Propeller jet flow and its associated scour hole around open quay structures

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**NANYANG
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UNIVERSITY**

SINGAPORE

**PROPELLER JET FLOW AND ITS ASSOCIATED
SCOUR HOLE AROUND OPEN QUAY STRUCTURES**

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Propeller Jet Flow and Its Associated Scour Hole around Open Quay Structures

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SUMMARY

This study presents the experimental results on the flow field of the confined propeller jet and its associated scour hole around an open-type quay. The experimental procedure was conducted in three phases.

Experiment Phase I (EP-I) started with a simple case of plane boundary confined propeller jet and focused on velocity measurement. The objective was to investigate the influence of the clearance height (vertical distance between propeller axis and plane boundary) on the development of the 3-dimensional propeller jet. To this end, both the streamwise and transverse flow fields were measured by using particle image velocimetry (PIV) technique, in such a way the 3-dimensional characteristics of the propeller jet was reconstructed. Similar to a confined offset jet, the propeller jet also exhibits a wall attachment behavior when it is placed near a plane boundary. As a result, in contrast to its unconfined counterpart, the confined propeller jet features three regions, namely the free jet, impingement and wall jet regions. The result shows that the extent of each region varies under different clearance heights. The development of the mean flow and turbulence characteristics associated with varying clearance heights are compared to illustrate boundary effects in these regions. In the impingement region, the measured transverse flow fields provide new insights on the lateral motions induced by the impingement of the swirling jet. In the wall jet region, observations reveal that the jet behaves like a typical 3-dimensional wall jet and its axial velocity profiles show good agreement with the classical wall jet similarity function.

Experiment Phase II (EP-II) shifted the focus to the scour measurement, in which the temporal and spatial developments of the scour hole around an open-type quay model have been investigated. The longitudinal distance between the propeller face and toe of the quay slope, *i.e.*, toe clearance, was systematically varied to examine its effect on the scour hole development. The results reveal that the asymptotic centerline profile undergoes significant transitions with varying toe clearances, during which three toe clearance fields have been recognized, namely the near toe clearance, intermediate toe clearance and far toe clearance fields. Based on characteristics of the asymptotic scour hole, it may be inferred that two scouring mechanisms, namely jet diffusion and quay obstruction, govern the scouring process and dictate whether the scour hole forms in any one of these three fields. The influence of these two mechanisms on the development of the scour characteristic dimensions in each field was also investigated based on which quantitative demarcations amongst the fields were obtained.

To further confirm the inference regarding the scouring mechanisms made in EP-II, the propeller jet flow within the developing scour hole was measured in Experiment Phase III (EP-III). The so obtained flow field data and its associated scour hole profile could, therefore, be connected directly, which provides a comprehensive understanding of the interaction between propeller jet flow and the erodible sand bed. By adopting a similar experimental configuration as that in EP-II experiments, EP-III was conducted at four selected toe clearances, which covered all three toe clearance fields defined in EP-II. The jet diffusion and quay obstruction mechanisms were visualized as the main jet flow and vortex in the form of vector and streamline plots. The relative importance of the main jet flow and vortex was discussed in the perspective of their contribution in shaping the final bedform in each toe clearance field. Moreover, turbulence intensity

and near-bed Reynolds stress were analyzed for the selected case in the intermediate field, both of them exhibit a declining trend with the development of the scour hole. As the scouring process approaches the asymptotic phase, the bed shear stress (estimated by the near-bed Reynolds stress) falls below the critical shear stress across the entire scour hole, and its longitudinal variation exhibits a similar trend with that of the critical shear stress.

LIST OF PUBLICATIONS

Journal Articles

- Wei, M. X., and Chiew, Y. M. (2017). "Influence of Toe Clearance on Propeller Scour Around an Open-Type Quay." *Journal of Hydraulic Engineering*, 04017012.
- Wei, M. X., Chiew, Y. M., and Hsieh, S. C. (2017). "Plane Boundary Effects on Characteristics of Propeller Jets." *Experiments in Fluids*, 58(10), 141.
- Wei, M. X., and Chiew, Y. M. (2017). "Characteristics of Propeller Jet Flow within Developing Scour Holes around an Open Quay." *Journal of Hydraulic Engineering*. (accepted, in press)
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- Wei, M. X., Chiew, Y. M., and Guan D. W. (2018). "Turbulent Flow Field of Propeller Jet around an Open-Type Quay." *The 15th International Coastal Symposium*. Busan, South Korea.
- Hsieh, S. C., Chiew, Y. M., Wei, M. X., and Low, Y. M. (2016). "Local Scour and Flow Characteristics Around a Circular Cylinder Undergoing Vortex-Induced Vibration." *The 8th International Conference on Scour and Erosion*. Oxford, UK.
- Wei, M. X., and Chiew, Y. M. (2015). "Propeller Scour Around an Open Berth Quay." *The 36th IAHR World Congress*. The Hague, the Netherlands.

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LIST OF SYMBOLS

The following symbols are used in this thesis:

A = area of actuator disc;

a_k, b_k = coefficients;

$c_{1,2}$ = numerical constant;

C = bed clearance measured from propeller tip;

C_o = a constant represents the ratio of the standard deviation of velocity with the axial distance;

C_D = drag coefficient;

C_L = lift coefficient;

C_t = thrust coefficient;

d = sediment grain size;

d_{16} = particle size where 16% of the particles are finer by weight;

d_{50} = median sediment size;

d_{84} = particle size where 84% of the particles are finer by weight;

d_l = deposition height on left side;

d_r = deposition height on right side;

D = diameter of jet at the nozzle, width of squared orifice or propeller diameter where applicable;

D_h = propeller hub diameter;

D_p = propeller diameter;

f = lens aperture;

F = hydrodynamic lift force;

F_o = densimetric Froude number;
 F_D = drag force;
 F_L = lift force;
 g = gravitational acceleration;
 G = gravity force;
 h_t = tailwater depth;
 I = equivalent turbulence intensity;
 i, j, k = index;
 $l_{m,c}$ = maximum asymptotic scour length in confined case;
 $l_{m,u}$ = maximum asymptotic scour length in unconfined case;
 L_m = propeller characteristic length term;
 n = propeller rotational speed;
 N = blade number;
 P = blade pitch;
 P' = pitch ratio;
 P_A = section A pressure;
 P_B = section B pressure;
 P_C = section C pressure;
 P_D = section D pressure;
 r = radial distance within the jet;
 R = resultant force;
 Re_{flow} = Reynolds number of flow;
 Re_{prop} = Reynolds number of propeller;
 R_h = radius of propeller hub;
 R_m = location of maximum velocity at an arbitrary section;

