Flow structures in evolving scour holes caused by 2-D plunging jets and wall jets

Si, Jinhua

2018

Si, J. (2018). Flow structures in evolving scour holes caused by 2-D plunging jets and wall jets. Doctoral thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/82981>

<https://doi.org/10.32657/10220/47543>

**NANYANG
TECHNOLOGICAL
UNIVERSITY**

SINGAPORE

FLOW STRUCTURES IN EVOLVING SCOUR HOLES CAUSED BY 2-D PLUNGING JETS AND WALL JETS

SI JINHUA

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

2018

FLOW STRUCTURES IN EVOLVING SCOUR HOLES CAUSED BY 2-D PLUNGING JETS AND WALL JETS

SI JINHUA

School of Civil and Environmental Engineering

A thesis submitted to the Nanyang Technological University

in partial fulfilment of the requirement for the degree of

Doctor of Philosophy

2018

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarized materials, and has not been submitted for a higher degree to any other University or Institution.

10 Jan 2019

Si Jinhua

Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

Sylin

Dr. Lim Siow Yong

14 Jan 2019

Authorship Attribution Statement

This thesis contains material from 3 paper(s) published (or to be published) in the following peer-reviewed journal(s) where I was the first and/or corresponding author.

Chapter 4 is published as J. H. Si, S. Y. Lim, and X. K. Wang (2018), Flow structures in evolving scour holes caused by a plunging jet downstream of a weir, *Journal Hydraulic Engineering*, 144(6), 04018018.

Chapter 5 is to be published as J. H. Si, S. Y. Lim, and X. K. Wang (2019), Jet-flipping in a scour hole downstream of an unsubmerged weir with an apron, *Journal Hydraulic Engineering* (Revision for editor only).

Chapter 6 is to be published as J. H. Si, S. Y. Lim, and X. K. Wang, Evolution of flow fields in a developing local scour hole formed by a submerged wall jet (Submitted for publication).

The contributions of the co-authors to each paper are as follows:

- A/Prof. Lim Siow Yong provided the initial direction of this project and maintained this project on the right track throughout; Prof. Lim also provided valued instructions on composing the papers and revised the manuscripts.
- Prof. Wang Xikun co-designed the experimental apparatus, revised the manuscripts and helped overcome technical problems with the PIV system that we encountered.
- I co-designed and set up the experimental apparatus, carried out the experiments, analyzed the data and prepared the manuscripts.

12 Jan 2019

Si Jinhua

ACKNOWLEDGMENTS

The author wishes to express his sincere gratitude to his supervisor, Prof. Lim Siow Yong, for his kindness and valuable guidance over the past years. Prof. Lim's profound knowledge and insightful advice lead the author to complete this dissertation. Prof. Lim mentored the author not only in the academic pursuit but also in the author's life.

The author wishes to express his sincere gratitude to Prof. Wang Xikun, for his valuable instructions on the PIV system and the design of the experiment carried out at the Maritime Research Centre. Prof. Wang's help makes the pursuit of PhD study easier and more interesting.

The author wishes to express his sincere gratitude to Prof. Cheng Niansheng who encouraged and inspired the author in the pursuit of PhD study. The author would also like to thank Prof. Tan Soon Keat for providing a nice research environment at the Maritime Research Centre.

The author also wishes to extend his sincere appreciation to the technicians from the Hydraulics Lab, Mr. Lim Kok Hin, Ms. Tin Zar Lwin and Mr. Hendro for their enormous help with the experimental works in the Hydraulics lab.

Finally, the author thanks his girlfriend, Ms. Liu Qian, for her persistent support and warm company over the past years.

TABLE OF CONTENTS

Statement of Originality.....	I
Supervisor Declaration Statement	II
Authorship Attribution Statement.....	III
ACKNOWLEDGMENTS.....	IV
TABLE OF CONTENTS	V
SUMMARY	VIII
LIST OF PUBLICATIONS	X
LIST OF TABLES.....	XI
LIST OF FIGURES.....	XII
LIST OF SYMBOLS.....	XVII
CHAPTER 1 INTRODUCTION.....	1
1.1 Background.....	1
1.2 Objectives and scopes of study.....	3
1.3 Thesis organization.....	3
CHAPTER 2 LITERATURE REVIEW	4
2.1 Introduction	4
2.2 Flow structures with a jet impinging on a flat surface	7
2.3 Flow structures in scour holes downstream of a submerged weir	10
2.4 Flow structures in scour holes caused by a wall jet.....	12
2.5 Evolutions of flow structures in a scour hole	17
2.6 Flow structures of jet-flipping	23
CHAPTER 3 EXPERIMENTAL SETUP AND METHODOLOGY	26
3.1 Introduction	26
3.2 Experimental flume for the case of a plunging jet without jet-flipping	27
3.3 Experimental flume for the case of a plunging jet with jet-flipping	29
3.4 Experimental flume for the case of a submerged wall jet	30
3.5 Particle Image Velocimetry (PIV) system.....	31

3.6 Applicability of PIV in measuring flow fields on a movable bed	33
CHAPTER 4 FLOW STRUCTURES IN SCOUR HOLES CAUSED BY A PLUNGING JET	36
4.1 Introduction	36
4.2 Flow Patterns	38
4.3 Distributions of Average Kinetic Energy (AKE)	41
4.3.1 Plunging jet zone	41
4.3.2 Bed impingement zone	43
4.3.3 Free-surface impingement zone	44
4.3.4 Summary of AKE distributions	45
4.4 Distributions of Turbulent Kinetic Energy (TKE)	45
4.5 Distributions of Reynolds Shear Stress (RSS)	48
4.6 Scour mechanism for plunging jets	50
4.7 Summary.....	51
CHAPTER 5 JET FLIPPING IN SCOUR HOLES DOWNSTREAM OF A FREE WEIR WITH AN APRON	53
5.1 Introduction	53
5.2 Flow Patterns	53
5.3 Distributions of Average Kinetic Energy (AKE)	60
5.4 Self-similarity of the main jet.....	65
5.5 Distributions of Turbulent Kinetic Energy (TKE)	68
5.6 Distributions of Reynolds Shear Stress (RSS)	73
5.7 Scour mechanism with an apron.....	77
5.8 Summary.....	78
CHAPTER 6 FLOW STRUCTURES IN SCOUR HOLES CAUSED BY A WALL JET.....	80
6.1 Introduction	80
6.2 Flow patterns	82
6.3 Evolution of the turbulence characteristics	88
6.4 Self-similarity of dynamic flow structures in local scour holes	92
6.5 Scour mechanism for wall jets.....	98

6.6 Summary.....	99
CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS.....	101
7.1 PIV methods	101
7.2 Flow structures	101
7.3 Scour mechanism.....	102
7.2 Recommendations	102
REFERENCES	104

SUMMARY

The present laboratory study used Particle Image Velocimetry (PIV) to measure the flow structures in evolving scour holes caused by two types of 2-D jet: a 2-D plunging jet downstream of a weir and a 2-D wall jet beneath a sluice gate with an apron. The interesting jet-flipping phenomenon has been measured using PIV in a local scour hole caused by a 2-D plunging jet onto an apron. Specifically, three cases were investigated: (1) the case of a 2-D plunging jet without jet-flipping; (2) the case of jet-flipping formed by a 2-D plunging jet onto an apron; and, (3) the case of a 2-D wall jet. The results clearly depicted that, in all cases, a total of four rollers are involved in the flow development, although the types of rollers vary slightly. The major roller, captive roller, and bed roller appear in all cases; an intermittent roller beside the captive roller is observed in the case of a 2-D plunging jet without jet-flipping, whereas, a secondary roller, instead of the intermittent roller, is found above the apron for other cases. Among all the rollers, only the major roller contributes to the development of scour.

The average kinetic energy (AKE) distributions reveal that the rollers are maintained by jet impingements on both the concave scoured bed and the water surface. Through the impingement of jet on the concave bed, the energy of the flow entering the scour hole mainly splits into two portions: one sustaining the dynamics of all component jets in the scour hole; the other entraining sediment as one of primary factors in scour. Another major contributing factor in scour is the capacity of the main jet in transporting the sediment outside the scour hole. The impingements of the jets and the mutual interactions among the rollers alternate the form of predominant energy between kinetic energy and potential energy along the main jet within the local scour hole. Therefore, various segments of the same main jet display different capacity to transport uplifted sediments. As the scour develops, a gap gradually enlarges between two segments of the main jet with high transport capability, which adversely affects scour development. The scour stops when the uplifted sediment cannot be transported out of the scour hole. In other words, the local bed shear stress on the bed profile is but a secondary factor, which remains higher than the critical value for sediment incipient motion in the equilibrium scouring stage.

For the case with a wall jet, both the flow structures and the bed profiles of the scour hole exhibit self-similarity throughout the scour process. At any scouring stage, the velocity profiles on the cross-jet sections preserve global self-similarity, whereas those along the jet centerlines preserve local self-similarity in regions with significant level of average kinetic energy (AKE). The profiles of the scour hole, as well as the distributions of the velocity vectors, AKE, kinetic turbulence energy (TKE) and Reynolds shear stress (RSS) inside it, all share some kind of self-similarity when scaled with proper length and velocity scales.

Furthermore, an apron downstream of a free weir can cause the main jet to flip up and down cyclically in a local scour hole and significantly influences the scouring process. The jet flipping behavior is linked with the cyclical appearance and disappearance of the bed roller beneath the main jet. With the cyclical jet-flipping, the main jet has a pivotal region with significant level of average kinetic energy (AKE) immediately downstream of the apron. Around this region, the turbulence kinetic energy (TKE) and Reynolds shear stress (RSS) distributions attain their peak values; the jet development also exhibits self-similarity along the streamline passing through the peak AKE when normalized with the local length and velocity. A quantitative assessment of the gross effects of the apron is made through comparison with that without an apron in terms of impingement angles, maximum scour depth and magnitude of the AKE.

LIST OF PUBLICATIONS

Flow structures in evolving scour holes caused by a plunging jet downstream of a weir
J. H. Si, S. Y. Lim, and X. K. Wang (2018), *J. Hydraul. Eng.*, 144(6), 04018018.

Jet-flipping in a scour hole downstream of an unsubmerged weir with an apron
J. H. Si, S. Y. Lim, and X. K. Wang (2018), *J. Hydraul. Eng.*, (Revision for Editor Only).

Evolution of flow fields in a developing local scour hole formed by a submerged wall jet
J. H. Si, S. Y. Lim, and X. K. Wang (Submitted for publication)

LIST OF TABLES

Table 5.1 Summary of jet impingement angles on the non-erodible bed (θ_a), the erodible bed (θ_b) and the water surface (θ_s) 59

LIST OF FIGURES

Fig. 2.1 A schematic sketch of a submerged plane jets [<i>Albertson et al.</i> , 1950]	4
Fig. 2.2 Sketch of plane wall jets [<i>Rajaratnam</i> , 1976].....	5
Fig. 2.3 Similarity of velocity profiles in plane wall jets [<i>Rajaratnam</i> , 1976]	5
Fig. 2.4 (a) Velocity profiles across boundary layers with favorable ($dp/dx < 0$) and adverse ($dp/dx > 0$) pressure gradients; (b) Streamlines and velocity profiles near a separation point [<i>Kundu et al.</i> , 2011].....	6
Fig. 2.5 Görtler vortices in a boundary layer along a concave wall [<i>Kundu et al.</i> , 2011].....	7
Fig. 2.6 Three distinct zones of plunging jet [<i>Beltaos and Rajaratnam</i> , 1973]	7
Fig. 2.7 (a) Sketch of a plunging jet overflowing a vertical drop; (b) Self-similarity plot of the jet mean velocity profiles on the demarcating cross section: $S = S_a$; and (c) Self-similarity plot of the mean velocity profiles for the deflected wall jet for the case of $Y_c/H = 0.383$; [<i>Lin et al.</i> , 2007]	8
Fig. 2.8 Sketch of the jet overflowing a vertical drop [<i>Robinson et al.</i> , 2000]	9
Fig. 2.9 (a) sketch of the plunging jet flow; (b) the mean velocity profile on cross sections in jet zone I; [<i>Liu et al.</i> , 1998a]	10
Fig. 2.10 (a) Time-averaged velocities in the central longitudinal profile of the channel at the scouring equilibrium stage; (b) An example of the turbulence intensity rms(u) (test T16); [<i>Meftah and Mossa</i> , 2006].....	11
Fig. 2.11 (a) Velocity vectors distribution in the longitudinal centerline section; the distributions of (b) downstream; (c) transverse; (d) vertical components of turbulence intensity on the longitudinal centerline section; [<i>Guan et al.</i> , 2014].....	12
Fig. 2.12 Velocity vector plot in the local scour holes for (a) Test A; (b) Test B in the cases with a submerged plane jet downstream of a sluice gate; [<i>Bey et al.</i> , 2007].....	13
Fig. 2.13 Turbulent shear stress at various axial stations in the local scour hole caused by a submerged plane jet downstream of a sluice gate; [<i>Bey et al.</i> , 2007].....	14
Fig. 2.14 Dimensionless normal Reynolds stress profiles. (a) Longitudinal (x-component) normal Reynolds stress $\bar{u}^2/U_m^2$, and (b) cross-stream (z component) normal Reynolds stress $\bar{w}^2/U_m^2$. $\blacktriangle$, $x/b_0 = 6$; $\blacktriangleright$, $x/b_0 = 8$, for concave wall and	

$\triangle$, $x/b_0 = 4.75$; $\triangleright$, $x/b_0 = 7.75$ for flat wall [Albayrak <i>et al.</i> , 2008]	15
Fig. 2.14 Streamwise oblique view of the sediment surface showing 8 longitudinal sediment streaks or ridges on the upstream-facing scour-hole slope [Hopfinger <i>et al.</i> , 2004].....	16
Fig. 2.15 Dimensionless scour profiles of wall jet for different (a) times of a single experiment, and (b) lengths of apron; (c) mean velocity distribution along the apron; [Hassan and Narayanan, 1985]	17
Fig. 2.16 Fixed-bed models constructed to represent various stages of development of the scour hole and downstream dune [Hill and YOUNKIN, 2006].....	18
Fig. 2.17 Two-dimensional vector representation of mean velocity fields in the scour hole for the five fixed-bed models (a) to (e) which correspond to Profiles 1 to 5 of Fig. 2.16, respectively [Hill and YOUNKIN, 2006]	19
Fig. 2.18 Variation of boundary shear with normalized alongslope distance [Hill and YOUNKIN, 2006].....	20
Fig. 2.19 Normalized velocity vectors for run 4a having (a) flat bed condition; (b) intermediate scour hole with $0.3d_{se}$; (c) intermediate scour hole with $0.8d_{se}$; and (d) equilibrium scour depth with $d_{se}=0.062$ m; [Dey and Sarkar, 2008]	21
Fig. 2.20 Horizontal distributions of bed shear stress, τ , for run 4a having (a) flat bed condition; (b) intermediate scour hole with $0.3d_{se}$; (c) intermediate scour hole with $0.8d_{se}$; and (d) equilibrium scour depth with $d_{se}=0.062$ m; [Dey and Sarkar, 2008].....	22
Fig. 2.21 Schematic view (not to scale) of the flow field during (a) the digging process and (b) the refilling process; [Balachandar and Kells, 1997]	23
Fig. 2.22 Local scour cycle: (a) phase A: maximum fill; (b) digging phase begins, cycle begins; (c) digging continues; (d) phase B: maximum dig; (e) filling phase begins; (f) filling continues; (g) phase A: maximum fill; and (h) digging phase begins, cycle begins, [Balachandar <i>et al.</i> , 2000]	24
Fig. 2.23 Run 122: (a) Aluminum 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) Aluminum 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; [Xie and Lim, 2015].....	25

Fig. 2.24 Flow field of Run 122 with (a) bed jet at the end of the first digging phase; (b) surface jet at the start of the second filling phase; (c) surface jet at the end of the second filling phase; (d) bed jet at the start of the third digging phase; [Xie and Lim, 2015].....	25
Fig. 3.1 Bed sediment sample ($d_{50} = 0.77\text{mm}$).....	26
Fig. 3.2 Sediment size distribution for the present study	27
Fig. 3.3 Schematic diagrams of experimental setup for the case of plunging jets: (a) Plan view and (b) Side view; all dimensions are in mm.	27
Fig. 3.4 Schematic diagrams of experimental setup for the case of plunging jets with an apron: (a) Plan view and (b) Side view; all dimensions are in mm.	29
Fig. 3.5 Schematic diagrams of experimental setup for the case of a submerged wall jet below a sluice gate: (a) Plan view and (b) Side view; all dimensions are in mm.....	30
Fig. 3.6 (a) Typical particle image and (b) calculated instantaneous velocity vector field (u, v) of an experiment ($Q = 1.5 \text{ L/s}$; $H = 50 \text{ mm}$ and $t = 18199 \text{ s}$)	35
Fig. 4.1 Temporal development of the maximum scour depth for the case with a plunging jet ($Q = 1.5 \text{ L/s}$ and $H = 50 \text{ mm}$)	36
Fig. 4.2 Sketch of flow patterns in the scour hole caused by a plunging jet	38
Fig. 4.3 Average velocity fields during the scour hole development within the inclusive time span of (a) 61 s to 64 s; (b) 66 s to 68 s; (c) 1363 s to 1374 s; (d) 18191 s to 18202 s	39
Fig. 4.4 Distributions of AKE during the scour hole development within the inclusive time span of (a) 61 s to 64 s; (b) 1363 s to 1374 s; (c) 18191 s to 18202 s, which correspond to the flow fields of Figs. 4.3 (a), (c) and (d), respectively.....	42
Fig. 4.5 Distributions of TKE during the scour hole development within the inclusive time span of (a) 61 s to 64 s; (b) 1363 s to 1374 s; (c) 18191 s to 18202 s, which correspond to the flow fields of Figs. 4.3 (a), (c) and (d), respectively.....	47
Fig. 4.6 Distributions of RSS during the scour hole development within the inclusive time span of (a) 61 s to 64 s; (b) 1363 s to 1374 s; (c) 18191 s to 18202 s, which correspond to the flow fields of Figs. 4.3 (a), (c) and (d), respectively.....	48
Figs. 5.1 Schematic sketches of flow patterns for (a) bed jet regime, (b) transitional jet regime and (c) surface jet regime in a scour hole downstream of an	

unsubmerged weir with an apron	54
Figs. 5.2 Average velocity fields of Run 1 ($Q = 1.5$ L/s, $H = 50$ mm and $A = 100$ mm) within the inclusive time span of (a) 110 ~ 111 s; (b) 112 ~ 113 s; (c) 114 ~ 116 s; (d) 117 ~ 121 s. Denoted as I.J. 1, I.J. 2, I.J. 3 and I.J. 4, respectively, as the jet is experiencing upward flipping at the initial scouring stage	55
Figs. 5.3 Average velocity fields of Run 1 ($Q = 1.5$ L/s, $H = 50$ mm and $A = 100$ mm) within the inclusive time span of (a) 1028 ~ 1029 s; (b) 1030 ~ 1031 s; (c) 1034 ~ 1036 s; (d) 1038 ~ 1039 s. Denoted as E.J. 1, E.J. 2, E.J. 3 and E.J. 4, respectively, as the jet is experiencing upward flipping at the equilibrium scouring stage	56
Figs. 5.4 Average velocity fields of Run 2 ($Q = 1.5$ L/s, $H = 55$ mm and $A = 100$ mm) within the inclusive time span of (a) 1207 ~ 1210 s; (b) 1397 s; (c) 1399 s; (d) 1401 s. Denoted as R.J. 4, R.J. 3, R.J. 2 and R.J. 1, respectively, as the jet is experiencing reverse (downward) flipping at the equilibrium scouring stage	57
Figs. 5.5 AKE distributions of Run 1 at (a) I.J. 1; (b) I.J. 2; (c) I.J. 3; (d) I.J. 4	61
Figs. 5.6 AKE distributions of Run 1 at (a) E.J. 1; (b) E.J. 2; (c) E.J. 3; (d) E.J. 4	62
Figs. 5.7 AKE distributions of Run 2 at (a) R.J. 4; (b) R.J. 3; (c) R.J. 2; (d) R.J. 1	63
Figs. 5.8 Definition sketch of mean velocity profiles and half-width along the streamline-wise direction.....	66
Figs. 5.9 Normalized velocity profiles at cross-sections (a) a-a; (b) b-b; (c) B; (d) c-c and (e) d-d.....	67
Figs. 5.10 Length scales of the flipping part of the main jet in (a) bed jet and early transitional regimes; (b) late transitional regime; and (c) surface jet regime	68
Fig. 5.11 TKE distributions of Run 1 at (a) I.J. 1; (b) I.J. 2; (c) I.J. 3; (d) I.J. 4	70
Fig. 5.12 TKE distributions of Run 1 at (a) E.J. 1; (b) E.J. 2; (c) E.J. 3; (d) E.J. 4	71
Fig. 5.13 TKE distributions of Run 2 at (a) R.J. 4; (b) R.J. 3; (c) R.J. 2; (d) R.J. 1	72
Figs. 5.14 RSS distributions of Run 1 at (a) I.J. 1; (b) I.J. 2; (c) I.J. 3; (d) I.J. 4	74
Figs. 5.15 RSS distributions of Run 1 at (a) E.J. 1; (b) E.J. 2; (c) E.J. 3; (d) E.J. 4	75
Figs. 5.16 RSS distributions of Run 2 at (a) R.J. 4; (b) R.J. 3; (c) R.J. 2; (d) R.J. 1	76
Fig. 6.1 Temporal development of (a) the maximum scour depth and (b) the scour width; for the case with a wall jet.....	82
Fig. 6.2 Sketch of flow patterns in the scour hole caused by a wall jet	83

