run time = 6 days, $d_{se}/d_0 = 13.9$)

Figure D-4 Centerline scour profiles for Run 5 ($F_0 = 6.19$, $H_t/d_0 = 11.9$, $L/d_0 = 0$, $d_0 = 9$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.67$ m/s, run time = 6 days, $d_{se}/d_0 = 12.3$)

Figure D-5 Centerline scour profiles for Run 6 ($F_0 = 6.19$, $H_t/d_0 = 17.8$, $L/d_0 = 0$, $d_0 = 9$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.67$ m/s, run time = 6 days, $d_{se}/d_0 = 11.2$)

Figure D-6 Centerline scour profiles for Run 7 ($F_0 = 10.02$, $H_t/d_0 = 17.8$, $L/d_0 = 0$, $d_0 = 9$ mm, $d_{50} = 0.73$ mm, $u_0 = 1.09$ m/s, run time = 7 days, $d_{se}/d_0 = 21.3$)

Figure D-7 Centerline scour profiles for Run 9 ($F_0 = 7.25$, $H_t/d_0 = 17.4$, $L/d_0 = 0$, $d_0 = 9$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.79$ m/s, run time = 6 days, $d_{se}/d_0 = 13.7$)

Figure D-8 Centerline scour profiles for Run 10 ($F_0 = 7.25$, $H_t/d_0 = 17.8$, $L/d_0 = 44$, $d_0 = 9$ mm, $d_{50} = 0.73$ mm, $u_0 = 0.79$ m/s, run time = 6 days, $d_{se}/d_0 = 3.7$)

Figure D-9 Centerline scour profiles for Run 11 ($F_0 = 13.05$, $H_t/d_0 = 31.4$, $L/d_0 = 80$, $d_0 = 5$ mm, $d_{50} = 0.73$ mm, $u_0 = 1.42$ m/s, run time = 6 days, $d_{se}/d_0 = 6.4$)

Figure D-10 Centerline scour profiles for Run 12 ($F_0 = 13.05$, $H_t/d_0 = 25$, $L/d_0 = 80$, $d_0 = 5$ mm, $d_{50} = 0.73$ mm, $u_0 = 1.42$ m/s, run time = 6 days, $d_{se}/d_0 = 8.0$)