- R_{mo} = location of maximum velocity at efflux plane;
 R_o = resultant efflux velocity;
 R_p = radius of propeller;
 t = time;
 T = thrust;
 t_s = time to start scouring processes;
 u = mean horizontal velocity;
 u_c = centerline velocity along propeller axis;
 u_m = local maximum horizontal velocity;
 u_s = flow velocity acting on a sediment particle;
 $u_{x,r}$ = mean velocity at any position in the jet defined by the axial direction x ,
from the initial efflux plane and the radial distance r , from the rotation
axis;
 $u_{x,z}$ = mean velocity at any position in the jet defined by the axial direction x ,
from the initial efflux plane and the vertical distance z , from the
rotation axis;
 u' = horizontal velocity fluctuations;
 $\frac{\sqrt{u'^2}}{U_o}$ = horizontal turbulence intensity;
 U_o = axial efflux velocity;
 v = mean lateral velocity;
 v' = lateral velocity fluctuations;
 V_o = rotational efflux velocity;
 V_A = section A velocity;
 V_B = section B velocity;

- V_C = section C velocity;
- V_D = section D velocity;
- w = mean vertical velocity;
- w' = vertical velocity fluctuations;
- $\frac{\sqrt{w'^2}}{U_o}$ = vertical turbulence intensity;
- $-\frac{\overline{u'w'}}{U_o}$ = Reynolds shear stress;
- W_o = radial efflux velocity;
- $w_{m,c}$ = maximum asymptotic scour width in confined case;
- $w_{m,u}$ = maximum asymptotic scour width in unconfined case;
- x = longitudinal distance measured from propeller face;
- x' = corrected coordinates in x direction;
- $X_{m,c}$ = longitudinal location of maximum asymptotic scour depth in confined case;
- $X_{m,u}$ = longitudinal location of maximum asymptotic scour depth in unconfined case;
- X_t = toe clearance;
- y = lateral distance measured from propeller axis;
- Y_w = Horizontal distance from the propeller axis to the face of the quay wall;
- z = vertical distance measured from bed;
- z' = corrected coordinates in z direction;
- z_m = the height where $u = u_m$ occurs;
- $z_{m/2}$ = the height where $u = u_m/2$ occurs;
- Z_b = clearance height measured from propeller axis to bed;

- α = depression angle of oblique camera
- α_{FH} = angle between hydrodynamic lift force and horizontal;
- α_{FR} = angle between hydrodynamic lift force and resultant force;
- β = blade area ratio;
- δ = the characteristic length scale of the jet profile;
- $\varepsilon_{\max}$ = maximum asymptotic scour depth induced by circular jets;
- $\varepsilon_{m,c}$ = maximum asymptotic scour depth in confined case;
- ε_{mfw} = maximum scour depth around the perpendicular quay wall;
- $\varepsilon_{m,r}$ = maximum scour depth in the presence of a rudder;
- $\varepsilon_{m,r,p}$ = maximum scour depth in the presence of a rudder and parallel quay wall;
- ε_{msw} = maximum depth of scour around the parallel quay wall;
- $\varepsilon_{m,t}$ = maximum scour depth at each time interval;
- $\varepsilon_{m,u}$ = maximum asymptotic scour depth in unconfined case;
- $\varepsilon_{m,u,a}$ = maximum asymptotic scour depth (measured from propeller axis) in unconfined case;
- θ = rudder angle in degrees or radians;
- θ' = sediment repose angle;
- $\theta_{1,2}$ = refraction angle;
- λ = sediment coefficient;
- λ_s = specific weight of the sediment;
- λ_w = specific weight of the water;
- ν = kinematic viscosity of the fluid;
- ξ = efflux coefficient;
- ρ = density of water;

ρ_s = density of sediment;

$\Delta\rho$ = difference between the sediment-grain density and water density;

σ = standard deviation of velocity at lateral section;

σ_g = geometric standard deviation of sediment particles;

T = experimental coefficient;

τ_b = near-bed Reynolds stress;

τ_c = critical shear stress for horizontal bed;

τ'_c = critical shear stress for sloping bed;

φ = angle between flow direction and the tangent to the highest downstream support point;

φ' = angle of sloping bed;

ψ = angle of friction of the sediment;

ω = angular velocity; and

Ω = experimental coefficient.

ADV = Acoustic Doppler Velocimetry

ADVP = Acoustic Doppler Velocity Profiler

EP = Experiment Phase

FOV = Field of View

LDA = Laser Doppler Anemometry

PIV = Particle Image Velocimetry

SPIV = Stereo Particle Image Velocimetry

CHAPTER 1

INTRODUCTION

1.1 Background

Marine transport or shipping has formed the backbone of the growing international market and globalization ever since the Age of Discovery. Today, it is still undergoing continuous development to satisfy the ever-changing demands of the world trade. PIANC (2015) reported that during the last decade the shipping industry development was based on an increase in capacity, which inevitably is accompanied by the increase in engine power. As a result, higher flow velocities generated by larger and more powerful propellers have caused more scour-related damages to the bed and banks of harbor basins and navigation channels, when the under-keel clearance is small and the sea bed and banks are not designed for such velocities. Although the tidal current can also induce scour around the quay structures, they are insignificant when compared with that related to ship propellers (PIANC 2015). For this reason, ship propeller-induced jet flow is commonly the main cause of scour. In addition to the main propeller at the rear of the ship, modern ships are also equipped with bow and stern thrusters (see Fig. 1.1) for maneuverability, which further aggravate the scouring problem during the mooring and unmooring process.

Fig. 1.1 Ship propellers, bow and stern thrusters (redrawn from Sumer and Fredsøe 2002)

Longe (1987) reported that the efflux velocity of a rotating propeller and the associated bed velocities could reach $11 \sim 12$ m/s and $3 \sim 4$ m/s, respectively. As for the thrusters, Sumer and Fredsøe (2002) reported that the nozzle velocities and the bed velocities could also reach as high as $8 \sim 9$ m/s and $3 \sim 3.5$ m/s, respectively. The bed sediment can, therefore, be easily eroded. de Gijt and Broeken (2005) stated that the propeller-induced scour hole might reach several meters deep if the bed material is sand and non-cohesive soils with low undrained shear strength. Since the quay structure is present in close proximity to the ship propeller, the maximum scour depth often occurs at the base of quay walls, which may result in structural instability or even failure. This is especially true for the roll-on roll-off ships, which dock at the same position of a berth because of the built-in ramps. Consequently, the quay structures are directly exposed to the cumulative attack by the propeller jet. Fig. 1.2 and Fig. 1.3 respectively illustrate how the jet flow is deflected in the case of a roll-on roll-off ship with a stern ramp and bow thruster.