Fig. 6.3 (a-f) flow patterns and (g-l) AKE distributions for M1 to 6 during the scour hole development; corresponding to the inclusive time spans of 38s – 49s, 235s – 246s, 297s – 308s, 916s – 927s, 3773s – 3784s, and 21595s – 21606s, respectively	84
Fig. 6.4 Temporal development of controlling points in the flow fields.....	88
Fig. 6.5 (a-f) TKE distributions and (g-l) RSS distributions for M1 to 6 during the scour hole development; corresponding to the inclusive time spans of 38s – 49s, 235s – 246s, 297s – 308s, 916s – 927s, 3773s – 3784s, and 21595s – 21606s, respectively	90
Fig. 6.6 Vorticity distributions for M1 to 6 during the scour hole development; corresponding to the inclusive time spans of 38s – 49s, 235s – 246s, 297s – 308s, 916s – 927s, 3773s – 3784s, and 21595s – 21606s, respectively.....	92
Fig. 6.7 Self-similar velocity profiles along the centerlines of the main jet	94
Fig. 6.8 Self-similar velocity profiles on the cross-jet sections	96
Fig 6.9 Self-similarity in spatial distributions of the flow fields.....	97
Fig. 6.10 Alternative self-similarity in spatial distributions of turbulence	97

LIST OF SYMBOLS

AKE	= Average Kinetic Energy
b	= Sluice gate opening size [m]
b _u	= Half jet width on the unbounded side of a cyclically flipping jet [m]
b _u '	= Half jet width on the bounded side of a cyclically flipping jet [m]
C _o	= velocity coefficient
d ₅₀	= Median sediment diameter [m]
d _{15.9}	= Sediment diameters that are finer than 15.9% of bed material [m]
d _{84.1}	= Sediment diameters that are finer than 84.1% of bed material [m]
d _s	= Scour hole depth [m]
Fr	= Froude number = $\frac{U_e}{\sqrt{gd_{50}}}$
g	= Gravitational acceleration [m/s ²]
H	= Tailwater depth [m]
h _o	= height of weir above the tailwater surface [m]
L	= Apron length [m]
M1	= The 1st PIV measurement
M2	= The 2nd PIV measurement
M3	= The 3rd PIV measurement
M4	= The 4th PIV measurement
M5	= The 5th PIV measurement
M6	= The 6th PIV measurement
q	= discharge per unit width [m ² /s]
Q	= Flowrate [m ³ /s]
Re	= Reynolds number

RSS	= Reynolds Shear Stress
s	= Jet-wise coordinate [m]
Sys. I	= Coordinate system I
Sys. II	= Coordinate system II
t	= Time [s]
T^*	= Dimensionless time = $\frac{gT}{U_0^2}$
TKE	= Turbulence Kinetic Energy
$\bar{u}$	= Mean velocity in the longitudinal direction (x-axis) [m/s]
u'	= Fluctuating velocity component in the longitudinal direction (x-axis) [m/s]
u_*	= Average shear velocity at a far downstream section [m/s]
u_c	= Critical shear velocity for sediment incipient motion in a local scour hole [m/s]
U_e	= average velocity at the jet entry point [m/s]
U_0	= Average flow velocity at a far downstream section [m/s]
$\bar{v}$	= Mean velocity in the vertical direction (y-axis) [m/s]
v'	= Fluctuating velocity component in the vertical direction (y-axis) [m/s]
V_A	= Jet-wise velocity at point A [m/s]
V_B	= Jet-wise velocity at point B [m/s]
V_C	= Jet-wise velocity at point C [m/s]
V_F	= Jet-wise velocity at point F [m/s]
V_m	= Maximum jet-wise velocity [m/s]
V_s	= Jet-wise velocity at the intersection between the streamline and the cross-jet section [m/s]
WJ	= Full jet width [m]
W_s	= Scour hole width [m]
x	= Horizontal coordinate [m]

X_D	= x coordinates of points D [m]
X_G	= x coordinates of points G [m]
X_P	= x coordinates of points P [m]
y	= Vertical coordinate [m]
y'	= Cross-jet coordinate [m]
y_c	= critical water depth at upstream of the weir [m]
y_e	= the thickness of the plunging jet at the entry point [m]
Y_G	= y coordinates of points G [m]
$y_{1/2}'$	= Half jet width [m]
α	= kinetic energy coefficient
θ_a	= Impingement angle on the apron
θ_b	= Impingement angle on the bed
θ_s	= Impingement angle on the water surface
ω_v	= Dimensional vorticity [1/s]
ρ	= Water density [kg/m ³]
ρ_s	= Sediment density [kg/m ³]
Δ	= Relative density of sediment = $(\rho_s - \rho)/\rho$
σ_g	= Sediment gradation = $\sqrt{d_{84.1}/d_{15.9}}$
μ	= Dynamic viscosity of water [kg/sm]

CHAPTER 1 INTRODUCTION

1.1 Background

Flow through a spillway typically enters the tailwater in the form of a plunging jet over a weir or a wall jet beneath a sluice gate. The jets may cause local scour at the alluvial bed immediately downstream, which may jeopardize the stability of the hydraulic structure. The foundation of a hydraulic structure is often considered an entity, despite the existence of many fractures. In the presence of downstream scour holes, pressure difference can cause relative movements between parts of the foundation along the fractures and the stability of the hydraulic structure is jeopardized. The possibility of the relative movements is positively associated with size of the scour hole which is characterized by the maximum depth. The maximum depth of the scour hole caused by the two types of jet have been extensively studied [Adduce and Sciortino, 2006; Ali and Lim, 1986; Bormann and Julien, 1991; D'Agostino and Ferro, 2004; Dey and Sarkar, 2006; Dey and Raikar, 2007; Dodaro et al., 2016; Fiorotto et al., 2014; Gaudio et al., 2000; Guan et al., 2015; 2016; Hopfinger et al., 2004; Lenzi et al., 2002; Mason and Arumugam, 1985; Meftah and Mossa, 2006; Schoklitsch, 1932; Stein et al., 1993; Xie and Lim, 2015]. Generally, the scour develops rapidly in the early scouring stage. Then the scour rate decreases continuously with time in the intermediate scouring stage and eventually approaches zero in the asymptotic equilibrium scouring stage, where the scour hole attains its maximum depth [Lim and Cheng, 1998; Xie and Lim, 2015]. The scour hole interacts with the flow structure within it intensely [Bey et al., 2007; Hoffmans and Booij, 1993; Hopfinger et al., 2004; Jia et al., 2001; Karim and Ali, 2000].

Several studies have focused on the flow structures resulting from a freely plunging jet into a tailwater pool with a flat solid bed [Beltaos and Rajaratnam, 1973; Lin et al., 2007; Liu et al., 1998a; Robinson et al., 2000]. Some other studies investigated the flow structures at the equilibrium stages in a local scour hole downstream of a submerged weir where the freely plunging jet is absent [Guan et al., 2014; Meftah and Mossa, 2006]. However, research on the flow structures in a local scour hole caused by a freely

plunging jet is not available to date. On the other hand, the flow structures in a local scour hole caused by a wall jet have been studied at the equilibrium scouring stage with a conventional technique using Acoustic Doppler Velocimeter (ADV) [Albayrak *et al.*, 2008; Bey *et al.*, 2007; Dey and Sarkar, 2008]. An ADV is typically used to measure the flow field at only one single point at a time; and therefore, the flow fields were assumed invariable over quite a period when various measurements were taken at only a number of points in the scour hole. In short, comprehensive local flow characteristics and time-dependent features have not been measured at all pertinent locations in the scour hole.

The rapidly evolving scour hole transforms the flow fields significantly and continuously at the early and intermediate scouring stages [Bey *et al.*, 2007; Lee *et al.*, 2017]. On the other hand, at the equilibrium stage, the flow fields interact the least with the scour hole. However, the evolution of the flow fields within a local scour hole, especially at the early and intermediate scouring stages, remains scarcely investigated. Dey and Sarkar [2008] studied the evolution of flow fields by measuring the flow in molded fixed bed scour hole models at several representative points during the scour process. Hill and Younkin [2006] simulated the profile of the scour hole at selected representative points with triangles made of polycarbonate sheets, instead of molded scour hole. The artificial scour holes not only introduced geometrical distortion from the original profiles but, more importantly, eliminated the dynamic interactions between sediments and flow, which underpins the scour mechanism.

Jet-flipping is an interesting phenomenon when a jet alternates cyclically between two regimes, i.e. the bed jet regime and the surface jet regime [Xie and Lim, 2015]. Jet-flipping results in alternate scouring and refilling of the scour hole during a flipping cycle. The jet-flipping phenomenon has been observed mostly downstream of two types of hydraulic structures: a sluice gate [Balachandar and Kells, 1997; 1998; Balachandar and Reddy, 2013; Johnston, 1990; Johnston and Halliwell, 1986; Kurniawan and Altinakar, 2002; Xie and Lim, 2015]; and a submerged weir with a solid flat bed [Azimi *et al.*, 2014; Fritz and Hager, 1998; Kabiri-Samani *et al.*, 2010; Lin *et al.*, 2008; Wu and Rajaratnam, 1996; Wu and Rajaratnam, 1998]. There is, however, very little literature which documented the jet-flipping phenomenon in a local scour hole

downstream of a free weir with an apron. Many of the above works mentioned the jet-flipping phenomenon in a scour hole but did not delve into quantitative details about the dynamic flow behavior. This dynamic behavior is of significance in understanding the dynamic flow structures under jet regime transitions, when the development of the scour hole undergoes alternate change of mode between the scouring process and the refilling process. The flow fields under transitions are difficult to measure directly using conventional point measurement techniques because the transitions are intermittent, transient, and very sensitive to any disturbance to the flow fields. The above problems can be overcome by replacing the conventional measuring technique, such as ADV, with Particle Image Velocimetry (PIV). PIV is an optical and non-intrusive technique that could be used to measure instantaneous 2-D planar flow fields in a global domain.

1.2 Objectives and scopes of study

The present study used PIV to investigate: (1) the evolution of the flow field, including the mean velocity and turbulence, within local scour holes caused by a plunging jet downstream of a weir and a wall jet downstream of an apron; (2) the intense interaction of the flow structures with the continuously evolving bed profiles; (3) the self-similarity of the flow structures within the scour hole over the entire scouring process.

1.3 Thesis organization

This thesis report comprises 7 chapters. An introduction of this project is implemented in Chapter 1. A critical review of relevant research performed by other researchers is presented in Chapter 2. Chapter 3 describes the experimental equipment and procedures. The flow structures in a local scour hole caused by a plunging jet are examined in Chapter 4. Chapter 5 documents the jet-flipping phenomenon in a local scour hole downstream of a free weir with an apron. Chapter 6 describes the flow structures in a local scour hole caused by a submerged wall jet downstream of a sluice gate with an apron. Finally, Chapter 7 concludes the report and recommends future work.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of previous works relevant to the present study. For convenience, the symbols used in this chapter conform to the original definitions in their respective studies; each of the symbols in this chapter is shown in its particular figure or described in word specifically. Note that a unified notation system is used in the subsequent chapters of the present study.

Fig. 2.1 A schematic sketch of a submerged plane jets [Albertson *et al.*, 1950]

It is reported that a plunging jet behaves like a submerged plane jet in the tailwater pool [Liu *et al.*, 1998a; Stein *et al.*, 1993] and Fig. 2.1 shows a schematic sketch of submerged plane jets from Albertson *et al.* [1950]. The submerged plane jet comprises two zones, “zone of flow establishment” and “zone of established flow”, as shown in Fig. 2.1. In the former, a pronounced velocity discontinuity between the jet and the surrounding fluid generates a great number of eddies which gradually accelerates the surrounding fluid while decelerating the fluid of the jet near the edges. The result is a lateral mixing process which progresses inward and outward with distance from the efflux section. In other words, the constant-velocity core steadily decreases in the lateral

Whether it is a plunging jet or a wall jet, the jet, upon entering a scour hole, is deflected by the bed profiles, and takes a curvy path in the scour hole. *Kundu et al.* [2011] documented the boundary layer across a convex surface when water flow past a circular cylinder, as shown in Fig. 2.4. At the stagnation point, the flow velocity is zero but the pressure is at its peak pressure according to the Bernoulli equation. Favorable pressure gradients appear on the upstream side of the semicircle and the flow accelerates from the stagnation point along the surface; on the downstream side, adverse pressure gradients decelerate the flow until its separation from the surface. Fig. 2.4(b) shows streamlines and velocity profiles near a separation point S where a streamline emerges from the surface. Furthermore, the flow in the wake region after separation is unstable and turbulence is amplified in the wake region.

Fig. 2.4 (a) Velocity profiles across boundary layers with favorable ($dp/dx < 0$) and adverse ($dp/dx > 0$) pressure gradients; (b) Streamlines and velocity profiles near a separation point [*Kundu et al.*, 2011]

Kundu et al. [2011] also documented that the boundary layer across a concave surface and that jet-wise secondary vortices, i.e. Görtler vortices, emerge in the boundary layer when the boundary layer becomes unstable, as shown in Fig. 2.5. The instability phenomenon of Görtler vortices is essentially the same as that in Taylor Couette flow,

with the only difference being the lack of the inner curved surface. *Hopfinger et al.* [2004] found that the concave curvature of the profile of scour hole gives rise to Görtler vortices by destabilizing the turbulent boundary layers.

Fig. 2.5 Görtler vortices in a boundary layer along a concave wall [*Kundu et al.*, 2011]

2.2 Flow structures with a jet impinging on a flat surface

Beltaos and Rajaratnam [1973] found that a vertical plunging jet flow has a length of the potential core which is approximately seven times the width of the jet upon entry, and that 3 characteristic zones of a plunging jet appear in the zone of established flow when the jet impinges perpendicularly on a flat solid surface, as sketched in Fig. 2.6. First is the free jet zone where the plunging jet behaves like a free jet and spreads laterally. The impingement zone follows where the plunging jet impinges on the solid surface and deflects from its original direction with the presence of significant pressure gradients. The third is the wall jet zone, where the deflected jet clings to the surface and is similar in characteristics with a submerged wall jet.

Fig. 2.6 Three distinct zones of plunging jet [*Beltaos and Rajaratnam*, 1973]

Lin et al. [2007] studied a plunging jet which overflows a weir-like vertical drop as can be seen in Fig. 2.7(a). Fig. 2.7(b) shows that the profiles of jet-wise velocity are self-similar at the cross section of jet entry ($S = S_a$) that divides the plunging jet into the falling jet and the sliding jet, under different hydraulic conditions, i.e. different values of Y_c/H . The self-similar profiles are symmetric about the point ($Y_r/b_r = 1$ and $u_s/(u_s)_{\max} = 0.5$), where b_r is the half-width of jet on the cross section. The jet after deflection on the floor depicts wall jet characteristics, and the velocity profiles on the cross sections of the wall jet in Fig. 2.7(c) are self-similar, and resemble the previous findings of *Beltaos and Rajaratnam* [1973] and *Rajaratnam* [1976].

Fig. 2.7 (a) Sketch of a plunging jet overflowing a vertical drop; (b) Self-similarity plot of the jet mean velocity profiles on the demarcating cross section: $S = S_a$; and (c) Self-similarity plot of the mean velocity profiles for the deflected wall jet for the case of $Y_c/H = 0.383$; [*Lin et al.*, 2007]

Robinson et al. [2000] measured the flow pattern for a plunging jet overflowing a weir-like vertical drop, with a distinct difference to the previous case of *Lin et al.* [2007] that the tailwater was elevated to a much higher level. Therefore, a large anti-clockwise roller appears in the tailwater pool, as shown in Fig. 2.8. *Liu et al.* [1998a] carried out a study similar to that of *Robinson et al.* [2000], as sketched in Fig. 2.9(a), and also found a large anti-clockwise roller in the tailwater. The plunging jet in a tailwater pool has three distinct zones: (1) the submerged jet zone, where the jet decelerates gradually; (2) the impingement zone, where the plunging jet impinges on the flat bed and deflects from its original direction; and (3) the wall jet zone, where the deflected jet diffuses rapidly along the bed. Similar finding was reported by *Beltaos and Rajaratnam* [1973] on a submerged plunging jet that impinges perpendicularly on a flat solid surface. The finding that the maximum jet-wise velocities appear on the centerline of the plunging jet (Fig. 2.9(b)) differs from the previous study without the tailwater [*Lin et al.*, 2007] where the maximum jet-wise velocities appear on the outer surface of the plunging jet (Fig. 2.7(b)). Accordingly, Fig. 2.9(b) shows self-similar profiles of jet-wise velocity at cross sections along the plunging jet after the jet entry are symmetric about the centerline of the jet, instead of being symmetric about the mid-point of a particular cross-section as shown in Fig. 2.7(b).

Fig. 2.8 Sketch of the jet overflowing a vertical drop [*Robinson et al.*, 2000]

Fig. 2.9 (a) sketch of the plunging jet flow; (b) the mean velocity profile on cross sections in jet zone I; [Liu *et al.*, 1998a]

2.3 Flow structures in scour holes downstream of a submerged weir

As compared to the cases of jet on a solid flat bed, the concave profile of a local scour hole increases the complexity of the flow structures [Bey *et al.*, 2007; Hill and Younkin, 2006]. Studies on the flow fields in a local scour hole specifically caused by a plunging jet is rarely found in the literature, possibly for the following reasons. The conventional point-measurement technique, ADV, is not effective in measuring the flow fields in a scour hole caused by a plunging jet. This is because the plunging jet is constantly oscillating and causes far more dynamic flow fields than any other kinds of local scour hole features such as those caused by wall jets. Flow fields in a scour hole downstream of a submerged weir have been partially described in several studies whose focuses are more on other aspects of local scour problems rather than the flow fields [Adduce and Rocca, 2006; Meftah and Mossa, 2006]. Adduce and Rocca [2006] documented a large roller (recirculation) in the scour hole when they described the flow patterns in a scour hole downstream of a submerged weir. Meftah and Mossa [2006] measured the flow structures within a concave scour hole downstream of a submerged weir at the

equilibrium scouring stage (see Fig. 2.10). In Fig. 2.10(a), a large clock-wise roller (recirculation) appeared in the scour hole, and high turbulent regions are observed close to the upstream slope of the scour hole, as shown in Fig. 2.10(b).

Fig. 2.10 (a) Time-averaged velocities in the central longitudinal profile of the channel at the scouring equilibrium stage; (b) An example of the turbulence intensity $rms(u)$ (test T16); [Mefteh and Mossa, 2006]

Guan et al. [2014] focused on the flow structures for a submerged weir and also found the large roller and significant turbulent regions on the upstream slope of the scour hole, see Fig. 2.11. *Guan et al.* [2014] provided more details of the turbulence by presenting distributions of the turbulent components of each direction within the entire scour hole at the equilibrium scouring stage.

Fig. 2.11 (a) Velocity vectors distribution in the longitudinal centerline section; the distributions of (b) downstream; (c) transverse; (d) vertical components of turbulence intensity on the longitudinal centerline section; [*Guan et al.*, 2014]

2.4 Flow structures in scour holes caused by a wall jet

Many researchers studied the flow fields at the equilibrium stage within the local scour hole downstream of a sluice gate. In the scour hole, the predominant roller usually comes with a companion, a small counter-recirculating roller that attaches to the upstream slope, as shown in Fig. 2.12 [*Adduce and Sciortino*, 2006; *Albayrak et al.*, 2008; *Bey et al.*, 2007].