Fig. 1.2 Jet flow deflection in the case of Ro-Ro ship (redrawn from Sumer and Fredsøe 2002)

Fig. 1.3 Jet flow deflection in the case of bow thrusters (redrawn from Sumer and Fredsøe 2002)

A number of case studies on propeller jet induced damages at quay structures have been reported, including both situations berthing with the stern directed toward the quay structure and using bow thrusters maneuvering parallel to the quay wall (Bergh and Cederwall 1981; Chait 1987; Quarraïn 1994; and Hamill *et al.* 1999). Tsinker (1995) suggested that propeller-induced scour should be taken into account when designing new port-related marine structures or reevaluating the performance of structures-in-service. He also reported that all types of marine structures could suffer from propeller-induced scour, especially those supported by a designed bottom level against horizontal and vertical loads, such as piled platforms, sheet pile bulkheads, gravity-type structures and open platforms type structures with rip-rap-protected slopes. PIANC (2015) also highlighted the significance of the insight into ship propeller induced flow and the resulting damage for protecting the quay structures. With reference to the impact of propeller jet, Sumer and Fredsøe (2002) and PIANC (2015) stated that the quay structures can mainly be categorized into two principal types, namely, closed and open quays as shown in Fig. 1.4. For the former, a vertical solid wall is constructed in the berth front to resist the horizontal load from the landfill and any other live loads. For the latter, a quay slab, which is supported by a group of piles, columns or lamellar walls

embedded in a dredged, filled or natural slope, is built. The scour issue associated with the closed quay is basically limited to the area in front of the berth front wall; however, it is more complex in the open quay where scouring could occur near the berthing face as well as the slope itself (PIANC 2015). Most previous studies hitherto have been focused on the scour problem in the closed quay, which will be discussed in Chapter 2.

Fig. 1.4 Quay structures: (a) Closed and (b) Open quays (redrawn from Sumer and Fredsøe 2002)

1.2 Purpose and Scope of This Study

de Gijt and Broeken (2005) suggested that designers of quay structures must consider the potential risk of propeller-induced scour damage in their design of the depth of foundation, position of the intermediate sheet piles and toe elevation. Thus far, considerable research has been carried out to study the characteristics of the propeller jet flow as well as the associated scouring action for both unconfined jet in the absence of any berthing structures and the confined jet in the presence of closed quay wall. However, there is limited work available for the case of propeller scour in the open-type quay. To bridge this gap, the primary objective of this study was to provide an

improved understanding of the characteristics of confined propeller jet flow and propeller scouring action around the open-type quay so that new design criteria regarding quay foundation or scour protection work may be proposed for reducing and preventing the occurrences of failure. To achieve these objectives, an extensive experimental program has been carried out based on the following phases:

Experiment Phase I (hereinafter referred to as EP-I): Measurement of flow field of the propeller jet has been conducted under different clearance heights (vertical distance between the propeller axis and the plane boundary) in the presence of a rigid plane boundary. The purpose of this phase is to examine boundary effects on the development of the propeller jet.

Experiment Phase II (hereinafter referred to as EP-II): Measurement of the propeller-induced scour hole around an open quay has been made under different toe clearances (longitudinal distance between propeller face and quay slope toe). The purpose of this phase is to investigate the influence of the toe clearance on the development of the scour hole.

Experiment Phase III (hereinafter referred to as EP-III): Measurement of flow field governing the scour hole development has been carried out by using the high-speed particle image velocimetry (PIV) technique. Based on the results of EP-I and EP-II, typical test conditions have been selected for the experiments in EP-III, whose purpose is to reveal the scouring mechanisms of the propeller jet in the open quay.

1.3 Layout of the Thesis

This thesis is organized into seven chapters. Chapter 1, *i.e.* the present chapter, starts with a background and motivation of the subject. The purpose and scope of the study are also presented in this chapter.

Chapter 2 gives an overview of the state-of-the-art researches concerning the characteristics of propeller jet and the associated scouring action for both the unconfined case as well as the confined case in the presence of a closed or open quay.

Chapter 3 describes the experimental apparatus and data acquisition techniques used in this study for measuring the velocity field and scour profile. The corresponding experimental setup and procedures applicable to the stated three experiment phases are also presented.

Chapter 4 (EP-I) presents the flow field characteristics of the confined propeller jet in the presence of a plane boundary. The influence of clearance height is examined in this chapter. Results of the mean flow field and turbulence characteristics are analyzed and discussed.

Chapter 5 (EP-II) reports the results and discussion regarding the propeller scouring action around an open quay under different test conditions. In particular, the influence of toe clearance is systematically studied. The associated scour profiles are compared with published data and characterized by three toe clearance fields.

Chapter 6 (EP-III) deals with the results of the flow field around the mobile bed in an attempt to explain the scouring mechanisms in different toe clearance fields defined in Chapter 5.

Finally, Chapter 7 summarizes the essential findings of the current study and proposes recommendations for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Ship Propeller Jet

2.1.1 Introduction

As the driving force of ship propeller scour, the propeller jet must be fully understood with respect to the characteristics of the velocity distributions within it. Experimental studies on ship propeller jets have received extensive attentions by both naval architects and hydraulic/coastal engineers. For the former, aiming to optimize the design of the propeller blade geometry, their concerns have been focused on the velocity and pressure measurements in the vicinity of the propeller, e.g. Felli *et al.* (2006). For the latter, in the view of hydraulic and coastal engineering, the research interests have been more concentrated on the downstream development of the propeller jet, which is essential to better understand the propeller scouring mechanisms and provide recommendations for designs of quay structures and scour prevention (Hamill and Kee 2016). The aim of this section is to give an overview of state-of-the-art researches of the latter, which is of great interest to the current study.

2.1.2 Formation of Propeller Jet

Due to the complex interactions between propeller rotation and the fluid medium, the ensuing velocity field is non-uniformly distributed. As the helicoidal blades rotate, the upstream water is drawn in, accelerated and discharged downstream; this increases the rearward momentum of the fluid, thus inducing a thrust that propels the ship forward. The discharge of water with high kinetic energy is referred to as “propeller jet”, which

comprises a complex three components of velocity in the axial, tangential (rotational) and radial components (see Fig. 2.1). With its direction along the axis of the propeller, the axial velocity has been the most studied and considered as the main contributor to the resultant velocity magnitude. On the other hand, the tangential and radial components of the velocity are responsible for the rotational and diffusive behaviors, respectively. This peculiar behavior differentiates the swirling propeller jet from the common 3-dimensional jets (Johnston *et al.* 2013). Fig. 2.2 shows a propeller jet with the swirl component behind the propeller blades. Sumer and Fredsøe (2002) termed such a jet in a water body without the interference of quay structures as an unconfined propeller jet.