Fig. 2.12 Velocity vector plot in the local scour holes for (a) Test A; (b) Test B in the cases with a submerged plane jet downstream of a sluice gate; [Bey *et al.*, 2007]

Besides, turbulence boosts the scouring process greatly since it produces uplift which in turn reduces the virtual density of sediment [Chien and Wan, 1999; Jia *et al.*, 2001; Liu *et al.*, 1998b]. Similar to the cases of submerged weir mentioned earlier, Bey *et al.* [2007] found that the most turbulent area in the scour hole is located above the upstream slope, as shown in Fig. 2.13. In Fig. 2.13 x is the stream-wise coordinate and x_c is the jet-wise location of the maximum depth of the scour hole.

Fig. 2.13 Turbulent shear stress at various axial stations in the local scour hole caused by a submerged plane jet downstream of a sluice gate; [Bey *et al.*, 2007]

Albayrak *et al.* [2008] not only measured the predominant roller in the scour hole, but, more importantly, compared the turbulence near the concave profiles of the scour hole and that on a horizontal floor. Albayrak *et al.* [2008] investigated the turbulence on two sections after the impingement of the jet on the profile of the scour hole and that on two sections near a flat surface at equivalent distances from the jet nozzle. It is found that, interactively, the concave profiles of the scour hole generate Görtler vortices which further contribute to turbulence, as can be seen in Fig. 2.14.

Fig. 2.14 Dimensionless normal Reynolds stress profiles. (a) Longitudinal (x-component) normal Reynolds stress $\overline{u^2}/U_m^2$, and (b) cross-stream (z component) normal Reynolds stress $\overline{w^2}/U_m^2$. $\blacktriangle$, $x/b_0 = 6$; $\blacktriangleright$, $x/b_0 = 8$, for concave wall and $\triangle$, $x/b_0 = 4.75$; $\triangleright$, $x/b_0 = 7.75$ for flat wall [Albayrak *et al.*, 2008]

The findings of Hopfinger *et al.* [2004] support the findings of Albayrak *et al.* [2008]: Görtler vortices emerge in the unstable turbulent boundary layers on the concave

profiles of the scour hole. Görtler vortices produce significant turbulence in the boundary layer, and this turbulence excited by Görtler vortices plays the primary role of uplifting the sediment. *Hopfinger et al.* [2004] also found sediment streaks or longitudinal sediment ridges on the concave profiles of the scour hole, which corresponded to the curvature-excited streamwise vortices, see Fig. 2.14.

Fig. 2.14 Streamwise oblique view of the sediment surface showing 8 longitudinal sediment streaks or ridges on the upstream-facing scour-hole slope [*Hopfinger et al.*, 2004]

The concave profiles of local scour holes preserve self-similarity throughout the scour development, as can be seen in Fig. 2.15(a) [*Adduce and Sciortino*, 2006; *Ali and Lim*, 1986; *Dey and Sarkar*, 2006; *Hassan and Narayanan*, 1985; *Hill and Yountkin*, 2006; *Rajaratnam*, 1981; *Tregnaghi et al.*, 2007]. Figs. 2.15(b) shows that the self-similarity of the scour hole is well preserved with different aprons downstream of a sluice gate. On the other hand, only the small part of the wall jet on the apron was reported as self-similar before the jet enters the scour hole [*Albayrak et al.*, 2008; *Hassan and Narayanan*, 1985; *Hogg et al.*, 1997]. Fig. 2.15(c) shows mean velocity profiles at

cross-jet sections along the apron, which resemble a wall jet, see Figs. 2.3 and 2.7(c).

Fig. 2.15 Dimensionless scour profiles of wall jet for different (a) times of a single experiment, and (b) lengths of apron; (c) mean velocity distribution along the apron; [Hassan and Narayanan, 1985]

2.5 Evolutions of flow structures in a scour hole

The rapidly evolving scour hole transforms the flow fields significantly and continuously at the early and intermediate scouring stages; e.g., *Lee et al.* [2017]

revealed numerically that the small roller on the upstream slope grows with the development of the scour hole. It is difficult to measure the flow fields with conventional point measurement techniques, because the dynamic nature of the flow fields during the development of scour holes makes it difficult to perform such measurement. Several researchers attempted to study the evolution of the flow fields using fixed bed artificial scour holes to simulate steady scour holes [Dey and Sarkar, 2008; Hill and Younkin, 2006; Xie and Lim, 2015]. The artificial scour holes involve distortion from the original profiles and, more importantly, they stop the interactions of the scour hole with the flow fields while the interactions underpin the scour mechanism. Besides, the repetition and interruption of the flow certainly caused disruption to the flow fields.

Fig. 2.16 Fixed-bed models constructed to represent various stages of development of the scour hole and downstream dune [Hill and Younkin, 2006]

Hill and Younkin [2006] simulated the profiles of the scour hole at each of five representative points with a triangle made of polycarbonate sheets, as shown in Fig. 2.16. In the plots of flow pattern, as shown in Fig. 2.17, the clockwise roller gradually

shrank in the scour hole and the impingement point on the profile of the scour hole moves upstream, while the predominant anti-clockwise roller mentioned earlier was not presented [Hill and Younkin, 2006]. Furthermore, Hill and Younkin [2006] estimated the bed shear stress along the profiles of the scour hole using the measured data of the flow fields. Fig. 2.18 shows that the general shear stress along the profile decreases with time, which explains the deceleration of the rate of scour.

Fig. 2.17 Two-dimensional vector representation of mean velocity fields in the scour hole for the five fixed-bed models (a) to (e) which correspond to Profiles 1 to 5 of Fig. 2.16, respectively [Hill and Younkin, 2006]

Fig. 2.18 Variation of boundary shear with normalized alongslope distance [Hill and Younkin, 2006]

Dey and Sarkar [2008] studied the evolution of the flow fields by measuring the flow at several representative instants during the scouring process using ADV. They repeated the same experiments, stopped each experiment at the selected representative instant, and then froze the scour hole with synthetic resin, instead of replacement with simulating triangles. Virtually invariable flow fields were thus obtained at each representative instant for ADV measurements by resuming the experiment with the corresponding fixed scour holes. The flow patterns (Fig. 2.19) revealed that the predominant anti-clockwise roller appeared just on the apron, instead of being in the scour hole, throughout the scouring process. In Fig. 2.19, one can see that the main jet skipped the scour hole when flowing clear of the apron, unlike in the case of Hill and Younkin [2006] where the jet impinged on the downstream slope. This difference suggests that the presence of a long apron prevented the impingement effect of the jet on the scouring process. Dey and Sarkar [2008] revealed that a peak of bed shear stress appeared above the upstream slope and was in good agreement with previous studies [Bey *et al.*, 2007; Guan *et al.*, 2014], and the general bed shear stress along the profiles of the scour hole was below the critical values of sediment inception, as shown in Fig. 2.20.

Fig. 2.19 Normalized velocity vectors for run 4a having (a) flat bed condition; (b) intermediate scour hole with $0.3d_{se}$; (c) intermediate scour hole with $0.8d_{se}$; and (d) equilibrium scour depth with $d_{se}=0.062$ m; [Dey and Sarkar, 2008]

Fig. 2.20 Horizontal distributions of bed shear stress, $\hat{\tau}$, for run 4a having (a) flat bed condition; (b) intermediate scour hole with $0.3d_{se}$; (c) intermediate scour hole with $0.8d_{se}$; and (d) equilibrium scour depth with $d_{se}=0.062$ m; [Dey and Sarkar, 2008]

2.6 Flow structures of jet-flipping

Balachandar and Kells [1997] observed two flow regimes within a local scour hole downstream of a sluice gate, i.e. bed jet regime and surface jet regime. These two jet regimes exhibit two opposite actions, i.e. scouring and refilling, on the sediment bed. Figure 2.21(a) shows a sketch of the bed jet regime where the main jet attaches to and scours the sediment bed. However, the main jet attaches to the water surface in the surface jet regime, as can be seen in the sketch in Fig. 2.21(b), and a jet returning upstream attaches to the sediment bed corresponding to the refilling process. These two regimes alternate cyclically under certain hydraulic flow conditions. *Balachandar et al.* [2000] presented a visual observation of a typical cycle of jet-flipping, which starts at the end of a surface jet regime (Fig. 2.22(a)), and ends at the end of the next surface jet regime (Fig. 2.22(g)) and the beginning of a new digging phase (Fig. 2.22(h)).

Fig. 2.21 Schematic view (not to scale) of the flow field during (a) the digging process and (b) the refilling process; [*Balachandar and Kells*, 1997]

Fig. 2.22 Local scour cycle: (a) phase A: maximum fill; (b) digging phase begins, cycle begins; (c) digging continues; (d) phase B: maximum dig; (e) filling phase begins; (f) filling continues; (g) phase A: maximum fill; and (h) digging phase begins, cycle begins, [Balachandar *et al.*, 2000]

Xie and Lim [2015] made an improvement on the knowledge of the jet-flipping and measured the flow fields of jet-flipping. They used aluminum model to simulate the bed profile at the critical instants of switching jet regimes as shown in Fig. 2.23, and then used ADV to measure the flow patterns for jet-flipping phenomenon at those critical instants. Fig. 2.24 shows the initial cycle of jet-flipping. In the bed jet regime (Fig. 2.24(a and d)), the jet mainly attaches to and scours the bed, whereas, in the surface jet regime (Fig. 2.24(b and c)), the jet detaches from the bed and clings to the water surface, forming a returning jet that transports sediment back to refill the scour hole developed during the bed jet regime.

Fig. 2.23 Run 122: (a) Aluminum 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) Aluminum 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; [Xie and Lim, 2015]

Fig. 2.24 Flow field of Run 122 with (a) bed jet at the end of the first digging phase; (b) surface jet at the start of the second filling phase; (c) surface jet at the end of the second filling phase; (d) bed jet at the start of the third digging phase; [Xie and Lim, 2015]

CHAPTER 3 EXPERIMENTAL SETUP AND METHODOLOGY

3.1 Introduction

The present study used a Particle Image Velocimetry (PIV) system to capture the flow structures in scour holes caused by two types of jet flow: (a) a plunging jet and (b) a wall jet. Since the presence of an apron downstream of a free weir can cause jet-flipping, the plunging jet cases can be further divided into two categories: jet-flipping with an apron, and no jet-flipping without an apron. The three categories of experiments were conducted in a 5.0 m long, 0.3 m wide by 0.45 m deep open channel at the Maritime Research Centre, Nanyang Technological University, Singapore. However, the specific setup of the flume differs for each category of experiment, and is to be illustrated one by one in latter sections. The two side walls of the flume were made of glass to allow for optical access. The channel bed consists of two parts, an erodible bed and a non-erodible bed. The erodible bed is 1.4 m long by 0.16 m deep and composed of non-cohesive brown-colored sand with diameter $d_{50} = 0.77$ mm. The relative density of sediment $\Delta = 1.65$, see Fig. 3.1. Figure 3.2 shows that the sediment size distribution is well sorted, with a sediment gradation $\sigma_g = 1.21$ ($\sigma_g = \sqrt{d_{84.1}/d_{15.9}}$).

Fig. 3.1 Bed sediment sample ($d_{50} = 0.77$ mm)

Fig. 3.2 Sediment size distribution for the present study

3.2 Experimental flume for the case of a plunging jet without jet-flipping

Fig. 3.3 Schematic diagrams of experimental setup for the case of plunging jets: (a) Plan view and (b) Side view; all dimensions are in mm.

The weir used was a 10 mm-thick rectangular Perspex plate, 100 mm in height, and spanned the full width of the channel. A sketch of the experimental setup is shown in Figs. 3.3(a and b). A Cartesian coordinate system is used and the coordinates, x , y and z , denoting the longitudinal, vertical and spanwise directions, respectively. A total of 15 cases under steady flow conditions were carried out over a range of flowrates ($Q = 0.5$ to 1.5 L/s) and tailwater depths ($H = 30$ to 90 mm). The corresponding Reynolds number and densimetric Froude number, denoted by Re and F_r , ranged from 2483 to 4965, and from 4.5 to 8.0, respectively. These parameters were calculated using Eqs. 3.1(a) to 3.1(e).

$$U_e = C_o \sqrt{2g(h_o + 1.5y_c)} \quad (1a)$$

$$y_c = \sqrt[3]{\frac{\alpha q^2}{g}} \quad (1b)$$

$$q = U_e y_e \quad (1c)$$

$$Re = \frac{U_e y_e}{\nu} \quad (1d)$$

$$F_r = \frac{U_e}{\sqrt{\Delta g d_{50}}} \quad (1e)$$

where U_e = average velocity at the entry point; C_o = velocity coefficient and a value of 0.672 was proposed by *Dey and Raikar* [2007]; g = gravitational acceleration; h_o = height of weir above the tailwater surface; y_c = critical water depth at upstream of the weir; α = kinetic energy coefficient which is approximately equal to 1.0 [*Zhao et al.*, 2009]; q = discharge per unit width; y_e = the width of the plunging jet at the entry point; ν = kinematic viscosity ($= 1.007 \times 10^{-6} \text{ m}^2/\text{s}$); and d_{50} = median particle diameter. This study presents the results (see Chapter 4) for a typical case ($Q = 1.5$ L/s, $H = 50$ mm, $Re = 4965$ and $F_r = 7.1$) for two reasons. Firstly, this case includes most of the key features observed in the other cases. Secondly, the scour development can be captured clearly where the scour hole is always completely covered by the view of the camera.

3.3 Experimental flume for the case of a plunging jet with jet-flipping

Fig. 3.4 Schematic diagrams of experimental setup for the case of plunging jets with an apron: (a) Plan view and (b) Side view; all dimensions are in mm.

Figs. 3.4(a and b) provide a sketch of the experimental setup for the case of plunging jet with an apron. The weir used was 100 mm in height, made of a 10 mm-thick rectangular Perspex plate, and spanned the full width of the flume. The length of the apron is defined as the distance from the weir to the borderline between the erodible and non-erodible beds. The tailwater depth is the water depth far downstream from the deposited mound (Section CC in Fig. 3.4). A Cartesian coordinate system is used to describe the scour hole, with the coordinates, x , y and z , denoting the longitudinal, vertical and spanwise directions, respectively. In order to cover more area of interest in the scour hole for the jet-flipping case, the measurement range was from $x = 10$ mm to 290 mm downstream of the weir, instead of starting from $x = 0$ mm to 280 mm (see figures to be presented in Chapter 5).

A total of 28 cases under steady flow condition were carried out over a range of

flowrates ($Q = 1.5$ to 2.5 L/s) and tailwater depths ($H = 30$ to 90 mm) for three apron lengths ($L = 50, 100$ and 150 mm). Jet-flipping was observed in cases with $L = 100$ mm and 150 mm, but not with $L = 50$ mm. This study presents the results of two typical cases: Run 1 ($Q = 1.5$ L/s, $H = 50$ mm and $L = 100$ mm); and Run 2 ($Q = 1.5$ L/s, $H = 55$ mm and $L = 100$ mm). For each run, multiple jet-flipping events were observed and the number of occurrences of jet-flipping (at least 10 cycles) was high enough to allow numerous attempts to clearly capture the momentary transitions. Run 1 was performed for 19 hours and intended to capture the upward flipping (transition from the bed jet regime to the surface jet regime), while Run 2 lasted for 2 hours to capture the downward flipping (transition from the surface jet regime to the bed jet regime).

3.4 Experimental flume for the case of a submerged wall jet

Fig. 3.5 Schematic diagrams of experimental setup for the case of a submerged wall jet below a sluice gate: (a) Plan view and (b) Side view; all dimensions are in mm

Figures. 3.5(a and b) show the experimental setup for the case of local scour caused by a submerged wall jet below a sluice gate with an apron. The sluice gate was made of a 10

mm-thick Perspex plate and was set with its lower edge 10 mm from the non-erodible bed, i.e. the sluice gate opening was $b = 10$ mm. The apron length, $L = 50$ mm, was the horizontal distance from the sluice gate to the erodible bed. The tailwater depth, H , was measured far downstream at Section CC as shown in Fig. 3.5. A Cartesian coordinate system is used, with the coordinates, x , y and z , denoting the longitudinal, vertical and spanwise directions, respectively.

The experiments were conducted for 3 tailwater depths ($H = 50, 70$, and 100 mm) and 2 constant flowrates ($Q = 2$ L/s and 2.5 L/s). This study focuses on the high submergence case ($H = 100$ mm) which is typical in engineering practice and has relatively steady flow fields. Results of the case ($Q = 2$ L/s, $H = 100$ mm) were presented herein, since the scour hole generated with the other flowrate ($Q = 2.5$ L/s, $H = 100$ mm) is far beyond the view of the camera coverage. Repeatability of the results, especially at the early and intermediate scouring stages, was confirmed by performing the experiments twice, which were reported as Run 1 and Run 2.

3.5 Particle Image Velocimetry (PIV) system

A digital PIV system (LaVision model) was used to measure the velocity distributions in the scour hole. The flow field was illuminated by a double-cavity Nd:YAG laser (Litron model, wavelength of 532 nm, power of 135 mJ per pulse and pulse duration of 5 ns), which was manufactured by Litron (Rugby, United Kingdom). As can be seen in Figs. 3.3(b), 3.4(b) and 3.5(b), the laser sheet (about 1 mm in thickness) was projected downwards from above the channel in the x - y plane, 50 mm from a side wall, as denoted by AA in Figs. 3.3(a), 3.4(a) and 3.5(a). This AA section, instead of the centerline section (denoted by BB), was chosen for PIV measurements mainly due to the following reasons. The non-cohesive bed consists of natural silica sand grains, and despite having been washed several times, the water recirculating in the channel was still turbid. The resulting particle images at Section BB with a larger spanwise distance were not as good as those at Section AA. Hollow glass spheres with diameter of 10–15 μm and relative density of 1.05–1.15 were used as tracer particles. The seeding density was about 5–10 particles/ mm^2 , which was sufficient to yield strong correlations [Raffel *et al.*, 2007]. The particle images were recorded using a 14-bit CCD camera with a

resolution of 1600×1200 pixels and a sampling frequency of 14 Hz, and the CCD camera was mounted on one side of the channel, see Figs. 3.3(a), 3.4(a) and 3.5(a). The time duration for a continuous sampling can be up to 12 seconds due to limitation on the memory of the camera, and an average of 20 seconds (storage interval) was required to store the images to a hard disk via the computer.

The particle images were recorded and evaluated using double-frame/double-exposure mode. Depending on the speed of the plunging jet at entry, the time interval between every pair of laser pulses was varied from 900 to 2000 μ s, yielding a maximum displacement of about 7 pixels in the jet core region, which satisfied the criterion proposed by *Boillot and Prasad* [1996]. LaVision Davis software was employed to process the particle images. The particle displacements were calculated using a cross-correlation algorithm with standard Gaussian sub-pixel fit structured as an iterative multi-grid method. The image processing procedure included two passes, starting with a grid size of 64×64 pixels and stepping down to the final interrogation area (IA) of 32×32 pixels overlapping by 50%, resulting in a set of 7500 vectors (100×75) for a typical field. The field of view was 280 mm $\times$ 210 mm for the weir cases and 350 mm $\times$ 262.5 mm for the sluice gate cases. Therefore, the spatial resolutions for the present measurements were 2.8×2.8 mm² and 3.5×3.5 mm², respectively. In between passes, the vector maps were filtered using a 3×3 median filter in order to remove possible outliers.

For each measurement, a set of 168 pairs of particle images were acquired at a frequency of 14 Hz (i.e., 12 seconds of recordings) and then processed to obtain 168 instantaneous velocity vector fields. The uncertainty in the instantaneous velocities (u , v) was estimated to be about 3%. In the present study, the statistical characteristics of the flow (including the mean velocities $\bar{u}$ and $\bar{v}$, and the Reynolds shears stresses $\overline{u'u'}$, $\overline{v'v'}$ and $\overline{u'v'}$) were obtained using ensemble averaging of the 168 instantaneous fields for the cases without jet-flipping. Following the procedure proposed by *Scarano and Riethmuller* [1999] for error analysis of data due to finite number of PIV samples, the uncertainties for the mean velocities (U and V) and the Reynolds shears stresses ($\overline{u'u'}$, $\overline{v'v'}$ and $\overline{u'v'}$) were about 6% and 12%, respectively.

To ensure capturing the flow fields at the significantly transforming stages, the measurements were taken continuously within the 1st hour of the start of scour in the experiments. Specifically, a measurement was taken immediately after the previous measurement was stored (average interval of 20 seconds). Throughout the entire study, the bed profile is even and uniform along the spanwise direction during the experiments, indicating that the flow inside the scour hole is 2-dimensional (2-D) in x-y plane. Furthermore, PIV measurements at different x-y planes confirmed that the majority of the flow is 2-D, and that wall effects are limited to a narrow region of approximately 10 mm from either side wall.