Fig. 2.1 Velocity components of a propeller jet (McGarvey 1996)

Fig. 2.2 Rotation in a propeller jet (Sumer and Fredsøe 2002)

As for a maneuvering ship, the flow field is more complicated since it is actually a co-flow of a swirling propeller jet, coupled with a turbulent wake from the hull (Lam *et al.* 2011). However, Prosser (1986) suggested that the influence of the hull's geometry on the propeller jet is insignificant when the ship is stationary, or the advance velocity is low. Therefore, subsequent studies on propeller jet were mostly based on the sole consideration of the action of propeller jet itself under the bollard pull condition.

2.1.3 Diffusion of Submerged Jet

Early studies on jets were performed with a submerged plain water jet rather than the actual propeller jet. Albertson *et al.* (1950) stated that the slip stream of a propeller jet differs little from any other submerged jets. Therefore, its velocity distribution should be subject to the same method of analysis.

As for a submerged jet, a schematic representation of jet diffusion was given in Albertson *et al.* (1950) as shown in Fig. 2.3, in which the flow pattern is divided into two distinct flow zones, namely, the zone of flow establishment (ZFE) and the zone of established flow (ZEF). It was assumed that the fluid discharged from the boundary opening has a constant velocity core. At the efflux section, the velocity discontinuity between the jet and the surrounding fluid causes a lateral mixing process both inward and outward, which decelerates the fluid within the jet and accelerates the surrounding fluid. As a result, with the increase of distance from the efflux section, the velocity at the central core gradually decreases until the mixing region penetrates the centerline (see Fig. 2.3). The zone of flow establishment reaches its limit at this point and the zone of established flow starts, in which the diffusion process continues without essential change in nature.

Fig. 2.3 Schematic of a submerged jet from an orifice (Albertson *et al.* 1950)

2.1.4 Diffusion of Propeller Jet

Following Albertson *et al.* (1950)'s approach, Blaauw and Kaa (1978) conducted one of the earliest experimental studies on propeller jets. Subsequently, Berger *et al.* (1981), Verhey (1983), Hamill (1987), Stewart (1992), Hashmi (1993), Qurrain (1994), Ryan (2002), Hong *et al.* (2013) and Hong *et al.* (2016) *etc.* also carried out experimental investigations on ship propeller jet by using actual propeller model. Following a similar approach as Albertson *et al.* (1950), the flow field behind a propeller jet was also divided into two zones, namely the zone of flow establishment in the vicinity of the propeller, followed by the zone of established flow as shown in Fig. 2.4. It should be noted that a Right-Handed Coordinate System is adopted in Fig. 2.4 as the x -axis is streamwise-oriented along the propeller rotation axis; the y -axis along the spanwise-oriented towards the starboard, and the z -axis along the upward vertical. Accordingly, the corresponding velocity components along these three directions will be denoted as u , v and w , hereinafter. For the sake of uniformity, the notations in this thesis will follow the same coordinate system.

Fig. 2.4 Schematic of a propeller jet (Hamill 1987)

Due to the presence of the propeller hub, there exists a low-velocity core immediately behind it in the zone of flow establishment, which makes the location of the maximum velocity to be offset from the axis of rotation, as is shown in Fig. 2.4 in which the lower half is not shown. The influence of the hub was found to decrease gradually as the high-velocity flow penetrates into the low-velocity core (Hamill 1987). McGarvey (1996) reported that in the zone of flow establishment the flow is mixing with the receiving water both inwardly and outwardly; in the zone of established flow, however, the flow will only be mixing outwardly, and the maximum velocity peak occurs at the centerline position at this juncture.

2.1.5 Efflux Velocity

Efflux velocity has been used as the prerequisite parameter for predicting the entire velocity distribution within a diffusing jet. Unlike the common jet issuing from a certain orifice or nozzle, whose efflux velocity can be simply calculated by the flow rate divided by the cross-section area, the flow produced by a propeller is actually passing

through the slots between rotating blades and being influenced by the presence of the hub, which makes it difficult for one to define the efflux velocity as the common jets do. For this reason, previous researchers have devoted many efforts in determining the efflux velocity for a propeller jet both theoretically and experimentally as will be reviewed in the following sections.

2.1.5.1 Froude's axial momentum theory for efflux velocity

Albertson *et al.* (1950) investigated the submerged plane jet based on the axial momentum theory proposed by Froude. Due to the complex nature of propeller jet, early studies on the axial velocity field within a propeller jet were investigated by Blaauw and Kaa (1978) using the similar theory related to a submerged plane jet, in which an “Ideal Actuator Disc” concept and the following assumptions were applied:

- (1) The propeller can be represented by an infinitely thin disc.
- (2) The disc comprises an infinite number of blades.
- (3) It rotates at an infinite speed.
- (4) The velocity of the fluid through the disc is uniform over the entire area of the disc.
- (5) All energy supplied to the disc is in turn supplied to the fluid.
- (6) The surrounding fluid of the disc is ideal.

The Froude's axial momentum theory has been employed as the basis of many subsequent researches of propeller jets. Fig. 2.5 shows a propeller, represented by the ideal actuator disc that rests in a steady flow.

Fig. 2.5 Propeller model as an ideal actuator disc (Massey and Ward-Smith 2006)

Massey and Ward-Smith (2006) suggested that there exists a discontinuity of pressure and velocity across the boundary surface of the slipstream. Somewhere upstream of the disc, section A has velocity and pressure noted by V_A and P_A respectively. As the fluid approaches the disc at section B, the velocity increases from V_A to V_B while the pressure decrease from P_A to P_B . Due to the assumption of an infinitely thin disc (that is its thickness in the axial direction is negligible), the continuity governs the velocity at section B, *i.e.* $V_B = V_C$. The pressure, however, increases to P_C as the flow passing through the disc. Somewhere downstream of the disc, at section D, the velocity further increases to V_D and the pressure returns to that of the undisturbed state, *i.e.* $P_D = P_A$. For the incompressible fluid, as the axial velocity increases downstream, the cross-section of the slipstream is contracted as shown in Fig. 2.5. Based on the momentum

theory, the thrust of the actuator disc can be obtained by applying Bernoulli's equation, as follows,

$$T = \frac{1}{2}\rho A(V_D^2 - V_A^2) \quad (2.1)$$

in which T = thrust of the actuator disc, ρ = fluid density, A = actuator disc area. By a dimensional analysis, this thrust can also be written as

$$T = C_t \rho n^2 D_p^4 \quad (2.2)$$

in which C_t = thrust coefficient (dimensionless), n = propeller speed of rotation, D_p = propeller diameter.

Equating the above two expressions gives,

$$\frac{1}{2}\rho A(V_D^2 - V_A^2) = C_t \rho n^2 D_p^4 \quad (2.3)$$

Since the concerning situation is under bollard pull condition, the velocity of the ship is taken as zero, *i.e.*, $V_A = 0$, and $A = \pi D_p^2/4$, therefore

$$V_D = 1.59 n D_p \sqrt{C_t} \quad (2.4)$$

The detailed derivation can be found in Hamill (1987) and Steward (1992). According to Hamill (1987), this equation was widely used for calculating the efflux velocity of propeller jet by Rowakiewicz (1966), Blaauw and Kaa (1978) and Fuehrer *et al.* (1981) in the form of

$$U_o = 1.59 n D_p \sqrt{C_t} \quad (2.5)$$

where U_o is the axial efflux velocity of the propeller jet.

2.1.5.2 Semi-empirical equations for efflux velocity

Fuehrer *et al.* (1987) stated that Eq. (2.5) gave the prediction of efflux velocity with an error of $\pm 20\%$. The reason is that the assumptions made in the axial momentum theory may be erroneous in describing the actual propeller jet. For this reason, in the past few

decades, experimental studies have been carried out by employing actual propeller models. As the most significant contributor, the axial efflux velocity has been extensively examined. For an actual propeller, Hamill *et al.* (2004) defined the efflux velocity as the maximum velocity taken from a mean velocity distribution across the propeller face (see Fig. 2.6).

Fig. 2.6 Efflux velocity location along the propeller face (Hamill *et al.* 2004)

Hamill (1987) experimentally investigated the efflux velocity by using two propeller models and modified Eq. (2.5) with a lower coefficient value, as

$$U_o = 1.33nD_p\sqrt{C_t} \quad (2.6)$$

Stewart (1992) stated that the coefficient of 1.59 or 1.33 in the above equations was not a constant and should be replaced with an efflux coefficient ξ , which is a function of the geometrical characteristics of the propeller. Therefore, Eq. (2.5) was refined into the following form,

$$U_o = \xi nD_p\sqrt{C_t} \quad (2.7)$$

$$\xi = D_p^{-0.0686} \left(\frac{P}{D_p} \right)^{1.519} \beta^{-0.323} \quad (2.8)$$

where β = blade area ratio; P = pitch that can be defined as the theoretical forward movement of a propeller during one revolution; and P/D_p = pitch ratio of the propeller.

Following Stewart (1992), a similar analysis was conducted by Hashmi (1993), in which the efflux coefficient ξ was further refined by normalizing the propeller diameter by the hub diameter, as follows,

$$\xi = \left(\frac{D_p}{D_h}\right)^{-0.403} (C_t)^{-1.79} (\beta)^{0.744} \quad (2.9)$$

where D_h = diameter of the propeller hub.

More recently, Hamill *et al.* (2015) compared the preceding semi-empirical equations and suggested that the narrow test ranges would cause large errors when results from using these equations are extrapolated. By employing four propellers operating at a wide range of rotational speeds which are considered to have covered the typical operational situations, Hamill *et al.* (2015) further updated the prediction of the axial efflux velocity, giving the following equation,

$$U_o = 1.22n^{1.01}D_p^{0.84}C_t^{0.62} \quad (2.10)$$

Equation (2.10) is now used in several design guidelines, such as PIANC (2015) according to Hamill and Kee (2016). Also, the same authors made attempts to propose empirical equations regarding the rotational and radial efflux velocities, which, hitherto, have received limited experimental investigations. They found that the same set of variables, *i.e.*, the propeller speed of rotation (n), propeller diameter (D_p) and thrust coefficient (C_t), also controls the magnitude of the rotational and radial efflux velocities, *i.e.* V_o and W_o , respectively. The corresponding equations were given as

$$V_o = 1.23n^{1.05}D_p^{0.798}C_t^{1.186} \quad (2.11)$$

$$W_o = 0.153n^{0.986}D_p^{0.719}C_t^{0.344} \quad (2.12)$$

Moreover, the resultant velocity, R_o , at the efflux plane was also presented for the first time by Hamill *et al.* (2015), as follows,

$$R_o = 1.2n^{0.994}D_p^{0.719}C_t^{0.344} \quad (2.13)$$

A 3-dimensional resultant velocity distribution across efflux plane is shown in Fig. 2.7, which clearly reveals the swirling nature of a propeller jet.

Fig. 2.7 3-dimensional resultant velocity distribution (Hamill *et al.* 2015)

2.1.6 Zone of Flow Establishment

2.1.6.1 Position of the maximum velocity

Albertson *et al.* (1950) experimentally studied the location of the efflux velocity in the case of a plain water jet and found that the maximum velocity was located at the centerline of the jet. For a propeller jet, Hamill (1987) showed that the maximum velocity was offset from the rotation axis due to the presence of the hub, which produces no significant forward thrust. By considering the hub effect, Oebius and Schuster (1975) proposed an equation to predict the radial position of maximum velocity from the rotation axis, R_m , as follows:

$$R_m = 0.3R_{mo} \left(\frac{x}{R_{mo}} \right)^{-0.3} \quad (2.14)$$

where R_m = location of maximum velocity at an arbitrary section; and R_{mo} = location of

maximum velocity at the efflux plane; and x = distance from the propeller face to the location under consideration.

As for R_{mo} , it can be determined by using the following equation proposed by Berger *et al.* (1981),

$$R_{mo} = 0.67R_p - R_h \quad (2.15)$$

where R_p = radius of propeller; and R_h = radius of propeller hub. This equation was validated by Stewart (1992) in his experimental investigations. However, McGarvey (1996) reported that the error caused by Eq. (2.15) could be up to 30%. Hamill *et al.* (2004) found that the position of maximum velocity at the efflux plane is highly dependent on the geometrical property of the propeller.