Convergence tests confirmed that this number of samples ($N = 168$) was sufficient to achieve reasonably converged statistics for both the 1st-order moments ($N > 50$), i.e. the mean velocities and AKE, and the 2nd-order moments ($N > 90$), i.e., TKE and RSS. On the other hand, the jet-flipping phenomena, though momentary and intermittent in nature, were repetitive from cycle to cycle in terms of the scour hole shape and overall flow patterns. The flow at a given instant of the jet-flipping cycle is largely quasi-steady within a duration of 1 – 3 s. Accordingly, 20 to 40 images taken for the duration were ensemble-averaged to obtain a representative snapshot of flow patterns for the particular instant in the jet-flipping cycle. The vortex parameters such as strength (circulation) and size did not vary by more than 10%. Therefore, this number of images, each taken at intervals of $\frac{1}{14}$ s, were considered sufficient to obtain the ensemble-averaged properties of the flow.

3.6 Applicability of PIV in measuring flow fields on a movable bed

Great care was taken to capture the particle images, especially for the measurements of flow fields in a scour hole caused by a plunging jet. Fig. 3.6(a) gives an example of a typical snapshot for such a case. Overall, the quality of the particle images is good as the seeding particles, appearing as bright dots because of light scattering, are readily identified. However, due to the disturbance of the plunging jet, it is noted that the water surface becomes wavy, which results in a non-uniform distribution of laser light power and hence affects the quality of the particle image. This situation is particularly severe in the upper left corner of the image, where the light is relatively weak and the density

of seeding particles is considerably lower. Also, there is some light reflection on the water surface and the bed, which undermines the effect at identifying the effective particles and hence the credibility of the calculated velocities at those regions near both the water surface and the bed. Combined with the other snapshot of the image pair (with similar quality, not shown here for brevity), the instantaneous velocity field (u , v) can be obtained, as shown in Fig. 3.6(b). A careful comparison of Fig. 3.6(a) and Fig. 3.6(b) could build up the linkage between the original image and the calculated velocities. At some regions very near the water surface and the bed, the velocity data are insignificant, because of the lack of seeding particles at those regions as shown in the particle image. Also, the velocity vectors in the upper-left corner (including the jet column and the jet entry region) are substantially underestimated in magnitude, which is also attributed to the insufficient density of seeding particles.

The fidelity of the PIV measurements has been carefully checked. Admittedly, in some regions, particularly in the upper left corner of the images for the plunging jet case, the density of seed particles is considerably low, which undermines the fidelity of the calculated velocities there. It is confirmed that for most region of the image, the seeding density (about 10 particles per interrogation area according to the recommendation by *Raffel et al.* [2007]) is enough to yield strong correlation. For the wall jet case, the jet is issued beneath the water surface which significantly reduces the disturbance on the water surface compared to the plunging jet cases. Therefore, the quality of particles images is better than those of the plunging jet case.

Fig. 3.6 (a) Typical particle image and (b) calculated instantaneous velocity vector field (u, v) of an experiment ($Q = 1.5 \text{ L/s}$; $H = 50 \text{ mm}$ and $t = 18199 \text{ s}$)

CHAPTER 4 FLOW STRUCTURES IN SCOUR HOLES CAUSED BY A PLUNGING JET

4.1 Introduction

A plunging jet may cause local scouring at the downstream channel bed. Local scouring is initiated at a rapid rate at the early scouring stage, then slows gradually through the intermediate scouring stage and finally stops at the equilibrium scouring stage when the scour hole attains the maximum size [Xie and Lim, 2015]. This chapter examines the evolving flow structures in scour holes caused by a plunging jet at each of the scouring stages.

Fig. 4.1 Temporal development of the maximum scour depth for the case with a plunging jet ($Q = 1.5$ L/s and $H = 50$ mm)

Figure 4.1 shows the temporal development of the scour hole: the scour hole depth, d_s , increases sharply before point S_1 , i.e., the early scouring stage, and that the rate of increase becomes insignificant after point S_2 , i.e., the asymptotic equilibrium scouring stage. The intermediate scouring stage is in between points S_1 and S_2 . Three measurements of the flow fields were taken at points M1 ($t = 61$ s ~ 72 s), M2 ($t = 1363$ s ~ 1374 s) and M3 ($t = 18191$ s ~ 18202 s) in the early, intermediate and equilibrium

scouring stages, respectively.

Four aspects of the evolving flow structures in the scour hole are presented in this chapter: (1) flow patterns in Section 4.2; (2) average kinetic energy (AKE) in Section 4.3; (3) turbulent kinetic energy (TKE) in Section 4.4; and (4) Reynolds shear stress (RSS) in Section 4.5. The flow patterns reveal a dynamic roller system versus the scour development; AKE is actually a representation of the velocity distributions for an incompressible fluid. TKE depicts the intensity of turbulent fluctuations, and RSS reflects the flux of turbulent momentum [Guan *et al.*, 2014; Meftah and Mossa, 2006; Zhao *et al.*, 2009]. In Section 4.6, a new perspective on the scour hole mechanism is elucidated: the scour stops due to reduced capability of jets for sediment transport, instead of the bed shear stress being lower than the critical value. Finally, a summary is given in Section 4.7.

The turbulence parameters, i.e. AKE, TKE and RSS, are calculated as follows

$$\text{AKE} = \frac{\bar{u}^2 + \bar{v}^2}{U_0^2} \quad (4.1a)$$

$$\text{TKE} = \frac{\overline{u'^2} + \overline{v'^2}}{U_0^2} \quad (4.1b)$$

$$\text{RSS} = \frac{-\overline{u'v'}}{u_*^2} \quad (4.1c)$$

where $\bar{u}$, $\bar{v}$ are mean velocities and u' , v' are fluctuating velocity components, in the longitudinal and vertical directions, respectively; U_0 and u_* are the average flow velocity and the average shear velocity at a far downstream section where the tailwater depth is set at 50 mm (Section CC in Fig. 3.3). It should be noted that the triangular region in the upper left corner of the figures in the following sections is omitted for the analysis of AKE, TKE and RSS, because of the substantial underestimation in velocity as explained in Section 3.6. The dashed line demarcating this triangle is just a nominal limit based on a visual check of the original particle images and the calculated velocity fields.

4.2 Flow Patterns

Figure 4.2 exhibits a qualitative sketch of the definitive flow patterns clarifying several concepts introduced in this study. It is found that, at each scouring stage, the flow patterns inside the scour hole are largely quasi-steady. Figures 4.3(a-d) show the flow patterns in the evolving scour hole at different stages of scouring. The plunging jet impinges at point S on the bed and then splits into two parts: the main jet and the minor jet. The minor jet forms a clockwise “captive roller” (Fig. 4.2) which is held captive below the plunging jet. On the other hand, the main jet is deflected upwards, detaches from the downstream slope at the detachment point (Fig. 4.2) and splits into three component jets when reaching the water surface. The surface returning jet (Fig. 4.2) is deflected upstream to re-join the plunging jet constituting a large anti-clockwise “major roller”. The tail jet (Second C.J. in Fig. 4.2) flows downstream along the channel. The bed returning jet (Fig. 4.2) turns clockwise to form the “bed roller” on the upper part of the downstream slope (UDS in Fig. 4.2). The findings are in good agreement with previous findings [Bennett *et al.*, 2000; Hoffmans and Verheij, 1997; Jia *et al.*, 2001; Liu *et al.*, 1998a; Robinson *et al.*, 2000], in which two rollers, i.e., the major and captive rollers, were observed. In addition, Hoffmans and Verheij [1997] documented the presence of the bed roller.

Fig. 4.2 Sketch of flow patterns in the scour hole caused by a plunging jet

Fig. 4.3 Average velocity fields during the scour hole development within the inclusive time span of (a) 61 s to 64 s; (b) 66 s to 68 s; (c) 1363 s to 1374 s; (d) 18191 s to 18202 s

The present PIV measurements also reveal a small transient anti-clockwise roller (“intermittent roller” in Fig. 4.2) on top of the upstream slope as shown in Fig. 4.3(a). Meanwhile, the plunging jet impinges on the bed profile relatively far downstream at around $x = 120$ mm, and the captive roller occupies the bottom of the scour hole. At the 65th second in Fig. 4.3 (b), the impingement point S shifts upstream drastically to around $x = 40$ mm, and the intermittent roller disappears. Accordingly, the measurement at M1 in the early scouring stage is separated into two sub-timespans of 4 and 3 seconds, represented by Figs. 4.3(a and b), respectively; but not so for M2 and M3, i.e., Figs. 4.3(c and d).

To the best of the authors' knowledge, this is the first work that clearly shows the presence of these four types of rollers in an evolving scour hole. Each of the four rollers plays a role in the scouring process and shapes a specific segment of the scour hole profile, as shown in Figs. 4.3(a-d). The major roller dominates the scouring process: a predominant portion of the uplifted sediments are scoured from the lower part of the downstream slope (LDS in Fig. 4.2), and almost only this portion of sediments is possible to be transported outside the scour hole. The bed roller shapes upper part of the downstream slope (UDS in Fig. 4.2) by assisting sediment rolling back slightly. A detachment point appears on the downstream slope (DS) at the interface where the bed roller and the major roller meet with each other. The captive roller mainly scours the upstream slope (US in Fig. 4.2), and the scoured sediments either fall back on the slope or enter the plunging jet. Sometimes, the captive roller scours the bottom of the scour hole to a degree that enough space is created beside it for the formation of an intermittent roller. The intermittent roller, though not strong enough to transport sediment, makes gentler the upper part of the upstream slope by preventing it from being continuously scoured by the captive roller.

The plunging jet in this study deviates from its original issuing direction at the entry point on the water surface as shown in Figs. 4.3(a-d). The actual direction of the plunging jet is marked by a curved dash-dot line leading to S, whereas the original issuing direction is denoted by a straight long-dash line. However, the published studies on a plunging jet in tailwater pool with a solid flat bottom [*Albertson et al.*, 1950; *Beltaos and Rajaratnam*, 1973; *Liu et al.*, 1998a; *Rajaratnam*, 1976; *Robinson et al.*,

2000] reported that the jet almost always sticks to its issuing direction. This disparity implies that the rollers in a concave scour hole have relatively stronger effect on the plunging jet than those in the case of a solid flat bottom.

4.3 Distributions of Average Kinetic Energy (AKE)

Figures 4.4(a-c) present the AKE distributions in the early, intermediate and equilibrium scouring stages, respectively. For clarity, the capital letters, A, B, C, D, E, F, H, J, K, M, P, Q, S, T and W, are used to denote various fixed locations in the scour hole. Three characteristic zones can be distinguished for the flow in the scour hole: (i) the plunging jet zone (i.e., from T to A), which exhibits contradictory characteristics compared to previous studies [*Beltaos and Rajaratnam*, 1973; *Liu et al.*, 1998a]; (ii) the bed impingement zone (i.e., from A via B to C), which is, however, in line with those of the previous studies; and (iii) the free-surface impingement zone (denoted by D), which has been hardly mentioned in the literature. The presence of this zone is attributed to the concave profile of the scour hole, which continuously deflects the main jet vertically upward to impinge the water surface. By contrast, the third zone is the wall jet zone (referring to the deflected jet along the bed) in previous studies with a flat solid bed [*Beltaos and Rajaratnam*, 1973; *Liu et al.*, 1998a].

4.3.1 Plunging jet zone

The plunging jet at its entry has an $AKE = 63.5$ estimated using Eq. 1a to 1c. It then undergoes a distinct drop in velocity and a subsequent acceleration from T to A (Figs. 4.4(a-c)). This observation is different from findings in the literature, where a jet decelerates monotonically with distance from the jet entry point [*Albertson et al.*, 1950; *Beltaos and Rajaratnam*, 1973; *Liu et al.*, 1998a; *Rajaratnam*, 1976]. Another major disagreement is that the measured peak AKE ($= 6.0$ or 7.0) at region A in Figs. 4.4(a-c) is substantially lower than the corresponding calculated values using previous findings [*Albertson et al.*, 1950; *Beltaos and Rajaratnam*, 1973; *Liu et al.*, 1998a]. The calculated AKE at region A should be around 32, which is about half the value ($AKE = 63.5$) at the jet entry point; while the measured AKE ($= 6.0$ or 7.0) is only about 1/10 of the incoming AKE ($= 63.5$).

Fig. 4.4 Distributions of AKE during the scour hole development within the inclusive time span of (a) 61 s to 64 s; (b) 1363 s to 1374 s; (c) 18191 s to 18202 s, which correspond to the flow fields of Figs. 4.3 (a), (c) and (d), respectively

These disagreements are believed to be associated with the formation of the major and captive rollers. Aside from the deviation of the plunging jet from the issuing direction (Figs. 4.3(a-d)), the temporal development of the scour in Fig. 4.1 suggests strong effect of the rollers on the plunging jet. The scour hole progresses rapidly by 40 mm in depth within the first 10 seconds as indicated by point A in Fig. 4.1. The rollers are undeveloped and limited to the very bottom of the small and narrow scour hole. Thereafter, the rollers are observed to expand outside the enlarging scour hole and to affect the plunging jet immediately upon its entry into the tailwater. The scouring rate decreases markedly as shown by points B and M1 in Fig. 4.1.

The First CJ and the minor jet re-join the plunging jet almost orthogonally, and their collisions dissipate the total energy considerably. The plunging jet further decreases in velocity with a substantial increase in mass upon the merging of the colliding jets (conservation of momentum). After merging, the flow is accelerated (from T to A) by the incoming plunging jet with high kinetic energy. It is probably also by the increasingly narrow passage between the major and captive rollers, whose centers are denoted by F and W (Figs. 4.4(a-c)), respectively. The peak AKE region A appears between F and W where the passage is the narrowest. The lowest boundary in region A can be considered as the end of the plunging zone and the start of the impingement zone, because AKE starts to decrease rapidly due to impingement on the bed [*Beltaos and Rajaratnam*, 1973; *Liu et al.*, 1998a].

4.3.2 Bed impingement zone

As shown in Figs. 4.4(a-c), the main jet undergoes continuous deceleration and deflection from A to B, and then accelerates to a maximum velocity at region C, which is the end of the impingement zone. This observation is consistent with the previous studies that the favorable pressure gradients due to jet impingement on the bed decelerate and deflect the jet first, and then accelerate the jet after deflection [*Beltaos*, 1976a; *Beltaos and Rajaratnam*, 1973; *Fiorotto et al.*, 2014; *Liu et al.*, 1998a]. Furthermore, as shown in Fig. 4.4(a), the main jet in the early scouring stage can be

separated by an imaginary line through B and C into two layers. The lower layer jet attaching to the bed profile starts acceleration immediately from S to H (a point on the scour profile to which BH is normal), much earlier than the upper layer jet which starts from B after a deceleration. Similar flow behaviors were reported by *Beltaos and Rajaratnam* [1973] that the pressure decreases with distance from the impingement point and the lower layer jet accelerates earlier than the upper one. This agreement with the literature further validates the data in the present study. The acceleration of the lower layer jet, however, disappears in the intermediate and equilibrium scouring stages (Figs. 4.4(b-c)). The plunging jet is then subject to increasing energy dissipation in the impingement zone and the deflection along the bed profile segment SH with greater curvature, compared to that in the early scouring stage (Fig. 4.4(a)).

4.3.3 Free-surface impingement zone

The main jet also impinges on the water surface and produces a similar impingement zone, denoted by D (Figs. 4.4(a-c)). This observation is interesting as it has hardly been documented in previous studies. Similar to the bed impingement zone, significant pressure gradients near the free surface deflect and accelerate the First and Second CJs to generate the peak AKE regions at E and J or M, respectively. The acceleration of the Second CJ from D to M or J is perhaps easily misunderstood to be caused by gradually narrowing the jet passage with the rise of bed profile. The presence of the bed roller beneath the Second CJ eliminates this possible misconception because the rise of the bed profile affects only the returning jet of the bed roller, i.e., the Third CJ. The Second CJ is accelerated by the rise of the bed profile just after the bed roller disappears at $x \approx 210$ mm and 255 mm in Figs. 4.3(a and c), and correspondingly at the P cross-section in Figs. 4.4(a-b), respectively. The bed roller disappears at a point outside the view range of Figs. 4.3(d) and 4.4(c), as the mound shifts further downstream (at $x \approx 373$ mm) in the equilibrium scouring stage. With the temporally enlarging distance from D to P, the continuous acceleration region from D to M in the early scouring stage (Fig. 4.4(a)), splits into two separate regions J and M from the intermediate scouring stage (Fig. 4.4(b)).

4.3.4 Summary of AKE distributions

The major roller is formed by the main jet returning to the plunging jet after deflections at various points from S to H along the concave bed profile and on the water surface. Hence, the major roller contains most of the energy brought into the scour hole by the plunging jet, as clearly shown in Figs. 4.4(a-c). This is the core difference between this study and the previous studies [Beltaos, 1976a; Beltaos and Rajaratnam, 1973; Liu *et al.*, 1998a] on a plunging jet in tailwater pool with a solid flat bed. In the literature, the main jets after deflection at a single point, i.e. the impingement point, just flow along the flat bed and do not impinge the water surface to affect the plunging jet. Meanwhile, the rollers on both sides of the plunging jet are formed due to the surrounding fluid entrainment by the plunging jet and the main jets. In the present study, the major roller and the captive roller scour the bed, but also mitigate the scouring action by impacting on the plunging jet. On the other hand, the intermittent roller and the bed roller formed by fluid entrainments exert insignificant scouring effects on the bed.

4.4 Distributions of Turbulent Kinetic Energy (TKE)

Figs. 4.5(a-c) present the TKE distributions in the early, intermediate and equilibrium scouring stages, respectively. TKE falls into three ranges in terms of magnitude: high regions with $TKE \geq 2.0$, low regions with $TKE \leq 1.0$ and intermediate regions with $TKE = 1.5$. Generally, the TKE distributions match the previous works in that relatively high TKE regions are located above the upstream slope of the scour hole and that TKE gradually decreases downstream [Guan *et al.*, 2014; Meftah and Mossa, 2006]. The present study adds more detail that TKE generally decreases downstream along the jet direction to low regions ($TKE \leq 1.0$) at B where the main jet is fully deflected by the concave scoured bed.

This study also reveals the linkages between TKE, AKE and the flow patterns. In the early (Figs. 4.4(a) and 4.5(a)) and intermediate (Figs. 4.4(b) and 4.5(b)) scouring stages, the high TKE (≥ 2.0) regions coincide with the regions of significant AKE gradient, viz., just between A and W on the upstream side of the plunging jet. Jet collisions contribute to the high TKE regions, in addition to the pronounced AKE gradients.

Consistently in the equilibrium scouring stage (Figs. 4.4(c) and 4.5(c)), the intermediate TKE ($= 1.5$) regions on the upstream side of A cover the favorable AKE gradient regions and are higher than that on the downstream side, although the high TKE (≥ 2.0) regions are located above A. The observations are partially supported by the findings in *Liu et al.* [1998a] where pronounced pressure gradients and relatively high turbulence were found on both sides of the plunging jet.

As the scouring progresses, the significant TKE (> 1.0) regions develop successively off the vicinity of the scour hole profile. In the early scouring stage as shown in Fig. 4.5(a), the high TKE (≥ 2.0) regions initially extend over most of the scour hole depth, when all contours of significant TKE ($= 2.0, 1.5$ and 1.0) are close to each other in proximity to the bed profile. Thereafter in the intermediate scouring stage (Figs. 4.5(b)), the high TKE ($= 2.0$) contour stops growing in length at around $y = -50$ mm and develops obviously away from the profile, while the intermediate TKE ($= 1.5$) and low TKE ($= 1.0$) contours remain near the profile. Finally, intermediate TKE ($= 1.5$) develops away from the bed profile while low TKE ($= 1.0$) remains close to the profile in the equilibrium scouring stage (Fig. 4.5(c)).

Fig. 4.5 Distributions of TKE during the scour hole development within the inclusive time span of (a) 61 s to 64 s; (b) 1363 s to 1374 s; (c) 18191 s to 18202 s, which correspond to the flow fields of Figs. 4.3 (a), (c) and (d), respectively.

4.5 Distributions of Reynolds Shear Stress (RSS)

Fig. 4.6 Distributions of RSS during the scour hole development within the inclusive time span of (a) 61 s to 64 s; (b) 1363 s to 1374 s; (c) 18191 s to 18202 s, which correspond to the flow fields of Figs. 4.3 (a), (c) and (d), respectively.

Figures. 4.6(a-c) present the RSS distributions in the early, intermediate and equilibrium scouring stages, respectively. Generally, the RSS distributions match previous works in that relatively high absolute RSS regions, similar to the high TKE regions, are located above the upstream slope of the scour hole [Guan *et al.*, 2014; Meftah and Mossa, 2006]. The present study takes a step further to investigate the relationship between RSS and TKE distributions in the evolving scour hole.