2.1.6.2 Decay of maximum axial velocity

Albertson *et al.* (1950) suggested that there was no maximum velocity decay within the zone of establishment and proposed a relationship between the maximum velocity, u_m , and the efflux velocity, U_o , as follows:

$$\frac{u_m}{U_o} = 1 \quad (2.16)$$

Hamill (1987) found Eq. (2.16) is only valid for the range of $0 < x/D_p < 0.35$ for a propeller jet. Beyond this distance there exists a gradual decay of the maximum velocity, which can be described by the following equation:

$$\frac{u_m}{U_o} = 0.87 \left(\frac{x}{D_p} \right)^{-(\beta/4)} \quad (2.17)$$

Following this, Stewart (1992) conducted further investigations and found that the length of the zone of flow establishment was up to $x/D_p = 3.25$ from the propeller face.

He also proposed a linear relationship between maximum velocity decay and the distance downstream from the propeller.

$$\frac{u_m}{U_0} = 1.0172 - 0.1835 \left(\frac{x}{D_p} \right) \quad (2.18)$$

Hsieh *et al.* (2013) experimentally investigated the swirling jet induced by a propeller by using the PIV technique, and proposed a new empirical equation with $R^2 = 0.98$,

$$\frac{u_m}{U_0} = 15.12 e^{(-1.807 \frac{x}{D_p})} \left[1 - e^{\left(-\frac{\frac{x}{D_p}}{3.345} \right)} \right] + 0.344 \left(\frac{x}{D_p} \right) e^{\left(-\frac{\frac{x}{D_p}}{3.345} \right)} \quad (2.19)$$

Employing the Laser Doppler Anemometry (LDA), Hamill and Kee (2016) measured the propeller jet velocities for a range of four different propeller models. They reported that propeller pitch to diameter ratio P/D_p is also an influential variable of the decay of the maximum axial velocity, and a new semi-empirical equation was proposed accordingly as follows,

$$\frac{u_m}{U_0} = 1.51 - 0.175 \left(\frac{x}{D_p} \right) - 0.46 \left(\frac{P}{D_p} \right) \quad (2.20)$$

2.1.6.3 Velocity distribution within the zone of flow establishment

For the plane jet, Albertson *et al.* (1950) suggested that the axial velocity distribution within the zone of flow establishment can be described by two symmetrical halves of the Gaussian normal probability curve connected with a straight line through the constant velocity core as shown in Fig. 2.8, in which $u_{x,r}$ = mean velocity at any position in the jet defined by the axial direction x , from the initial efflux plane and the radial distance r , from the rotation axis; σ = standard deviation of velocity; and r = radial distance within the jet. They assumed that the diffusion process is dynamically similar at all cross sections and σ/x is constant, indicating that the diffusion angle is constant.

$$\frac{\sigma}{x} = C_o \quad (2.21)$$

where C_0 = a constant that represents the ratio of the standard deviation of velocity with the axial distance.

Fig. 2.8 Definition sketch of the zone of flow establishment (Albertson *et al.* 1950)

Considering the Gaussian normal probability curve alone, it can be expressed in the form of Eq. (2.22) and plotted as Fig. 2.9.

$$\frac{u_{x,r}}{u_m} = e^{\left(\frac{-r^2}{2\sigma^2}\right)} \quad (2.22)$$

Fig. 2.9 Gaussian normal probability curve (Albertson *et al.* 1950)

Subsequently, in order to describe the entire profile, r was replaced with a term to take account of the potential core where $u_m = U_o$, Eq. (2.22) was therefore refined as

$$\frac{u_{x,r}}{U_o} = e^{\left[\frac{-(r+C_0x-\frac{D_0r}{2})^2}{2(C_0x)^2}\right]} \quad (2.23)$$

For the propeller jet, its definition sketch of propeller jet in the zone of flow establishment is shown in Fig. 2.10.

Fig. 2.10 Definition sketch of propeller jet in the zone of flow establishment (after Hamill 1987)

Following a similar exponential expression as Eq. (2.22), Hamill (1987) proposed a piecewise function in terms of x to describe the axial velocity distribution within the zone of flow establishment as follows,

When $x < 0.5D_p$,

$$\frac{u_{x,r}}{u_m} = e^{\left[-\frac{1}{2} \left(\frac{r-R_{mo}}{\frac{R_{mo}}{2}} \right) \right]^2} \quad (2.24)$$

When $x > 0.5D_p$, an additional equation was given for determining the axial velocities for the remainder of the zone of flow establishment as follows,

$$\frac{u_{x,r}}{u_m} = e^{\left[-\frac{1}{2} \left(\frac{r-R_{mo}}{\frac{R_{mo}}{2} + 0.075(x-R_p)} \right) \right]^2} \quad (2.25)$$

Stewart (1992) conducted further experiments within the zone of flow establishment, whose results supported the above equations. In addition, he reported that the length of the zone of flow establishment would reach the distance about $3.25D_p$ downstream the propeller.

2.1.7 Zone of Established Flow

2.1.7.1 Decay of the maximum axial velocity

In the zone of established flow, the maximum axial velocity decays by entraining the surrounding fluid. Albertson *et al.* (1950) proposed a relationship between the decay of the maximum velocity of a submerged jet with respect to the distance from the efflux plane as follows,

$$\frac{u_m}{U_o} = \frac{1}{2C_o} \left(\frac{x}{D} \right)^{-1} \quad (2.26)$$

in which C_o = the same constant as that in Eq. (2.21).

Following this approach, subsequent researchers carried out further investigations on the decay of the maximum axial velocity within the propeller jet and produced a series of equations to predict the maximum velocity with respect to x/D_p , as tabulated in Table 2.1.

Table 2.1 List of equations for the decay of maximum axial velocity

Authors	Equations	No.
Fuehrer and Romisch (1977)	$\frac{u_m}{U_o} = 2.6 \left(\frac{x}{D_p} \right)^{-1.0}$	(2.27)
Blaauw and Kaa (1978)	$\frac{u_m}{U_o} = 2.8 \left(\frac{x}{D_p} \right)^{-1.0}$	(2.28)
Berger <i>et al.</i> (1981)	$\frac{u_m}{U_o} = 1.025 \left(\frac{x}{D_p} \right)^{-0.6}$	(2.29)
Verhey (1983)	$\frac{u_m}{U_o} = 1.275 \left(\frac{x}{D_p} \right)^{-0.7}$	(2.30)
Hamill (1987)	$\frac{u_m}{U_o} = A' \left(\frac{x}{D_p} \right)^{B'}$ $A' = -11.4C_t + 6.65\beta + 2.16\left(\frac{P}{D_p}\right)$ $B' = -(1.0C_t)^{-0.216}\beta^{1.024}\left(\frac{P}{D_p}\right)^{-1.0}$	(2.31)

Stewart (1992), however, suggested that the decay of the maximum velocity has nothing to do with the propeller geometry and rotational speed. A linear equation was given by Stewart (1992) as follows

$$\frac{u_m}{U_o} = 0.543 - 0.0281 \left(\frac{x}{D_p} \right) \quad (2.32)$$

Eq. (2.32) was deemed to be applicable up to a downstream distance of $x/D_p = 10$ within the zone of established flow. Hashmi (1993) found the length of the zone of established flow could be up to a downstream distance of $x/D_p = 16$. Accordingly, an additional equation was proposed to estimate the decay of maximum velocity in this range as follows,

$$\frac{u_m}{U_o} = 0.638e^{-0.097 \left(\frac{x}{D_p} \right)} \quad (2.33)$$

In conjunction with Eq. (2.20), Hamill and Kee (2016) also proposed a paired equation for the decay of the maximum axial velocity within the zone of established flow, as follows,

$$\frac{u_m}{U_o} = 0.964 - 0.039 \left(\frac{x}{D_p} \right) - 0.344 \left(\frac{P}{D_p} \right) \quad (2.34)$$

2.1.7.2 Velocity distribution within the zone of established flow

For the plane jet, Albertson *et al.* (1950) stated that the probability curve representing the velocity distribution is found to cross the line of symmetry in the zone of established flow as shown in Fig. 2.11, in which the rate of outward spread of the diffusion region can be directly represented by the ratio σ/x .

Fig. 2.11 Definition sketch of the zone of established flow (Albertson *et al.* 1950)

For the propeller jet, Fuehrer and Romisch (1977) determined a relationship for describing the axial velocity distribution within the zone of established flow, as follows,

$$\frac{u_{x,r}}{u_m} = e^{\left[-22.2\left(\frac{r}{x}\right)^2\right]} \quad (2.35)$$

This equation was verified by subsequent studies that involved actual propellers by Hamill (1987), Stewart (1992) and McGarvey (1996).

2.1.8 Propeller Jet in the Presence of Rudder

2.1.8.1 Effect of rudder

The rudder is a steering device located in front of the propeller and used for ship maneuvering (Sumer and Fredsøe 2002). Most researches dealing with the velocity distribution behind a ship's propeller were conducted in the absence of a rudder. While as a navigational device, the rudder may generate a different flow field. Robakiewicz (1966) suggested that the propeller jet would be split into two jets, namely surface and bottom jet, in the presence of a rudder in a central position in the propeller jet, the former directed upwards to the surface and the latter directed downwards to the seabed as shown in Fig. 2.12.

Fig. 2.12 Sketch of propeller jet splitting in the presence of a rudder (Sumer and Fredsøe 2002)

McGarvey (1996) conducted a series of experiments involving propeller flows in the presence of a rudder whose angle, θ , was changed in a range of $-35^\circ < \theta < +35^\circ$ as shown in Fig. 2.13. The rudder angle of 35° is the practical limit for effective steering (Sumer and Fredsøe 2002). McGarvey (1996) found that negative angles produced the bottom jet and positive angles produced the surface jet for right rotating propellers.

Fig. 2.13 Sketch of the rudder angle (Sumer and Fredsøe 2002)

2.1.8.2 Decay of the maximum velocity

Verhey (1983) experimentally investigated the velocities behind a rotating propeller in the presence of a rudder and suggested the following relationship to determine the maximum axial velocity in the case of zero rudder angle.

$$\frac{u_m}{U_0} = \left[\frac{2cx}{D_0} \right]^{-b} \quad (2.36)$$

where $D_0 = 0.71D_p$; b = coefficient averaged at 1.1; and c = coefficient averaged at 0.18. Since Eq. (2.36) was proposed for the case of the single rudder at zero rudder angle only, the same author also proposed an additional equation to account for the varying rudder angles, as follows:

$$\frac{u_m}{U_0} = \delta \left[\frac{x}{2.8D_0} \right]^{-b} \quad (2.37)$$

where $\delta = [1 + (5.2 \times 10^6)\theta^{3.2}]^{-1}$; θ = rudder angle in degree; $b = 1.1$ and 0.6 for a ship with one rudder and a ship with two rudders, respectively.

McGarvey (1996) investigated the decay of velocity behind a rotating propeller with a rudder and confirmed the split of the jet reported by Robackiewicz (1966). By studying the bottom jet, McGarvey (1996) found that the decay of the maximum velocity was dependent on rudder position and irrelevant to the propeller rotational speed. The following logarithmic relationship was developed to predict the decay of the velocity,

$$\frac{u_m}{U_0} = A - 0.293 \left(\ln \frac{x}{D_p} \right) \quad (2.38)$$

where $A = 0.915 - 0.004\theta$ in the range $0^\circ < \theta < +35^\circ$ or $A = 1.0 - 0.007\theta$ in the range $-35^\circ < \theta < -15^\circ$.

2.1.8.3 Velocity distribution with a rudder

McGarvey (1996) found that the equations used to determine the velocity distribution within the unconfined propeller jet could not be applied to a confined jet with a rudder. For this reason, he showed that the rudder position would significantly influence the diffusion characteristics of the propeller jet and proposed the following equation for determining the vertical velocity distribution in vertical central plane,

$$\frac{u_{x,r}}{u_m} = e^{\left[-\frac{1}{2} \left(\frac{R_m - r}{R_\sigma - R_m} \right)^2 \right]} \quad (2.39)$$

where r = vertical distance from propeller axis to the points under consideration; R_σ = distance to one standard deviation of velocity about the position of maximum velocity, and

$$R_\sigma = -0.8R_{mo} - (-0.322 + 0.0012\theta)x \quad (2.40)$$

2.1.9 Propeller Jet in the Presence of Plane Boundary

The preceding literature review reveals that most studies concerning propeller jets had been focused on the free expanding jet, *i.e.* an unconfined jet. More recently, Johnston *et al.* (2013) studied the influence of a plane boundary on the development of the propeller jet. In their study, they found that in the presence of a boundary the lower jet below the propeller axis expands faster than its counterpart above the propeller axis due to the pressure reduction beneath the jet. At the same time, confinement of the jet limited jet diffusion, consequently reducing the decay rate of the axial velocity. In terms of the development of near-bed velocity, three zones were recognized in their study, namely, (1) the zone prior to jet impact, (2) the zone of boundary layer development and (3) the zone of developed boundary layer flow (see Fig. 2.14).

Fig. 2.14 Schematic of boundary layer development (Johnston *et al.* 2013)

2.1.10 Propeller Jet in the Presence of Inclined Sea Bed

Qurraïn (1994) reported that open-type quays are often accompanied by sloping banks as revetments under the quayside. As the ships maneuver to dock near the berth, the propeller jet will impinge directly onto the inclined banks or revetments. For this reason, he carried out an investigation of the influence of an inclined bed on the axial velocities within the propeller jet. A schematic diagram for propeller jets with different slope positions is shown in Fig. 2.15.