RSS is linked to TKE because both are caused by velocity fluctuations. Similarly, the absolute RSS (negative) values in the plunging jet zone are higher than that in any other zones within the scour hole (Figs. 4.6(a-c)), indicating that momentum exchange over there is the most intense. The peak negative RSS regions ($RSS = -80$ or -120) are centered approximately at $(x, y) = (65 \text{ mm}, -10 \text{ mm})$ since the intermediate scouring stage (Figs. 4.6(b and c)). Furthermore, the high RSS regions ($|RSS| > 30$) are confined in the regions of $TKE > 0.5$, which can be explained with Eqs. 4.1(b and c) and the double-angle identity ($\sin 2\alpha = 2 \sin \alpha \cos \alpha$).

Despite the correspondence, RSS is distinctly different from TKE because the former is governed by the distribution of fluctuations in the two orthogonal components, i.e., u' and v' . The peak negative RSS ($= -80$) regions, though included in the high TKE (≥ 2.0) regions, do not coincide exactly with the peak TKE ($= 2.5$ or 3.0) regions (Figs. 4.5 and 4.6). Moreover, the magnitude of RSS on the upstream side of the plunging jet is roughly equal to (Figs. 4.6(a and b)), or even lower than (Fig. 4.6(c)) that on the downstream side, which is opposed to the observations in Figs. 4.5(a-c) that TKE on the upstream side of the jet is always higher.

In the early scouring stage (Fig. 4.6(a)), the peak positive RSS ($= 35$) region appears on the downstream slope from S to H, where the corresponding $TKE = 0.5$ contour is attached to the bed (Fig. 4.5(a)). This peak positive RSS region disappears in the intermediate scouring stage (Fig. 4.6(b)), because of reduced jet impingement effect. However, Fig. 4.6(b) shows that the peak positive RSS ($= 32$) is formed above Q in the bed roller zone (see also Fig. 4.3 (c)) and another relatively high positive RSS ($= 20$) region just behind H on the bed profile. In the equilibrium scouring stage (Fig. 4.6(c)), the peak RSS ($= 31$) expands substantially in the bed roller zone while the high RSS ($=$

20) region behind H shrinks significantly.

A projection of negative RSS regions is controlled by three points, B, C and F; the absolute RSS values in the projection are apparently less than that in the plunging jet zone (Figs. 4.6(a-c)). Consider a right-handed coordinate system where the z-axis points vertically outward from the paper (the x-y plane), x-axis is tangential to and y-axis normal to flow directions. The shapes of this projection and the positive RSS regions generally comply with the features of turbulent shear flow. For a turbulent shear flow where mean-flow shear maintains persistent turbulence, a positive mean velocity gradient always leads to positive RSS value ($-\overline{u'v'} > 0$) and negative velocity gradient causes negative RSS values ($-\overline{u'v'} < 0$) [Kundu *et al.*, 2011; Zhao *et al.*, 2009]. However, this does not hold in the plunging jet zone where jet collision, other than mean-flow shear, is the main contributor to turbulence.

4.6 Scour mechanism for plunging jets

Many studies have indicated the importance of the bed shear stresses along the bed profile in initiating sediment motion, and the stresses decrease below the critical value for sediment motion when a local scour hole reaches the equilibrium stage [Bey *et al.*, 2007; Fiorotto *et al.*, 2014; Guan *et al.*, 2014; Hill and Younkin, 2006; Hoffmans and Booij, 1993; Hopfinger *et al.*, 2004; Stein *et al.*, 1993]. In the present study, however, the local bed shear stresses were found to remain higher than the critical value even in the equilibrium scouring stage: the profile of the scour hole is constantly transforming, especially with the intermittent occurrence of Group 2 sediment (to explain later) and the movement of sediment back and forth within the scour hole. The scour hole stops growing in depth in the equilibrium scouring stage, mainly because the initiated sediments cannot be transported out of the scour hole. Therefore, this study provides a new perspective in terms of sediment transportation and sheds some light on the scour mechanism in such a scour hole.

A major portion of sediment is uplifted by the major roller in the jet impingement zone on the bed, caused by the combined effects of large pressure gradients and significant bed shear stress [Beltaos, 1976a; Hill and Younkin, 2006; Stein *et al.*, 1993]. The

uplifted sediments can be classified into three groups based on their movements: (a) Group 1 sediments moving upstream and recirculating with the major roller; (b) Group 2 sediments being entrained towards downstream but falling back onto the downstream slope of the scour hole; and (c) Group 3 sediments being successfully transported out of the scour hole and over the top of the downstream mound. Only Group 3 contributes to the growth of the scour hole, while Groups 1 and 2, though initiated from the bed, do not.

Literature reported that the capability of sediment transportation is positively correlated to jet velocity, and that turbulence facilitates sediment transportation by considerably reducing the virtual weight of sediment [Chien and Wan, 1999; Jia *et al.*, 2001; Stein *et al.*, 1993; Zhang, 2008]. Figs. 4.4(a-c) reveal a gap between two jet regions with high capacity of sediment transport, i.e. the peak AKE region C and another peak AKE region M. The sediments that are successfully entrained past this gap form the Group 3 sediments and maintain the growth of the scour hole. Otherwise, these are the Group 2 sediments and fall back onto the scour slope. In the early scouring stage (Figs. 4.4(a)), most sediments successfully pass the narrow gap from C to M; as an illustration, one can take the $AKE = 2.0$ contours in regions C and M as a reference to measure their distance. Meanwhile, the high TKE (≥ 2.0) regions which extend near the bed profile in the bed impingement region facilitate the sediment transportation in the early scouring stage (Fig. 4.4(a)). As the scour develops, the gap enlarges between the jet regions with high transport capability (Figs. 4.4(a-c)). Besides, the high TKE regions gradually move further away from the bed and even away from the impingement region (Figs. 4.5(a-c)), and the bed shear stress gradually decreases [Hill and Yountin, 2006; Stein *et al.*, 1993]. Consequently, a decreasing amount of sediment is uplifted with the scour development; and Group 3 sediments are reduced significantly, which slows the scour development. Eventually, the scour hole stops developing in depth, i.e., reaching the equilibrium scouring stage, when the gap grows large enough and Group 3 sediment transportation becomes insignificant.

4.7 Summary

This chapter employed the PIV technique to investigate the flow structures within an

evolving local scour hole caused by a freely plunging jet. The flow is described in terms of four aspects, i.e., mean flow patterns, AKE, TKE and RSS, as well as their inter-relationships at typical instants in the early, intermediate and equilibrium scouring stages. The results for a concave erodible bed exhibit considerable difference from those of the previous studies with a flat solid bed. Based on the distributions of AKE, TKE and RSS, three characteristic zones can be discerned for the flow inside the scour hole: the plunging jet zone, the bed impingement zone, and the free-surface impingement zone. This study is innovative in clearly depicting the presence of four different rollers, each of which shapes a specific segment of the bed profile. The concave profile of the scour hole continuously deflects the main jet upward to impinge the water surface. A large portion of the main jet is deflected backward (or upstream) by the water surface to interact with the plunging jet, resulting in the latter to be no longer a simple planar jet as described by previous researchers. Furthermore, the scouring process in the scour hole is found to be mostly controlled by sediment transportation, and local bed shear stress on the bed profile remains higher than the critical value for sediment incipient motion in the equilibrium scouring stage. Sediments uplifted by the major roller can be categorized into three groups (i.e., Group 1, 2 and 3 sediments) depending on the ensuing sediment movement. Only Group 3 sediments can be transported out of the scour hole and contributes to the growth of the scour hole. With the scour development, the gap of low capacity for the main jet to transport sediment gradually enlarges, and significant turbulence zones successively move away from the bed. As a result, Group 3 sediments gradually decreases in its quantity and eventually almost disappears in the equilibrium scouring stage.

CHAPTER 5 JET FLIPPING IN SCOUR HOLES DOWNSTREAM OF A FREE WEIR WITH AN APRON

5.1 Introduction

Extending the case of free weir flow, an apron is added downstream of the free weir. Cyclical flipping of the main jet that significantly influences the scouring process may be observed in the local scour hole. The scour hole subject to jet-flipping does not follow the conventional 3-stage development of scour, and the conventionally defined equilibrium scouring stage where the maximum scour depth is maintained is not achieved, because jet-flipping constantly alternate the scouring action at the bed jet regime and refilling action at the surface jet regime. A temporary maximum scour depth appears almost the same at the end of each bed jet regime in every jet-flipping cycle. On the other hand, the main sediment mound following the scour hole initially moves downstream over the jet-flipping cycles and will end asymptotically. The profiles of the scour hole and the flow structures at corresponding moments within the consecutive jet-flipping cycles are rather similar. The equilibrium scouring stage, therefore, is defined as the state when the mound movement downstream has stopped.

The present chapter investigates the dynamic flow within a temporally transforming local scour hole downstream of a free weir with an apron. The emphasis is placed on the transitions between the bed jet regime and the surface jet regime. The flow characteristics are discussed in the following aspects: (a) instantaneous flow pattern in Section 5.2; (b) average kinetic energy (AKE) in Section 5.3; (c) the self-similarity of the main jet in Section 5.4; (d) turbulence kinetic energy (TKE) in Section 5.5; and (e) Reynolds shear stress (RSS) in Section 5.6. A quantitative assessment of the gross effects of the apron is carried out by comparing with the no-apron case in terms of impingement angles, maximum scour depth, magnitude of AKE, see Section 5.7. Finally, a summary is presented in Section 5.8.

5.2 Flow Patterns

Figures 5.1 (a-c) are schematic sketches of the flow patterns in the bed jet, transitional

jet and surface jet regimes, respectively. Figures 5.2 and 5.3 show the measured velocity fields undergoing upward flipping transition from the bed jet regime to the surface jet regime at the initial (I.J.) and equilibrium (E.J.) scouring stages, respectively. For better illustration of the jet-flipping process, each transition is presented in four distinct consecutive jet regimes: (1) the bed jet regime, (2) early transitional regime, (3) late transitional regime and (4) surface jet regime, and they are numbered 1, 2, 3 and 4, respectively. Here, Figs. 5.2(a-d) show I.J. 1 to I.J. 4 corresponding to the four distinct consecutive jet regimes for upward jet flipping at the initial scouring stage. Similarly, E.J. 1 to E.J. 4 for the equilibrium scouring stage are presented in Figs. 5.3(a-d). Figures 5.4(a-d) show R.J. 4 to R.J. 1 corresponding to the reverse (downward) jet flipping from the surface jet regime to the bed jet regime.

Figs. 5.1 Schematic sketches of flow patterns for (a) bed jet regime, (b) transitional jet regime and (c) surface jet regime in a scour hole downstream of a free weir with an apron

Figs. 5.2 Average velocity fields of Run 1 ($Q = 1.5$ L/s, $H = 50$ mm and $A = 100$ mm) within the inclusive time span of (a) 110 ~ 111 s; (b) 112 ~ 113 s; (c) 114 ~ 116 s; (d) 117 ~ 121 s. Denoted as I.J. 1, I.J. 2, I.J. 3 and I.J. 4, respectively, as the jet is experiencing upward flipping at the initial scouring stage

Figs. 5.3 Average velocity fields of Run 1 ($Q = 1.5$ L/s, $H = 50$ mm and $A = 100$ mm) within the inclusive time span of (a) 1028 ~ 1029 s; (b) 1030 ~ 1031 s; (c) 1034 ~ 1036 s; (d) 1038 ~ 1039 s. Denoted as E.J. 1, E.J. 2, E.J. 3 and E.J. 4, respectively, as the jet is experiencing upward flipping at the equilibrium scouring stage

Figs. 5.4 Average velocity fields of Run 2 ($Q = 1.5$ L/s, $H = 55$ mm and $A = 100$ mm) within the inclusive time span of (a) 1207 ~ 1210 s; (b) 1397 s; (c) 1399 s; (d) 1401 s. Denoted as R.J. 4, R.J. 3, R.J. 2 and R.J. 1, respectively, as the jet is experiencing reverse (downward) flipping at the equilibrium scouring stage

It was observed that the duration for the bed jet regimes varies from 24 s to 129 s at different cycles, whereas that for the surface jet regimes range from 344 s to 536 s. In comparison, the transitional flipping regimes between the bed jet and surface jet regimes are observed over much shorter time spans of about 3 ~ 5 s, depending on the plunging jet conditions, the direction of transition (upward or downward), or the stage of scour development (initial or equilibrium). In Figs. 5.2-5.4, a triangular area is demarcated by a dashed line at the upper left corner. The velocity vectors in this triangular area are considerably underestimated in magnitude, as the jet entry created water wavy surface resulting in non-uniform reflection of laser light. Therefore, this triangular area is omitted for subsequent analysis of AKE, TKE and RSS.

Figures. 5.1, 5.2, 5.3 and 5.4 show a plunging jet impinges on the apron at $x \approx 50$ mm with an angle, θ_a , (a range from 50° to 64° (see Table 5.1)), and then splits into three components: a minor jet, a bounced jet and a main jet. Consequently, four types of roller (large-scale recirculating vortex), i.e. a major roller, a bed roller, a secondary roller and a captive roller, are formed (see Fig. 5.1). The minor jet recirculates clockwise forming a ‘captive roller’, and is always confined by the plunging jet. The bounced jet forms an anti-clockwise ‘secondary roller’, which is enclosed by and merges with the anti-clockwise ‘major roller’ in the surface jet regime. The main jet exhibits cyclical flipping behaviors upon entering the scour hole after going through a short horizontal wall jet region on the apron. The wall jet region, observed in nearly all the literature on the jet-flipping scour [Balachandar and Kells, 1997; 1998; Balachandar and Reddy, 2013; Johnston, 1990; Johnston and Halliwell, 1986; Kurniawan and Altinakar, 2002; Xie and Lim, 2015], appears to be a prerequisite for the jet-flipping phenomenon in a local scour hole.

In this study, the writer observe that the flipping behavior is characterized by the cyclical appearance and disappearance of the ‘bed roller’ beneath the main jet. In the bed jet regime, the main jet which forms the major roller mainly attaches to and continuously scours the bed (see Figs. 5.1(a), 5.2(a) and 5.3(a)). Thereafter and in the early transitional regime (see Figs. 5.1(b), 5.2(b) and 5.3(b)), the bed roller appears immediately downstream of the apron, and continues to grow in size in the late transitional regime (see Figs. 5.2(c) and 5.3(c)). Meanwhile, the main jet detaches from

the bed, and the major roller shrinks gradually to merge with the secondary roller. Eventually and in the surface jet regime, as shown in Figs. 5.1(c), 5.2(d) and 5.3(d), the bed roller develops to its maximum size and entrains sediment back from the downstream slope to refill the scour hole. The reverse process for the development of the bed roller is depicted in Figs. 5.4(a-d). It is noted that the flow patterns are essentially the same for both Run 1 (Figs. 5.2 and 5.3) and Run 2 (Fig. 5.4), despite the slight difference in tailwater depth (55 mm vs. 50 mm) for these two runs.

Table 5.1 Summary of jet impingement angles on the non-erodible bed (θ_a), the erodible bed (θ_b) and the water surface (θ_s).

	Apron Case									No-apron Case
	Run 1 (Initial Scouring stage)			Run 1 (Equilibrium Scouring stage)			Run 2			
	B.J. ^a	T.J. ^b	S.J. ^c	B.J.	T.J.	S.J.	B.J.	T.J.	S.J.	
θ _a	57.1°	55.0° ~ 62.1°	52.5°	60.1°	58.8° ~ 59.6°	52.9°	56.8°	50.1° ~ 63.4°	54.4°	N/A
θ _b ^d	N/A	28.3° ~ 29.6°	N/A	N/A	19.1° ~ 23.7°	N/A	N/A	7.9° ~8.3°	N/A	70.5° ~ 79.6°
θ _s	27.5°	24.3° ~ 28.3°	42.6°	26.3°	26.8° ~ 28.5°	41.0°	46.6°	46.7° ~ 49.5°	46.6°	90.6° ~ 92.3°

^a Bed Jet Regime.

^b Transitional Jet Regime.

^c Surface Jet Regime.

^d The impingement angle on the bed when the main jet becomes horizontal for the current apron case.

Figures 5.2(a-d) show the transition of flow patterns at the initial scouring stage ($t = 110 \sim 121$ s). The main sediment mound moves downstream gradually while the scour depth remains almost constant ($d_s \approx 20$ mm), and the downstream slope becomes gentler. In comparison to Fig. 5.2, Fig. 5.3 may be considered at the equilibrium scouring stage ($t = 1028 \sim 1039$ s), because the position of the main sediment mound is almost stationary at $x = 335$ mm (which is beyond the field of view). Figures. 5.3(a-c) show a secondary mound at the equilibrium scouring stage. The bed profile upstream of the secondary mound appears to be relatively more sensitive to the flow structure than that downstream of the mound. The bed roller and the major roller are mostly confined to

upstream of the secondary mound only. The scour hole becomes similar in both size and shape at the corresponding instants across consecutive jet-flipping cycles. Furthermore, the water depth above the scour hole at the equilibrium scouring stage (Fig. 5.3) is lower than that at the initial scouring stage (Fig. 5.2), probably due to the milder downstream slope of the scour hole that effectively reduces the resistance to the flow. This further makes the water surface more wavy at the equilibrium scouring stage than before, especially in the surface jet regime as shown in Fig. 5.3(d).

5.3 Distributions of Average Kinetic Energy (AKE)

Figs. 5.5, 5.6 and 5.7 present the AKE distributions corresponding to the flow fields in Figs. 5.2, 5.3 and 5.4, respectively. In the analysis, a number of segments in the AKE distributions are denoted by using the uppercase letters, A, B, C, D, E, F, G, H, I, J, K and S. AKE indicates the magnitude of mean velocity vectors for incompressible fluid and is calculated by using Eq. 5.1;

$$AKE = \frac{\bar{u}^2 + \bar{v}^2}{U_0^2} \quad (5.1)$$

where $\bar{u}$ and $\bar{v}$ are mean velocities in the longitudinal (x) and vertical (y) directions, respectively; and U_0 (= 0.1 m/s) is the average flow velocity at a far downstream section (Section CC in Fig. 1). AKE of the plunging jet at the entry point on the water surface can be estimated to be 63.5, using Eqs. 5.1, 5.2 [Dey and Raikar, 2007], 5.3 [Zhao et al., 2009] and the continuity equation, Eq. 5.4:

$$U_e = C_o \sqrt{2g(h_o + 1.5y_c)} \quad (5.2)$$

$$y_c = \sqrt[3]{\frac{\alpha q^2}{g}} \quad (5.3)$$

$$q = U_e y_e \quad (5.4)$$

where U_e = average velocity at the jet entry point; y_e = the thickness of the plunging jet at the entry point, which is estimated to be 7 mm; C_o = velocity coefficient and a value of 0.672 proposed by Dey and Raikar [2007] was used; h_o = height of weir above the

tailwater surface; y_c = critical water depth at upstream the weir; α = kinetic energy coefficient which is approximately equal to 1.0 [Zhao *et al.*, 2009]; q = discharge per unit width; and g = gravitational acceleration.

Figs. 5.5 AKE distributions of Run 1 at (a) I.J. 1; (b) I.J. 2; (c) I.J. 3; (d) I.J. 4

Figs. 5.6 AKE distributions of Run 1 at (a) E.J. 1; (b) E.J. 2; (c) E.J. 3; (d) E.J. 4

Figs. 5.7 AKE distributions of Run 2 at (a) R.J. 4; (b) R.J. 3; (c) R.J. 2; (d) R.J. 1

In Figs. 5.5, 5.6 and 5.7, Region A with peak AKE = 4.0 to 6.0 is always located in the plunging jet zone, see Figs. 5.2, 5.3 and 5.4, indicating that the potential core of the plunging jet (defined as the region where the centerline velocity remains essentially constant and equal to the jet exit velocity [Beltaos and Rajaratnam, 1973]) is absent. This is probably because the water depth above the apron is relatively shallow and is approximately equal to the length of the assumed potential core, which is about $7y_e$ [Albertson *et al.*, 1950; Beltaos and Rajaratnam, 1973]. The impingement by the plunging jet on the apron generates favorable pressure gradients, which decelerate and deflect the upcoming jet but accelerate the deflected jets [Beltaos, 1976a; b; Beltaos and Rajaratnam, 1973; Liu *et al.*, 1998a]. This explains the acceleration of the deflected main jet and the bounced jet, as indicated by the presence of Region B immediately downstream of the apron and Region I above the apron, respectively.

Figures 5.5(a-c) show that the main jet decelerates from Region B to Region C and then accelerates to Region D. These regions are elongated when the main jet uplifts and impinges increasingly downstream at K on the bed. Region F follows and is apparently caused by the narrowed flow passage above the main mound and maintains a similar shape. Under this transition (Figs. 5.5(a-c)), Region J appears and develops beneath the main jet corresponding to the development of the bed roller; Regions I and H (representing the surface returning jet) move closer while the major roller shrinks. In the surface jet regime as shown in Fig. 5.5(d), the direct impingement of the main jet on the free surface results in similar variations in AKE from B via C to D, and Region J develops significantly in both magnitude and size in accordance with the fully developed bed roller. Meanwhile, the stagnation region G does not coincide with the intersection point of the water surface with line BC (i.e. the centre-line of the main jet), which is supported by the previous findings [Beltaos, 1976a; b; Kamoi and Tanaka, 1972].

The AKE distributions at the equilibrium scouring stage (Fig. 5.6) are similar to those at the initial scouring stage but with two major differences. Firstly, Region F observed previously has now shifted downstream with the main mound and moved beyond the field of view. Secondly, Regions B, C and D are substantially extended in Figs. 5.6(a-c), which indicates weaker mean velocity gradient and smaller impingement effect during

the bed and transitional regime at the equilibrium scouring stage. *Beltaos* [1976a; 1976b] pointed out that the impingement effect is positively correlated to the impingement angle, θ_b (see Fig. 5.1(b)). As compared to the initial scouring stage, the value of θ_b at the equilibrium scour becomes relatively smaller due to generally the milder downstream slopes (see Table 1). Figure 5.7(a-d) present the AKE distributions for the reverse transition, i.e. downward flipping from the surface jet regime to the bed jet regime. Under this condition, Region D discussed previously in the transitional regime is absent in Fig. 5.7(c), and the decrease in AKE from B to C is mainly due to diffusion, turbulence and viscosity effects instead [*Liu et al.*, 1998a]. This is because the flatter bed profile after the refilling process reduces the impingement effect. Fig. 5.7(d), corresponding to the start of the bed jet regime for the next jet-flipping cycle, shows that the main jet continuously decelerates after Region B towards the water surface.

5.4 Self-similarity of the main jet

Region B represents the cyclical flipping part of the main jet, and dominates the alternate scouring (bed jet regime) and refilling (surface jet regime) processes of the scour hole. This part of the main jet is apparently not a free jet that decelerates monotonically with distance [*Beltaos and Rajaratnam*, 1973]. It is analogous to the free jet in terms of its mean velocity profile and how it spreads laterally along the jet direction. Figure 5.5 shows a streamline through the peak AKE point B, and Fig. 5.8 is a definition sketch of jet development in terms of jet half-width along the streamline-wise direction. In Fig. 5.8, s denotes the distance along the streamline from point B; b_u and b_u' are the values of y' where the local velocity reaches half of its local maximum velocity ($V_{0.5} = 0.5V_{\max}$) above and below the streamline, respectively. Figure 5.5(a) highlights 5 cross-sections perpendicular to the streamline: a-a, b-b, B, c-c and d-d, where the velocity on the streamline V_s (see Fig. 5.8) equals to 0.7, 0.8, 1, 0.8 and 0.7 times V_B , respectively. This streamline can be considered as the centreline of the main jet in Region B, because V_s is very close to $V_{\max}$ on these sections.

Figs. 5.8 Definition sketch of mean velocity profiles and half-width along the streamline-wise direction

Figures 5.9(a-c) show self-similarity of the normalized mean velocity profiles on the accelerating side SB of the main jet, while Figs. 5.9(c-e) show the decelerating side BC. The fitted self-similar relationship is approximated using the Least Mean Squares method, as follows:

$$\frac{V}{V_m} = e^{-(0.844 \frac{y'}{b_u})^2} \quad (5.5 \text{ a})$$

$$\frac{V}{V_m} = e^{-(0.844 \frac{y'}{b_u'})^2} \quad (5.5 \text{ b})$$

This agrees satisfactorily with that proposed by *Beltaos and Rajaratnam* [1973] to describe the self-similar velocity profiles of the free jet:

$$\frac{V}{V_m} = e^{-(0.834 \frac{y'}{b_u'})^2} \quad (5.6)$$

Figure 5.10 presents the lateral jet spreading in terms of jet half-widths (b_u and b_u'), which are normalized by the thickness of the plunging jet upon entry (y_e), as well as the total jet width $W_J = b_u/y_e + |b_u'/y_e|$. It is apparent that the rate of jet spreading depends on the jet regime. In the bed and early transitional regimes (Fig. 5.10(a)), both b_u/y_e and W_J decrease on the accelerating side SB and then increase on the decelerating side BC, while $|b_u'/y_e|$ increases. The data points are scattered in this figure, because the bed profile transforms rapidly and its interactions with the main jet are strong. However, in

the late transitional and surface jet regimes (Figs. 5.10(b and c)), all the length scales, i.e. b_u/y_e , $|b_u'/y_e|$ and W_J , exhibit a consistently linear increase, regardless of the scouring stage (initial or equilibrium). This observation is supported by previous findings that the free jet spreads linearly with downstream distance [Albertson *et al.*, 1950; Beltaos and Rajaratnam, 1973; Liu *et al.*, 1998a].

Figs. 5.9 Normalized velocity profiles at cross-sections (a) a-a; (b) b-b; (c) B; (d) c-c and (e) d-d

Figs. 5.10 Length scales of the flipping part of the main jet in (a) bed jet and early transitional regimes; (b) late transitional regime; and (c) surface jet regime

5.5 Distributions of Turbulent Kinetic Energy (TKE)

The importance of TKE to the scouring processes lies in the fact that TKE causes pressure fluctuations and uplifting forces acting on the sediments [Jia *et al.*, 2001; Kamoi and Tanaka, 1972; Liu *et al.*, 1998b]. Manes and Brocchini [2015] proposed a novel method for relating the depth of the scour hole formed around vertical cylinder and local turbulence. TKE is calculated as

$$\text{TKE} = \frac{\overline{u'^2} + \overline{v'^2}}{U_0^2} \quad (5.7)$$

where u' and v' are the fluctuating velocity components in the longitudinal and vertical directions, respectively. Figures 5.11 and 5.12 show the TKE distributions under the upward flipping transition, while Fig. 5.13 shows the downward transition. Significant TKE is always evident around Region A, and is linked to pronounced velocity gradients [Albertson *et al.*, 1950; Lin *et al.*, 2008] and jet collisions among the plunging jet, the minor jet and the surface returning jet. The peak wall TKE regions at the apron ($x = 70$ to 90 mm in Figs. 5.11 and 5.12, and $x = 50$ to 70 mm in Fig. 5.13) vary in magnitude with time. It is probably linked to the temporal variation of TKE around Region A, as Kamoi and Tanaka [1972] had demonstrated earlier that the turbulence level of the incoming jet affects peak wall fluctuations. These peak wall TKE regions tend to be significant in the surface jet regime (see Figs. 5.11(d), 5.12(d) and 5.13(a)), compared to the transitional regime (see Figs. 5.11(c), 5.12(c) and 5.13(c)).

The TKE distributions in the bed jet regime (Figs. 5.11(a) and 5.12(a)) confirm two key observations of Guan *et al.* [2014] and Meftah and Mossa [2006]: (i) Significant TKE regions in the scour hole are located on the upstream slope; and (ii) TKE dissipates gradually downstream with the main jet. The significant TKE regions detach from the bed to surround B at the birth of the bed roller in the early transitional regime (Figs. 5.11(b) and 5.12(b)). They then move behind B and extend in length just between the major and bed rollers in the late transitional regime (Figs. 5.11(c) and 5.12(c)) and the surface jet regime (Figs. 5.11(d) and 5.12(d)). Consistent with this dynamic behavior of TKE, the velocity gradients change around B and become significant in the shear layer just between the bed and major rollers. This was also observed by Lin *et al.* [2008]. Figures 5.13(a) to (d) show that TKE distributions develop in an opposite manner for the reverse transition of jet regimes; the extended and significant TKE regions between the two rollers in Fig. 5.13(a) gradually shrink around B in Figs. 5.13(c and d). However, the TKE regions around B appear more scattered in the transitional regime (see Figs. 5.13(b and c)) and not yet attach to the upstream slope of the scour hole at the start of the bed jet regime (see Fig. 5.13(d)).

Fig. 5.11 TKE distributions of Run 1 at (a) I.J. 1; (b) I.J. 2; (c) I.J. 3; (d) I.J. 4

Fig. 5.12 TKE distributions of Run 1 at (a) E.J. 1; (b) E.J. 2; (c) E.J. 3; (d) E.J. 4

Fig. 5.13 TKE distributions of Run 2 at (a) R.J. 4; (b) R.J. 3; (c) R.J. 2; (d) R.J. 1

5.6 Distributions of Reynolds Shear Stress (RSS)

Figures 5.14, 5.15 and 5.16 show the RSS distributions, given by

$$\text{RSS} = \frac{-\overline{u'v'}}{u_*^2} \quad (5.8)$$

where u_* is the average shear velocity at a far downstream section (Section CC in Fig. 3.4). RSS represents the velocity of turbulence, a reflection of flow velocity fluctuation, similar to TKE, and implies momentum exchanges in the flow [Kamoi and Tanaka, 1972; Zhao *et al.*, 2009]. Likewise, the plunging jet zone depicts peak absolute RSS (negative RSS around Region A) and significant momentum exchanges, which agrees with that without an apron. In the scour hole, significant negative RSS regions appear on the upstream slope and gradually decrease in magnitude during the transition from the bed jet regime to the surface jet regime (see Figs. 5.14 and 5.15). The peak positive RSS regions are initially congregated above B in the bed jet regime (Figs. 5.14(a) and 5.15(a)) and the early transitional regime (Figs. 5.14(b) and 5.15(b)). These regions extend in length from B to C along the main jet in the late transitional regime (Figs. 5.14(c) and 5.15(c)) and the surface jet regime (Figs. 5.14(d) and 5.15(d)). Figure 5.16 shows the reverse development of the RSS regions in a scattered manner. Compared to TKE, RSS is also influenced by the direction of velocity fluctuation. Negative RSS reaches its possible maximum absolute value when the direction of fluctuation is approximately orthogonal to the upstream bed slope, see Figs. 5.14(a) and 5.15 (a).

Figs. 5.14 RSS distributions of Run 1 at (a) I.J. 1; (b) I.J. 2; (c) I.J. 3; (d) I.J. 4

Figs. 5.15 RSS distributions of Run 1 at (a) E.J. 1; (b) E.J. 2; (c) E.J. 3; (d) E.J. 4

Figs. 5.16 RSS distributions of Run 2 at (a) R.J. 4; (b) R.J. 3; (c) R.J. 2; (d) R.J. 1

5.7 Scour mechanism with an apron

Generally, most of the energy from the plunging jet is found in the main jet and flow over the mound and outside the scour hole. Only an insignificant portion returns upstream with the surface returning jet, as indicated by the almost invariant impingement point of the plunging jet on the apron. In contrast, in the case without an apron ($L = 0$ mm) and under the same flow conditions [Si *et al.*, 2018], a remarkable portion of energy, even larger than that carried downstream and outside the scour hole, returns upstream to impact on the plunging jet and causes the plunging jet to oscillate back and forth substantially.

The presence of the apron brings about substantial change in the interactive mechanism between the jet and the scour hole profile. Firstly, the apron clearly dissipates the energy of the main jet, and the peak AKE level just before impinging the bed, i.e. Region B with $AKE \approx 4.0$, is substantially lower than that of $AKE \approx 7.0$ for the case without an apron. Moreover, the apron deflects the plunging jet almost horizontally to impinge on the erodible bed at a considerably smaller angle ($\theta_b = 8^\circ$ to 30°), as compared to the case without an apron ($\theta_b = 70^\circ$ to 80°). Since the impingement angle correlates positively to scouring action [Bormann and Julien, 1991; Hoffmans, 1998; Mason and Arumugam, 1985], the scour hole significantly decreases in terms of the maximum scour depth ($d_s = 20$ mm versus 130 mm for the case without an apron), while the scour length is only slightly reduced, i.e. $L_s = 335$ mm versus 373 mm for the case without an apron. On the other hand, the considerably milder scour slope deflects the main jet to impinge on the water surface at a substantially smaller angle ($\theta_s = 24^\circ$ to 50°), as compared to the case without an apron where the steep slopes deflect the main jet nearly vertically towards the water surface ($\theta_s = 90^\circ$ to 92°). Beltaos [1976b] and Jalil and Rajaratnam [2006] reported that insignificant returning jets are the results of small impingement angles.

It is worth noting that the values of impingement are also dependent on the direction of jet-flipping. As can be seen in Table 1, $\theta_b (=7.9^\circ$ to $8.3^\circ)$ for Run 2 with downward flipping is appreciably smaller than that ($=19.1^\circ$ to 29.6°) for Run 1 with upward flipping. The former was measured just after the refilling process of the scour hole which has a flatter bed profile, and the latter just after the scouring process of the scour.

However, θ_s ($=46.6^\circ$ to 49.5°) for Run 2 in the bed and transitional jet regimes are larger than that ($=24.3^\circ$ to 28.5°) for Run 1 in the corresponding regimes. Whereas in the surface jet regime there is no significant difference ($\theta_s = 41.0^\circ$ to 46.6°) for both runs. This is attributed to the fact that the jet interacts intensely with the bed profile in the bed and transitional jet regimes, but little interaction in the surface jet regime. On the other hand, the downward flipping takes place at the start of a scouring process with the main jet attached to a steep segment of the downstream slope (Fig. 5.4(d)). The upward flipping at the end of the scouring process depicts a fully developed and stretched scour hole (Figs. 5.2(a) and 5.3(a)).

5.8 Summary

This study aims at improving the understanding of the jet-flipping phenomenon in the local scour hole downstream of a free weir with an apron. The results clearly demonstrate the usefulness of PIV in providing the quantitative information on the coherent structures of the flow in the evolving scour hole. Details of the flow structures associated with the cyclical jet-flipping phenomenon are presented. Four types of roller, namely, a major roller, a bed roller, a secondary roller and a captive roller, are observed in different jet regimes (bed, transitional, and surface) of the scour evolution. The principal features of the rollers, such as their shape, size and location, are deduced explicitly from the PIV measurements. The apron serves as an effective scour countermeasure and causes cyclical flipping of the main jet from the bed to the water surface and vice versa. As compared to the case without an apron, the apron remarkably reduces the maximum depth of the scour hole, d_s , by dissipating the energy of the plunging jet and adjusting the impingement angle with the scour hole. The alternate scouring and refilling processes during a jet-flipping cycle are basically associated with the different actions of the major roller and the bed roller: the former scours the bed in the bed jet regime and the latter refills the scour hole in the surface jet regime. The two rollers develop in the opposite manner during the transitions of jet regime: one grows and acts on the bed profile, while the other shrinks in size and reduces its actions on the scour bed hole. The results also reveal the existence of a significant AKE region, i.e. Region B, immediately downstream of the apron and just before the impingement location of the main jet on the bed profile. Region B changes substantially at different

scouring stages and also during the jet regime transitions, mainly because of the temporally varying scour slopes. However, the peak positive RSS and peak TKE are attained mostly in Region B with cyclical jet-flipping. Furthermore, the main jet within this region consistently exhibits self-similarity in terms of the normalized mean velocity profiles along the jet centerline.

CHAPTER 6 FLOW STRUCTURES IN SCOUR HOLES CAUSED BY A WALL JET

6.1 Introduction

Sluice gate is a common hydraulic structure, such as that at the Marina Barrage in Singapore, in which flood water is discharged in the form of wall jets, and a wall jet may cause local scour hole. In this study, experiments were conducted to measure the shape of the scour hole caused by a wall jet downstream of a sluice gate. Figures 6.1(a and b) show the temporal developments of the max scour depth, d_s , and of the scour length, L_s , for the two independent runs. These 2 sets of data collapse quite well, confirming good repeatability of the experiment. Based on Fig. 6.1(a), the evolution of the scour hole undergoes three distinct stages: (1) Stage I (early scouring stage) for scouring time $T < 300$ s, during which the scour depth increases rapidly from 0 to about 50 mm, and the scour depth may be approximated with a quadratic function in the form of Eq. 6.1(a), with the fitted curve shown as an inset in Fig. 6.1(a); (2) Stage II (intermediate scouring stage) for $T = 600 \sim 10000$ s, and the curve can be approximated by another quadratic function, Eq. 6.1(b); and (3) Stage III (equilibrium scouring stage) for $T > 10000$ s, when the scour depth reaches the asymptotic (maximum) value.

$$d_s = -169.1T^2 + 149.6T + 20.6 \quad (6.1a)$$

$$d_s = -0.24T^2 + 5.56T + 51.7 \quad (6.1b)$$

Here d_s is in mm and T is in second. It is interesting to note that the characteristic length of the scour hole L_s also exhibits similar variation trends over the three stages (Fig. 6.1(b)). This resemblance implies that although the scour hole continues to increase in size, its shape might remain similar. This hypothesis is later confirmed by the similarity results presented in Section 6.4.

Among the three stages, Stage I is most important in investigating the scour mechanism, where the flow fields are most dynamic and their interactions with the scour hole is most intense. However, Stage I is significantly short (with a duration of only about 3%

of Stage II), and hence is generally insufficiently investigated by the few reported studies on the evolution of a scour hole [*Dey and Sarkar, 2008; Hill and Yountin, 2006*]. To capture a full picture of the initial rapid evolution, PIV measurements were taken continuously within the first hour from the jet start-up, at an interval of about 20 s (for storage of data in between consecutive measurements). Each ensemble-averaged measurement is analogous to the “instantaneous” flow fields over the scour process, because the sampling duration (12s) of a measurement is short enough for the associated flow fields to be considered temporally stationary, with reference to the long-lasting and relatively slow scour process. On the other hand, the segmental duration (12s) with a sampling rate of 14 Hz is also considered long enough to provide statistical validity of the results (up to 2nd-order moments), and has been confirmed using a convergence test. To characterize the evolution of the flow fields over the scour process, measurement data at 6 moments (M1 – M6 as labelled in Fig. 6.1(a)) from Run 1 were carefully selected. The 6 measurements, M1, M2, M3, M4, M5 and M6, cover the following time ranges, 38 – 49 s, 235 – 246 s, 297 – 308 s, 916 – 927 s, 3773 – 3784 s, and 21595 – 21606 s respectively. Amongst these, M1 – M3 fall in Stage I; M4 and M5 represent early Stage II and late Stage II, respectively; and M6 is located at Stage III of the scour process.

This chapter investigates three aspects of the evolving flow structures: flow patterns in Section 6.2, which elucidate the dynamic roller system and the distributions of average kinetic energy (AKE) with the scour development; turbulent characteristics, which present the evolution of kinetic energy (TKE) and Reynolds shear stress (RSS), presented in Section 6.3; and the self-similarity of dynamic flow structures within the local scour holes presented in Section 6.4. In Section 6.5, a new perspective on the scour hole mechanism is proposed: The energy transfer from the jet to sediment is mainly attributable to the impingement of the jet on the bed profile. Finally, a summary is presented in Section 6.6.

Fig. 6.1 Temporal development of (a) the maximum scour depth and (b) the scour width; for the case with a wall jet

6.2 Flow patterns

The general flow patterns inside the scour hole are composed based on the PIV data and is shown in Fig. 6.2. The terminology used in this study is also shown. The ensemble-averaged velocity vector plots for M1 – M6 are shown in Figs. 6.3(a-f)). The figures clearly reveal the flow evolution in the scour hole at various scouring stages. It is also found that sediment movement is closely linked to the evolution of flow patterns; and the uplifted sediments may be categorized into 3 groups depending on their ensuing transport trajectories. Upon initiation, the issuing jet clings to and flows the bed profile of scour hole, and detaches at the end of the concave bed. Thereafter, the jet impinges

on the free water surface and bifurcates into two parts: the surface returning jet forming the major roller (anti-clockwise); and the tail jet, as shown in Fig. 6.2. Meanwhile, substantial amount of sediments are uplifted and transported in either one of the two ensuing paths: (1) forming Group 1 sediment that recirculates with the major roller; and (2) Group 3 sediment that is transported out of the scour hole with the tail jet. Note that Group 2 sediment is absent at this moment of evolution. These behaviors of the jets and sediment are observed and continue at M1 (Fig. 6.3(a)), except that the issuing jet is on the verge of separation from the upstream slope (denoted as US in Fig. 6.2). Shortly afterward at M2 (Fig. 6.3(b)), the issuing jet separates from the US, reattaches itself onto the bed at point P and then splits into the main jet and the minor jet. The minor jet returns upstream to form the clockwise captive roller jet (Fig. 6.2). At this point, the above observations of both the major and captive rollers agree with the previous findings in the literature [Albayrak *et al.*, 2008; Bey *et al.*, 2007; Hill and Younkin, 2006].

Fig. 6.2 Sketch of flow patterns in the scour hole caused by a wall jet

Fig. 6.3 (a-f) flow patterns and (g-l) AKE distributions for M1 to 6 during the scour hole development; corresponding to the inclusive time spans of 38s – 49s, 235s – 246s, 297s – 308s, 916s – 927s, 3773s – 3784s, and 21595s – 21606s, respectively

It is also shown in Fig. 6.2, that the main jet separates from the downstream slope (DS) at the detachment point (DP), and divides DS into two parts: the lower downstream slope (LDS) and the upper downstream slope (UDS). The scouring of sediment bed is, however, restricted to LDS, and Group 2 sediment that just falls back on UDS appears at M2. Thus, it is clear that only Group 3 sediment is being removed and sustains the growth of the scour hole. Both Groups 1 and 2 sediments are always detained in the scour hole. Similar 3-group sediment movements were observed in the scour hole caused by a plunging jet over a free weir without an apron. All 3 groups of sediment continue until M3 (Fig. 6.3(c)), when the transient bed roller emerges and the captive roller further develops. A careful check of the measurements of adjacent time windows of M3 indicates that the transient bed roller disappears approximately 300 s later. Furthermore, a more uniform DS is formed, which means that the demarcation between LDS and UDS becomes less distinct. At M4 (Fig. 6.3(d)) which is located at early Stage II, the flow patterns are similar to that at M3, except for the absence of the bed roller. It is observed that the amount of uplifted sediment is reduced considerably. Group 1 sediment decreases most significantly and very little amount of sediment is circulated with the major roller. Later at M5 (Fig. 6.3(e)), most of the uplifted sediment enters Group 2, i.e. just falling on the downstream slope. The circular inset in Fig. 6.3(e) shows the enlarged view of the secondary roller (Fig. 6.2) caused by entrainment of the surface returning jet. At the equilibrium scouring stage (Fig. 6.3(f)), the Group 3 sediment motion completely disappears while the Group 2 sediments are observed intermittently. The profile of the scour hole is still changing, and the scour depth dynamically fluctuates around an average value. This observation elucidates that at the equilibrium scouring stage the bed shear stress remains higher than the threshold for sediment inception, and the scour hole stops growing only because the uplifted cannot be transported outside of the scour hole.

The above description indicates that the flow patterns evolve rapidly with sequential appearance of four rollers (major roller, captive roller, bed roller and secondary roller) at the early and intermediate scouring stages (Stages I and II). The bed roller has a relatively short life span (lasting only for a few minutes near the end of Stage I), but it always exists in the case of a plunging jet. The bed roller, resulting from the separation

of the main jet at DP, seems to be dependent on the angle between LDS and UDS. The freely plunging jet generates a non-uniform DS all the time, with LDS at an angle of 55° to 70° to the x-axis and UDS at 29° to 32° as can be seen in Chapter 4. In comparison, the wall jet causes either a uniform DS at an angle of 30° to 32° (Figs. 6.3(c and e)) or a non-uniform DS with LDS at an angle of 42° to 43° and UDS at 28° to 30° (Figs. 6.3(b, d and f)). Similar to UDS in the case of a plunging jet, UDS or the uniform DS in the present study is at the angle of repose for the particular sediment, with reference to the works of *Chien and Wan* [1999] and *Zhang* [2008].

Figures 6.3(g-l) show the AKE distributions at M1 – M6. Here, AKE represents the velocity magnitude for incompressible fluid given as follows

$$AKE = \frac{\bar{u}^2 + \bar{v}^2}{U_0^2} \quad (6.2)$$

where $\bar{u}$, $\bar{v}$ are mean velocities along the x- and y- axes, and U_0 is the section-averaged velocity far downstream of the scour hole (Section CC in Fig. 3.5). In Figs. 6.3(g-l), each capital letter (A, B, C, D, E, F, G, H, I, J, G and P) denotes a typical region or point in the scour hole. In each AKE plot (also TKE and RSS to be shown later), the region within a dashed rectangle is not analyzed because of poor image quality there.

As can be seen in Figs. 6.3(g-l), the issuing jet carrying all energy input enters region A with the most significant AKE. When it attaches to the bed, the issuing jet decelerates from region A up to region B, and then accelerates from region B to region C. These variations in velocity magnitude from A to C are almost imperceptible from the vector plots, but show up clearly in the AKE distributions. *Beltaos and Rajaratnam* [1973] reported that substantial pressure gradients arising from the impingement (reattachment) of a jet on a surface slow down the coming jet (from A to B) during the early deflection along the bed (from P to J, where J is the point on the bed profile nominally corresponding to point B on the main jet) and then speed up the jet (from B to C) during the late deflection along the bed (from J to DP). In comparison with each corresponding vector plot in Figs. 6.3(a-f), the early deflection is distinct with substantial change in jet directions from A to B, while the late deflection is moderate. The jet kinetic energy

converts into the potential energy from A to B during the early deflection, and then the potential energy is converted back to kinetic energy from B to C during the later deflection. The main jet then impacts on the water surface at region D where favorable pressure gradients also arise and generate both regions F and H by accelerating the surface returning jet and the tail jet, respectively. Letters A, B, C and D signify the centerline of the issuing/main jet, while other letters, E, G and I, represent the point with the lowest AKE before F on the centreline of the surface returning jet, the centre of the major roller, and the minor jet, respectively.

As the scour develops, the AKE level at region A exhibits the following trend: it maintains the highest level during Stage I (Figs. 6.3(g-i)), drops substantially at M4 (early Stage II) (Fig. 6.3(j)) and thereafter rises moderately (Figs. 6.3(k and l)). Similar trend is found for other significant AKE regions, e.g. C and F, albeit at varying degrees. There are two possible reasons for the drop in AKE of region A at M4. Firstly, despite that the scour hole becomes larger, the jet-wise length of the issuing jet from A to B at M4 (Fig. 6.3(j)) is noticeably shorter than that at any moment during Stage I (Figs. 6.3(g-i)), which will be verified again by the self-similarity analysis in Section 6.4. It suggests that after the growth of the captive roller, the issuing jet is subject to stronger impingement effect on the bed. Secondly, at M4 (Fig. 6.3(j)) a new region, I, appears in between region A and US, which indicates that the issuing jet separates from the scour hole bed. Note that flow separation is a major factor of local energy loss [Kundu *et al.*, 2011; Zhao *et al.*, 2009]. From M4 onwards, region I varies insignificantly as shown in Figs. 6.3(k and l). In other words, there is little change in the amount of energy drop due to separation. However, AKE in region A rises noticeably to the moderate level at M5 and M6 (Figs. 6.3(k and l)). The impingement effect is clearly relaxed, as indicated by the increase in the jet length and the decrease in velocity gradient.

Fig. 6.4 Temporal development of controlling points in the flow fields

At this juncture, one may conclude that these three points, P, D and G, control the flow and sediment dynamics in the scour hole. The rollers resulting from the impingements of jet at points P and D distribute energy around the center G. Moreover, only through the impingement at point P does the flow mobilize stationary sediment on LDS, and the impingement at D plays an integral role in accelerating the tail jet to transport the uplifted sediment out of the scour hole. Figure 6.4 shows the temporal development at these points. Here $T^* = \frac{gT}{U_0^2}$ and g is the gravitational acceleration. X_D , X_P , X_G and Y_G denote the x-locations of points D, P, G and the y-location of point G, respectively. Figs. 6.4(a and b) show that, finally, the centre of the major roller is located horizontally half way across the scour hole width and its vertical distance from the deepest point of the scour hole is roughly equal to the tailwater depth. Figs. 6.4(c and d) show that both two impingement points, P and D, gradually move upstream.

6.3 Evolution of the turbulence characteristics

Previous studies had examined the 1st- and 2nd-order moments independently at the equilibrium scouring stage, whereas the following looks into the evolutions of the 2nd-order moments and their evolving relationship with respect to the 1st-order moment. Figures 6.5(a-f) and 6.5(g-l) present the TKE and RSS distributions, respectively,

corresponding to AKE shown in Figs. 6.3(g-l). TKE and RSS are evaluated with Eqs. 6.3(a and b), respectively:

$$\text{TKE} = \frac{\overline{u'^2} + \overline{v'^2}}{u_c^2} \quad (6.3a)$$

$$\text{RSS} = \tau_{uv} = \frac{-\overline{u'v'}}{u_c^2} \quad (6.3b)$$

where u' , v' are velocity fluctuations along the x- and y- axes, respectively; u_c is the critical shear velocity for incipient motion of the current sediment in a local scour hole ($u_c^2 = 9 \times 10^{-5} \text{ m}^2/\text{s}^2$) [Lim, 1997]. Those capital letters marked in the TKE and RSS distributions are at the exact locations as they are in the corresponding AKE distributions, and thus act as reference to reveal the spatial connections among the three quantities.

The two 2nd-order moments (TKE and RSS) each have some major features consistent throughout the scour process. In Figs. 6.5(a-f), the region of the most significant TKE is just below A, which coincides with the separation of the issuing jet and normally maintains a distance from the bed, except for M1 (very early scouring stage, see Fig. 6.5(a)). Turbulence in this region mostly arises from the separation of the issuing jet and the large velocity gradient in the shear layer between the issuing jet and the minor jet [Kundu *et al.*, 2011; Zhao *et al.*, 2009]. Significant TKE regions extend below A and B along the bed from P or the bottom of US to J, where the main jet is subject to early deflection. Albayrak *et al.* [2008] found that these significant TKE regions are generated by Görtler vortices. Additionally, a slightly significant TKE region lies behind C, which corresponds to the separation of the main jet from the bed profile, see Figs. 6.3(a-f). For the RSS distributions (Figs. 6.5(g-l)), the region with the most significant negative RSS (white region below A) mostly coincides with the most turbulent region (see Figs. 6.5(a-f)). The negative RSS regions overlie the entire US and are annotated by letters A, G, E, B, and C. On the other hand, the most significant positive RSS region (black region) underlies B on LDS and another significant positive RSS region appears behind C due to the separation of the main jet from DS. These three significant RSS regions

correspond to the significant TKE regions below letters A, B and C along the bed profile.

Fig. 6.5 (a-f) TKE distributions and (g-l) RSS distributions for M1 to 6 during the scour hole development; corresponding to the inclusive time spans of 38s – 49s, 235s – 246s, 297s – 308s, 916s – 927s, 3773s – 3784s, and 21595s – 21606s, respectively

During the scour development, turbulence level is at its lowest at M1 (the very early scouring stage, see Fig. 6.5(a)). The significant TKE under region A is almost indiscernible, probably because: (1) the issuing jet has yet to separate from US; (2) the absence of the minor jet reduces the velocity gradient in the shear layer; and (3) the issuing jet experiences continuous mild deflection along the concave bed profile instead of direct impingement. TKE increases not only in the significant regions below A, B and C, but also in the scour hole as a whole, until the end of Stage I (Fig. 6.5(b and c)). With reference to Fig. 6.3(c and i), the scour hole grows with full separation of the issuing jet and the complete development of the minor jet. Against the increase in TKE, the scour rate decreases (see the inset in Fig. 6.1(a)) during Stage I. Thereafter, TKE decreases with the scour development. Similarly, RSS has smaller magnitude in both the most significant positive and negative regions at the very early scouring stage, as implied by the absence of the contours $RSS = -200$ and 50 in Fig. 6.5(g). Besides, RSS decreases to an insignificant level at the equilibrium scouring stage, especially for the most significant positive RSS regions. This similarity between TKE and RSS is due to the fact that both TKE and RSS are derived from the same velocity fluctuations. On the other hand, RSS does not exactly follow the rise-and-drop pattern of the TKE development, but varies slightly in both the negative and the positive regions (Figs. 6.5(h-k)) during the scour process. This distinction is because the directions of fluctuations are another factor in determining RSS but not for TKE.

Kundu et al. [2011] pointed out that turbulence involves rotation of fluid particles and eddies over a wide range of size, and that kinetic energy and vorticity continuously cascade to smaller scales of eddies and finally dissipate in the smallest eddies by viscosity. Fig. 6.6 shows the distributions of normalized vorticity ($\frac{\omega h}{u_c}$ where ω is the dimensional spanwise vorticity) across the scour process. With reference to Fig. 6.3, the centrelines of jets just partition the distributions of vorticity and mean velocity gradient into positive and negative zones. Region of negative vorticity and positive mean velocity gradient corresponds to the lower side of the main jet (the side below letters A, B and C), the upper side of the surface returning jet (above F) and the lower side of the tail jet (below H). In contrast, the other regions (those above DH and those enclosed by

Fig. 6.6 Vorticity distributions for M1 to 6 during the scour hole development; corresponding to the inclusive time spans of 38s – 49s, 235s – 246s, 297s – 308s, 916s – 927s, 3773s – 3784s, and 21595s – 21606s, respectively

letters A, B, C, D and F) in the scour hole have positive vorticity and negative mean velocity gradient. Besides, the magnitude of vorticity is positively correlated to the mean velocity gradients. The negative vorticity regions below letters A, B and C are clearly higher in magnitude than those above; and the positive vorticity decreases with the development of scour. With reference to Fig. 6.5, the negative vorticity regions cover all the significant TKE regions and both the negative and positive significant RSS regions.

6.4 Self-similarity of dynamic flow structures in local scour holes

Fig. 6.3(i) shows the examples of two centreline-based coordinate systems, Sys. I and Sys. II, specifically for the centerline of the issuing/main jet from A to D and that of the surface returning jet, respectively. S indicates the jet-wise axis (which originates at

point A increasing from A to D for Sys. I, and at point F decreasing from F backwards to E for Sys. II), and y' is the normal axis that is always pointing positively towards the center of the major roller. Fig. 6.7(a) shows the profile of the normalized jet-wise centerline velocity (V_m/U_o) versus distance (S/b) for the issuing/main jet from A via B and C to D. Similar profile was reported by *Hill and Younkin* [2006] but no self-similarity was mentioned. Figure 6.7(a) demonstrates that the jet-wise length (S/b) length of M4 is the shortest, an observation consistent with the flow patterns. The present study finds that the centerline velocity exhibits self-similarity when normalized with local length and velocity scales depending on the scouring stage, see Figs. 6.7(b-f).

Figures 6.7(b and c) present the centerline velocity profiles at M1 – M4 (from jet start-up to early Stage II), whereas Figs. 6.7(d and e) show those at M4 – M6 (Stages II and III). Fig. 6.7(b) shows that self-similarity of the issuing jet from A to B is local to region A, where $V_{m1}' = V_m/(0.6V_A)$, $S_{A1}' = S/S_{0.6A}$ ($S_{0.6A}$ is the distance from A where V_m is $0.6V_A$). In comparison, self-similarity of the main jet from B to D via C is local to region C, as shown in Fig. 6.7(c) where $V_{m2}' = V_m/(0.6V_C)$ and $S_{C1}' = S_C/S_{0.5C}$ in which S_C is the jet-wise distance starting from C, and $S_{0.5C}$ is the location where $V_m = 0.5V_C$. At M4 – M6, the jets also attain self-similarity but with different length and velocity scales. In Fig. 6.7(d), $V_{m3}' = V_m/V_{t1}$, $S_{A2}' = S/S_{t1}$ where S_{t1} is the distance from A at which the slope of V_m becomes discontinuous, and V_{t1} is the velocity at this discontinuous point. In Fig. 6.7(e), $V_{m4}' = (V_C - V_m)/(V_C - V_{t2})$ and $S_{C1}' = S_C/S_{t2}$ for $S_C < 0$ while $V_{m4}' = (V_C - V_m)/(V_C - V_{t3})$ and $S_{C1}' = S_C/S_{t3}$ for $S_C > 0$ (S_{t2} and S_{t3} are locations where the slope of V_m becomes discontinuous on the negative and positive side of the origin, i.e. point C, respectively; V_{t2} and V_{t3} are the velocities at the two discontinuous points, respectively). It is worth noting that M4 (early Stage II) is located in the transition zone between scouring stages, and thus can be self-similarly scaled in either manner. Finally, Fig. 6.7(f) presents the jet-wise velocity profile of the surface returning jet (V_m/V_F , where V_F is the streamwise velocity at point F) along the centreline from E through the entire region F. S_F' is $S/S_{0.5F}$, and $S_{0.5F}$ is where $V_m = 0.5V_F$. The above discussion provides a perspective about self-similar features of the centerline velocities within the scour hole with various scales. Generalized scaling methods can be further explored with more measurement data available.

Fig. 6.7 Self-similar velocity profiles along the centerlines of the main jet

It is found that the profiles of jet-wise velocity are also self-similar on cross-jet sections. Fig. 6.8(a) presents the jet-wise velocity (V/U_o versus y'/b) at various cross-jet sections along the centerline from A to D for M3, and the legend shows the locations of the cross-jet sections. For example, A denotes the cross-jet section originates at point A; $0.7A$ denotes the point where $V_m=0.7V_A$, and D equals $0.1C$ where $V_m=0.1V_C$, as shown in Fig. 6.3(i). All the three jets (issuing, main and surface returning) preserve self-similarity within the scour hole across the entire scour process, with V/V_m versus $y'/y_{1/2}'$ on the cross-jet sections (located at points A, B, C and F) along these jets for M1 to M6, as shown in Fig. 6.8(b). Here $y_{1/2}'$ denotes the half width of jets, i.e. the value of y' where the jet-wise velocity $V = 0.5V_m$. Note that $y_{1/2}'$ on the two sides of the jets are

different from each other even at the same cross-jet section, since the lower side is also affected by the bed. Furthermore, *Beltaos and Rajaratnam* [1973] proposed Eq. 6.4 to approximate the self-similar jet-wise velocity profiles on cross-stream sections for a free jet.

$$\frac{V}{V_{max}} = e^{-(0.834 \frac{y'}{y_{1/2}'})^2} \quad (6.4)$$

Interestingly, Fig. 6.8(b) shows satisfactory agreement with Eq. 6.4 for the issuing jet, main jet and surface returning jet. Fig. 6.8(c) shows the half widths on both sides of the centreline from A via 0.7A, B and C to 0.7C for M1 – M6. It is estimated from Fig. 6.8(c) that the full jet widths, i.e. the sum of the absolute values of $y_{1/2}'$ on both sides gradually increase along the jet from A to B, then decrease from B up to C, and increase again after C, which is in line with the continuity equation for incompressible fluid. In Fig. 6.8(d), each profile in Fig. 6.8(c) is shifted upwards or downwards to coincide all the A points on the half jet width profile of a free jet [*Beltaos and Rajaratnam*, 1973]. In comparison, the issuing jet (from A to B) and the main jet after deflection (after C) spread laterally faster than a free jet, while the main jet under deflection (from B to C) contracts, as shown in Fig. 6.8(d).

Moreover, self-similarity is preserved around the center of the major roller in terms of the spatial distributions of all the 1st- and 2nd-order moments, as well as the profiles of the scour hole, during the scour process. In Fig. 6.9 with axes of $X' = (x - X_G)/X_D$ versus $Y' = (y - Y_G)/(Y_G + ds)$, the normalized bed profiles for M1 to M6 are plotted; The peak or lowest AKE points at the typical regions are also annotated with the letters: A, B, C, D, E, F and G, for the respective measurements. In this figure, the dashed lines denote the contours of significant AKE which has the value ranging between 5 and 6 for various measurements, while the solid lines denote the contours of zero vorticity ($\omega = 0$). By comparing Figs. 6.3(a-f) and 6.3(g-l), it can be seen that these typical points are also located in controlling positions for vector plots, and thus one may conclude that the velocity vector plots are also self-similar about the centre of the major roller under the same scaling methods. Furthermore, significant TKE is predominant below regions A, B and C; the negative RSS regions are enclosed by letters A, G, E, C and B, while the

Fig. 6.8 Self-similar velocity profiles on the cross-jet sections

significant positive RSS regions are below B and after C. With reference to Fig. 6.9 where all these points preserve self-similarity, the 2nd-order moments, therefore, preserve self-similarity in spatial distributions around the centre of the major roller. In Fig. 6.9, the scaling lengths involve the developments of both the flow fields by considering the centre of the major roller and the scour hole by its length and depth. However, the most significant areas of the 2nd-order moments are closely attached to the profile of the scour hole, quite independent of the development of the flow fields. Fig. 6.10 provides an alternative to present the self-similar feature of the most significant 2nd-order moments with $X'' = x/L_S$, $Y'' = y/d_s$, where the centre of the major roller is excluded.

Fig 6.9 Self-similarity in spatial distributions of the flow fields

Fig. 6.10 Alternative self-similarity in spatial distributions of turbulence

6.5 Scour mechanism for wall jets

A piece of sediment initiates only when the shear stress acting on it exceeds the critical incipient stress [*Chien and Wan*, 1999; *Zhang*, 2008], and the appropriate estimation of the shear stress has been considered as the key to the scour mechanism. The findings about shear stress on a channel bed has been applied to estimate the shear stress of the wall jet on the concave bed of a local scour hole [*Hill and Younkin*, 2006]. An improvement on the analogy with a channel bed is the discovery that the concave curvature enhances the wall-friction coefficient due to turbulence generated by Görtler vortices [*Albayrak et al.*, 2008]. The present study finds that the contribution of the jet impingement on the bed to the shear stress has not received its due attention yet. Unlike a flat solid bed under exceptional pressure due to jet impingement [*Beltaos and Rajaratnam*, 1973], the sediment bed under pressure relaxes to become fluidic in nature [*Kou et al.*, 2017]. Therefore, exceptional pressure exists on the interface between the water-fluid and the sediment-fluid, i.e. the segment of the sediment bed where the issuing jet reattaches. The water-fluid side, as mentioned earlier, is accelerated due to favorable pressure gradients, i.e. pressure energy converted to the kinetic energy of the water-fluid. As an analogy to the water-fluid, pressure gradients arise on the sediment-fluid side and similarly mobilize or accelerate the sediment-fluid, i.e. pressure energy converting back to the kinetic energy of the sediment-fluid. One needs to point out that the pressure on the interface for both sides is identical but the pressure gradients may not be. Figures 6.3(g-l) imply that the energy introduced by the issuing jet is possibly transferred more into the sediment-fluid than be retained in the water-fluid through the intense contact of the jet with the sediment bed over P to DP. As in the figures, region A has the contour of peak AKE=20, which is much higher than that of region C with AKE=5–6; on the other hand, Fig. 6.8(c) indicates that the jet width at C does not change much from that at A. Since the energy remaining in region C alone supports the entire dynamics of the water fluid within the scour hole, the even larger portion of energy suffices to mobilize sediment fluid significantly. This should explain that the non-uniform DS appears most of the time and that the steeper LDS varies with the oscillation of the impingement point. Another major factor controlling the scour and the three groups of sediment, instead of the shear stress being below the critical incipient

stress, is the capability of the jet to transport sediment out of the scour hole. This transport capability is positively correlated to AKE. The uplifted sediment is increasingly difficult to pass the enlarging gap between the highly capable region C and another capable region H which transports the sediment out of the scour hole, except at the very early scouring stage (Fig. 6.3(a)). The scour stops when region C is so distant from region H that no sediment can pass, even though the bed shear stress is still higher than the critical value and the profile of the scour hole is constantly transforming. The present study is supported by the findings of previous studies that turbulence plays an important role in initiating sediment [Albayrak *et al.*, 2008; Hill and Younkin, 2006; Jia *et al.*, 2001], and turbulence is but just a secondary factor in the scour mechanism. The scour reduces substantially with the increase in turbulence at the early scouring stages as shown in Figs. 6.3(a to c); and sediment particles remain in continuous motion locally near the bed even at the equilibrium scouring stage.

6.6 Summary

Three characteristics of PIV enable us to comprehensively study the undisturbed evolution of the flow inside the scour hole formed by a wall jet with an apron. The flow inside the scour hole is featured by dynamically varying patterns consisting of four rollers that intensely interact with the scour hole and the free water surface and control the scour process at different stages (early, intermediate and equilibrium). The major roller, the captive roller and the bed roller appear successively at the early scouring stage, and the secondary roller emerges late at the intermediate scouring stage when the flow becomes stable. The mutual interactions among the rollers alternate the predominant energy (kinetic and potential) of the jets, and hence generate significant influence on the distributions of 1st- and 2nd-order moments. The present study, possibly for the first time, investigates the self-similar flow features in the dynamically evolving scour hole. For the different jets in the scour hole, the velocity profiles always exhibit self-similarity on cross-jet sections and is analogous to a free jet. In addition, the velocity profiles along the centrelines of jets are self-similar, but with scaling methods specific to typical AKE regions and different scouring stages. Another interesting feature is that both the profiles of the scour hole and the spatial distributions of AKE within the scour hole also exhibit self-similarity. Moreover, since the 2nd-order moments

are spatially connected to mean velocities, the self-similar distributions of AKE bring about the self-similar distributions of the 2nd-order moments. The scour actions of the jets take place not on the entire profile of the scour hole, but merely on a particular segment, i.e. the lower downstream slope from the reattaching point to the detachment point. Only through this interface does a sizable portion of energy in the issuing jet, even possibly more sizable than the other portion retained in the jets collectively in the scour hole, transfer from the issuing jet to the sediment. This portion of energy primarily uplifts sediment and transports sediment collectively, and then controls the scour mechanism. Turbulence just plays a secondary role in the scour mechanism.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

This study used a Particle Image Velocimetry system to investigate experimentally the dynamic flow structures in local scour holes caused by a 2-D plunging jet and a 2-D wall jet. The jet-flipping phenomenon is also observed and investigated for a free weir case with an apron. The evolution of the flow structures in the scour hole is examined in four major aspects: mean flow patterns, AKE, TKE and RSS. The findings of the study on the flow structures lead to a new perspective to the scour mechanism.

7.1 PIV methods

Three characteristics of using PIV in the present study stand out in its capability as a flow measurement tool: the globality of the instantaneous flow fields; non-intrusive capture of the development of the movable bed; and continuous measurements of the flow fields at the most crucial stages of scour formation. These characteristics enable the evolution of the transient flow fields to be captured and elucidated comprehensively over the entire scour process, as well as successfully capturing the momentary transitions of jet flipping in the scour hole.

7.2 Flow structures

For the two cases without jet-flipping by a 2-D plunging jet and a 2-D wall jet, four rollers, i.e. the major roller, the captive roller, the bed roller and the intermittent roller (for the plunging jet case) or the secondary roller (for the wall jet case), are formed within the local scour holes. The rollers exist because of intense interactions of the various component jets with each other, with the scour holes, and the free surface. The study found that, among the rollers, the major roller is the principal component in the scouring mechanism while the other 3 rollers are the complementary scouring agents. The scouring action is confined mainly on a short interface between the major roller and the lower downstream slope of the scour hole, starting from the jet reattaching point up to its detachment point. The most turbulent area appears in the shear layer between the major roller and the captive roller. In addition, the flow structures, including both the 1st- and 2nd-order moments, are self-similar, along with the profiles of the scour hole,

throughout the entire scour development process. On the other hand, it was found that jet-flipping in the scour hole is associated with the opposite actions of the major roller and the bed roller: the former grows and acts (scouring or refilling) on the bed profile, while the latter shrinks in size and reduces its action on the bed profile.

7.3 Scour mechanism

The uplifted sediments from the short interface on the bed slope can be classified into three groups based on the repetitive sediment movements: Group 1 sediments move upstream and recirculate with the major roller; Group 2 sediments are entrained towards downstream but falling back onto the downstream slope of the scour hole; and Group 3 sediments are successfully transported out of the scour hole and over the top of the downstream mound. Only Group 3 sediment contributes to the growth of the scour hole, while Groups 1 and 2, though uplifted from the bed, do not play this role. The profile of the scour hole is constantly transforming with uplifted sediment up to the equilibrium scouring stage. The scour hole stops growing in depth then, mainly because the uplifted sediments are not transported out of the scour hole. In other words, local bed shear stress on the bed profile plays but a secondary role in the scour mechanism, although it remains higher than the critical value for sediment incipient motion during the equilibrium scouring stage.

The impingement of jet on the scour hole bed caused the predominant energy of the jet to alternate between kinetic and potential energy components. Only through this impingement does a significant portion of energy in the issuing jet is transferred from the jet to the kinetic energy of sediment, i.e. uplifting the sediment. On the other hand, a gap gradually enlarges between two regions of the main jet with high capacity of sediment transport. The sediments that are successfully entrained past this gap consist of the Group 3 sediments. With the enlarging gap, the entrainment of Group 3 sediments reduces significantly, and eventually, disappear leading to an equilibrium scouring stage.

7.2 Recommendations

The present study focuses on the principal features of dynamic flow structures in a local scour hole, and more efforts are needed to study the impact of each important parameter

on the flow structures, such as the flowrate, apron length, weir height, and tailwater depth. Precise mathematical model of dynamic flow fields, e.g. the size of the rollers and the distributions of the 1st and 2nd-order moments, in a local scour hole can be developed and validated using the PIV data in the future. The mathematical model provides a solid support to simulate the scouring mechanism numerically, given that the traditional considerations of the bed shear stress alone are not sufficient to accurately model the scouring action.

REFERENCES

- Adduce, C., and G. Sciortino (2006), Scour due to a horizontal turbulent jet: Numerical and experimental investigation, *J. Hydraul. Res.*, 44(5), 663-673.
- Adduce, C., and M. L. Rocca (2006), Local scouring due to turbulent water jets downstream of a trapezoidal drop: Laboratory experiments and stability analysis, *Water Resour. Res.*, 42(2), W02405.
- Albayrak, I., E. Hopfinger, and U. Lemmin (2008), Near-field flow structure of a confined wall jet on flat and concave rough walls, *J. Fluid Mech.*, 606, 27-49.
- Albertson, M. L., Y. Dai, R. Jensen, and H. Rouse (1950), Diffusion of submerged jets, *Trans. Am. Soc. Civ. Eng.*, 115(1), 639-664.
- Ali, K., and S. Y. Lim (1986), Local scour caused by submerged wall jets, *Proc. Inst. Civ. Eng.*, 81(4), 607-645.
- Azimi, A. H., N. Rajaratnam, and D. Z. Zhu (2014), Submerged flows over rectangular weirs of finite crest length, *J. Irrig. Drain. Eng.*, 140(5), 06014001.
- Balachandar, R., and J. A. Kells (1997), Local channel scour in uniformly graded sediments: the time-scale problem, *Can. J. Civ. Eng.*, 24(5), 799-807.
- Balachandar, R., and J. A. Kells (1998), Instantaneous water surface and bed scour profiles using video image analysis, *Can. J. Civ. Eng.*, 25(4), 662-667.
- Balachandar, R., and H. P. Reddy (2013), *Scour caused by wall jets*, InTech Open Access Publisher.
- Balachandar, R., J. Kells, and R. Thiessen (2000), The effect of tailwater depth on the dynamics of local scour, *Can. J. Civ. Eng.*, 27(1), 138-150.
- Beltaos, S. (1976a), Oblique impingement of plane turbulent jets, *J. Hydraul. Eng. Div.*, 102(9), 1177-1192.
- Beltaos, S. (1976b), Oblique impingement of circular turbulent jets, *J. Hydraul. Res.*, 14(1), 17-36.
- Beltaos, S., and N. Rajaratnam (1973), Plane turbulent impinging jets, *J. Hydraul. Res.*, 11(1), 29-59.
- Bennett, S. J., C. V. Alonso, S. N. Prasad, and M. J. M. Römkens (2000), Experiments on headcut growth and migration in concentrated flows typical of upland areas, *Water Resour. Res.*, 36(7), 1911-1922.

- Bey, A., M. A. A. Faruque, and R. Balachandar (2007), Two-dimensional scour hole problem: Role of fluid structures, *J. Hydraul. Eng.*, 133(4), 414-430.
- Boillot, A., and A. K. Prasad (1996), Optimization procedure for pulse separation in cross-correlation PIV, *Exp. Fluids*, 21(2), 87-93.
- Bormann, N. E., and P. Y. Julien (1991), Scour downstream of grade-control structures, *J. Hydraul. Eng.*, 117(5), 579-594.
- Chien, N., and Z. Wan (1999), *Mechanics of Sediment Transport*, American Society of Civil Engineers.
- D'Agostino, V., and V. Ferro (2004), Scour on alluvial bed downstream of grade-control structures, *J. Hydraul. Eng.*, 130(1), 24-37.
- Dey, S., and A. Sarkar (2006), Scour downstream of an apron due to submerged horizontal jets, *J. Hydraul. Eng.*, 132(3), 246-257.
- Dey, S., and R. V. Raikar (2007), Scour below a high vertical drop, *J. Hydraul. Eng.*, 133(5), 564-568.
- Dey, S., and A. Sarkar (2008), Characteristics of submerged jets in evolving scour hole downstream of an apron, *J. Eng. Mech.*, 134(11), 927-936.
- Dodaro, G., A. Tafarojnoruz, G. Sciortino, C. Adduce, F. Calomino, and R. Gaudio (2016), Modified Einstein sediment transport method to simulate the local scour evolution downstream of a rigid bed, *J. Hydraul. Eng.*, 142(11), 04016041.
- Fiorotto, V., E. Caroni, and S. Calligaris (2014), Scour on alluvial bed downstream of falling jets, in *River Flow 2014*, edited by A. J. Schleiss, G. DeCesare, M. J. Franca and M. Pfister, pp. 1509-1517, CRC Press-Taylor & Francis Group, Boca Raton.
- Fritz, H. M., and W. H. Hager (1998), Hydraulics of embankment weirs, *J. Hydraul. Eng.*, 124(9), 963-971.
- Gaudio, R., A. Marion, and V. Bovolin (2000), Morphological effects of bed sills in degrading rivers, *J. Hydraul. Res.*, 38(2), 89-96.
- Guan, D., B. W. Melville, and H. Friedrich (2014), Flow patterns and turbulence structures in a scour hole downstream of a submerged weir, *J. Hydraul. Eng.*, 140(1), 68-76.
- Guan, D., B. W. Melville, and H. Friedrich (2015), Live-bed scour at submerged weirs, *J. Hydraul. Eng.*, 141(2), 04014071.
- Guan, D., B. W. Melville, and H. Friedrich (2016), Local scour at submerged weirs in sand-bed channels, *J. Hydraul. Res.*, 1-13.

- Hassan, N. M. K. N., and R. Narayanan (1985), Local scour downstream of an apron, *J. Hydraul. Eng.*, 111(11), 1371-1385.
- Hill, D. F., and B. D. Younkin (2006), PIV measurements of flow in and around scour holes, *Exp. Fluids*, 41(2), 295-307.
- Hoffmans, G. J. C. M. (1998), Jet scour in equilibrium phase, *J. Hydraul. Eng.*, 124(4), 430-437.
- Hoffmans, G. J. C. M., and R. Booij (1993), Two-dimensional mathematical modelling of local-scour holes, *J. Hydraul. Res.*, 31(5), 615-634.
- Hoffmans, G. J. C. M., and H. J. Verheij (1997), *Scour Manual*, Rotterdam, Netherlands : A.A. Balkema, 1997.
- Hogg, A. J., H. E. Huppert, and W. B. Dade (1997), Erosion by planar turbulent wall jets, *J. Fluid Mech.*, 338, 317-340.
- Hopfinger, E., A. Kurniawan, W. Graf, and U. Lemmin (2004), Sediment erosion by Görtler vortices: the scour-hole problem, *J. Fluid Mech.*, 520, 327-342.
- Jalil, A., and N. Rajaratnam (2006), Oblique impingement of circular water jets on a plane boundary, *J. Hydraul. Res.*, 44(6), 807-814.
- Jia, Y., T. Kitamura, and S. S. Y. Wang (2001), Simulation of scour process in plunging pool of loose bed-material, *J. Hydraul. Eng.*, 127(3), 219-229.
- Johnston, A. J. (1990), Scour hole developments in shallow tailwater, *J. Hydraul. Res.*, 28(3), 341-354.
- Johnston, A. J., and A. R. Halliwell (1986), Jet behavior in shallow receiving water, *Proc. Inst. Civ. Eng., Part 2 Res. Theory*, 81, 549-568.
- Kabiri-Samani, A., A. Ansari, and S. M. Borghei (2010), Hydraulic behaviour of flow over an oblique weir, *J. Hydraul. Res.*, 48(5), 669-673.
- Kamoi, A., and H. Tanaka (1972), Measurements of wall shear stress, wall pressure and fluctuations in the stagnation region produced by oblique jet impingement, Conference on Fluid Dynamic Measurements in the Industrial and Medical Environment, 217-227.
- Karim, O. A., and K. Ali (2000), Prediction of flow patterns in local scour holes caused by turbulent water jets, *J. Hydraul. Res.*, 38(4), 279-287.
- Kou, B., Y. Cao, J. Li, C. Xia, Z. Li, H. Dong, A. Zhang, J. Zhang, W. Kob, and Y. Wang (2017), Granular materials flow like complex fluids, *Nature*, 551(7680), 360.
- Kundu, P. K., I. M. Cohen, and D. R. Dowling (2011), *Fluid Mechanics*, 5th ed., London: Academic, 2011.

Kurniawan, A., and M. S. Altinakar (2002), Velocity and turbulence measurements in a scour hole using an acoustic doppler velocity profiler, The third International Symposium on ultrasonic Doppler methods for fluid mechanics and fluid engineering, Lausanne, Switzerland, 37-43.

Lee, C.-H., C. Xu, and Z. Huang (2017), A three-phase flow simulation of local scour caused by a submerged wall jet with a water-air interface, *Adv. Water Resour.*

Lenzi, M. A., A. Marion, F. Comiti, and R. Gaudio (2002), Local scouring in low and high gradient streams at bed sills, *J. Hydraul. Res.*, 40(6), 731-739.

Lim, S. Y. (1997), Equilibrium clear-water scour around an abutment, *J. Hydraul. Eng.*, 123(3), 237-243.

Lim, S. Y., and N. S. Cheng (1998), Prediction of live-bed scour at bridge abutments, *J. Hydraul. Eng.*, 124(6), 635-638.

Lin, C., W. Y. Hwung, S. C. Hsieh, and K. A. Chang (2007), Experimental study on mean velocity characteristics of flow over vertical drop, *J. Hydraul. Res.*, 45(1), 33-42.

Lin, C., S. C. Hsieh, K. J. Kuo, and K. A. Chang (2008), Periodic oscillation caused by a flow over a vertical drop pool, *J. Hydraul. Eng.*, 134(7), 948-960.

Liu, P. Q., J. Z. Gao, and Y. M. Li (1998a), Experimental investigation of submerged impinging jets in a plunge pool downstream of large dams, *Sci. China, Ser. E*, 41(4), 357-365.

Liu, P. Q., J. R. Dong, and C. Yu (1998b), Experimental investigation of fluctuation uplift on rock blocks at the bottom of the scour pool downstream of Three-Gorges spillway, *J. Hydraul. Res.*, 36(1), 55-68.

Manes, C., and M. Brocchini (2015), Local scour around structures and the phenomenology of turbulence, *J. Fluid Mech.*, 779, 309-324.

Mason, P. J., and K. Arumugam (1985), Free jet scour below dams and flip buckets, *J. Hydraul. Eng.*, 111(2), 220-235.

Meftah, M. B., and M. Mossa (2006), Scour holes downstream of bed sills in low-gradient channels, *J. Hydraul. Res.*, 44(4), 497-509.

Raffel, M., C. E. Willert, and J. Kompenhans (2007), *Particle Image Velocimetry: A Practical Guide*, Springer Science & Business Media.

Rajaratnam, N. (1976), *Turbulent Jets*, Elsevier.

Rajaratnam, N. (1981), Erosion by plane turbulent jets, *J. Hydraul. Res.*, 19(4), 339-358.

Robinson, K. M., K. R. Cook, and G. J. Hanson (2000), Velocity field measurements at

an overfall, *Trans. ASAE*, 43(3), 665-670.

Scarano, F., and M. L. Riethmuller (1999), Iterative multigrid approach in PIV image processing with discrete window offset, *Exp. Fluids*, 26(6), 513-523.

Schoklitsch, A. (1932), Kolkbildung unter überfallstrahlen, *Wasserwirtschaft*, 24.

Si, J. H., S. Y. Lim, and X. K. Wang (2018), Flow structures in evolving scour holes caused by a plunging jet downstream of a weir, *J. Hydraul. Eng.*, 144(6), 04018018.

Stein, O. R., P. Y. Julien, and C. V. Alonso (1993), Mechanics of jet scour downstream of a headcut, *J. Hydraul. Res.*, 31(6), 723-738.

Tregnaghi, M., A. Marion, and R. Gaudio (2007), Affinity and similarity of local scour holes at bed sills, *Water Resour. Res.*, 43(11).

Wu, S., and N. Rajaratnam (1996), Submerged flow regimes of rectangular sharp-crested weirs, *J. Hydraul. Eng.*, 122(7), 412-414.

Wu, S., and N. Rajaratnam (1998), Impinging jet and surface flow regimes at drop, *J. Hydraul. Res.*, 36(1), 69-74.

Xie, C., and S. Y. Lim (2015), Effects of jet flipping on local scour downstream of a sluice gate, *J. Hydraul. Eng.*, 141(4), 04014088.

Zhang, R.-J. (2008), *Mechanics of Sediment Transportaion in Rivers (in Chinese)*, China Electric Power Press.

Zhao, X., X. Zhang, M. Zhao, and H. Tong (2009), *Hydraulics (in Chinese)*, China Electric Power Press.