Fig. 2.15 Schematic of propeller jet with different slope positions (Qurraïn 1994)

Two slope angles (7.5° and 15°) and three slope positions ($2D_p$, $5D_p$, and $9D_p$) were adopted in his study. The principal findings are given as follows,

- (1) The efflux velocity was not affected by the presence of the inclined bed, even at the nearest dock location where the distance between the propeller and the slope toe was $2D_p$. Therefore, the efflux velocities can be determined by using the empirical equations derived from unconfined propeller jets.
- (2) Similar to an unconfined propeller jet, the decay of the maximum velocity was found to be independent of the rotational speed of the propeller and linearly related to the toe clearance (= longitudinal distance between propeller face and slope toe).

- (3) The decay rate of the maximum velocity was increased by the confinement of the slope. A significant reduction in the axial velocities was observed near the slope, as anticipated. The retarding effect of the slope on the propeller jet was proportional to the slope angle and the distance between the propeller and the slope.

2.2 Ship Propeller Scour

2.2.1 Introduction

As discussed in Section 2.1, for an unconfined propeller jet, the jet velocity decreases during the jet diffusion process by entraining the surrounding still water. However, as introduced in Chapter 1, in the case of a low clearance height condition, say, in the harbor basin, the critical shear stress of the seabed sediments could be easily exceeded, which may lead to erosion of the bed material and consequently cause berth structure instability. Bergh and Magnusson (1987) conducted a survey of harbors in Sweden and found that 25 quays suffered scouring damage induced by propeller jet. Longe et al (1987) reported that propeller scour damage in 29 piers within French ports. Prosser (1986) and Chait and (1987) also documented similar problems in the UK and South Africa, respectively. Qurain (1994) undertook a detailed survey of British ports with reference to propeller induced scour. He reported that a total of 42% of major ports over the British Isles had encountered propeller-induced scour at their sea bed, and 29% of them were identified as a problem causing quay structures damage.

A comprehensive understanding of the nature of propeller-induced scouring action will provide a proper guidance for the design of quay structures so as to reduce and prevent failure during the ship's mooring and unmooring. The aim of this section is to review the state-of-the-art researches on the scouring process induced by ship propeller, and

the empirical scour formulae proposed in the published literature.

2.2.2 Sediment Transport

The forms of motion of the transported sediments can be categorized into three modes, namely bed load, saltation load and suspended load. The bed load is composed of larger particles that move on or near the bed, by either rolling or sliding in the bed layer. The suspended load comprises small particles that are transported in suspension in the water column. The saltation load is composed of sediments with a size between the bed and suspended load and moved by bouncing along the bed.

2.2.2.1 Incipient sediment motion on horizontal bed

Yalin (1977) studied the forces acting on an individual grain (see Fig. 2.16), where R = resultant of the hydrodynamic lift force F and gravity G acting on a grain that rests on the bed surface.

$$R = F + G \quad (2.41)$$

where F = hydrodynamic lift force which grows with the velocity of the fluid; and G = weight of the grain. Yalin (1977) simplified the force diagram by assuming that the angle between F and the horizontal, α_{FH} , (see Fig. 2.16) is a constant. Thus, the vector F varies along the straight-line S , and the resultant R moves along S' , which is parallel to S .

Fig. 2.16 Forces acting on an individual grain (after Yalin 1977)

When the angle between the resultant force R and the direction of the normal force n approaches the angle of friction of the sediment ψ , the grain will start to move. At the critical stage, by applying the “sine theorem”, Yalin (1977) derived the following relationship,

$$\frac{F}{\sin(\varphi+\psi)} = \frac{G}{\sin \alpha_{FR}} \quad (2.42)$$

in which α_{FR} = angle between F and R . Considering $\alpha_{FR} = \frac{\pi}{2} - (\varphi + \psi - \alpha_{FH})$, the following relationship of detachment of an individual grain can be given as

$$\frac{F}{G} \geq \frac{\sin(\varphi+\psi)}{\cos[\alpha_{FH}-(\varphi+\psi)]} \quad (2.43)$$

where φ = angle between the direction of flow and the tangent to the highest downstream support B (see Fig. 2.16); and ψ = angle of friction of the sediment. Thus, the initiation of sediment transport is determined by the angles φ , ψ and α_{FH} , which are dependent on the geometry of the grain and the Reynolds number. Note that Eq. (2.43) may be re-written as

$$\frac{F_y}{G} \geq \sin \alpha_{FH} \frac{\sin(\varphi+\psi)}{\cos[\alpha_{FH}-(\varphi+\psi)]} \quad (2.44)$$

and

$$\frac{F_x}{G} \geq \cos \alpha_{FH} \frac{\sin(\varphi+\psi)}{\cos[\alpha_{FH}-(\varphi+\psi)]} \quad (2.45)$$

By postulating that $\alpha_{FH} \approx \pi/2$, a further simplified version of Eq. (2.43), *i.e.*, the condition of detachment, was obtained as

$$\frac{F_y}{G} \geq 1 \quad (2.46)$$

Shields (1936) experimentally investigated erosion of an artificially flattened bed in a fully developed turbulent flow in a flume. The following dimensionless equation for bedload transport was obtained,

$$\frac{\tau_c}{(\gamma_s - \gamma_w)d_{50}} = f\left(\frac{u_* d_{50}}{\nu}\right) \quad (2.47)$$

where τ_c = critical shear stress; γ_s = specific weight of the sediment; γ_w = specific weight of the fluid; d_{50} = median particle size; ν = kinematic viscosity of the fluid; and u_* = shear velocity.

2.2.2.2 Incipient sediment motion on sloping bed

Chiew and Parker (1994) examined the incipient sediment motion on a sloping bed by considering the forces acting on an individual grain, *i.e.*, the hydrodynamic drag force F_D , lift force F_L , and the submerged weight force G (see Fig. 2.17). The angle of repose θ' was related the ratio of the tangential force to the normal force as follows,

$$\tan \theta' = \frac{G \sin \varphi' + F_D}{G \cos \varphi' - F_L} \quad (2.48)$$

where φ' = sloping bed angle; and

$$G = (\rho_s - \rho) g c_1 d^3 \quad (2.49)$$

$$F_D = \frac{1}{2} C_D \rho c_2 d^2 u_s^2 \quad (2.50)$$

$$F_L = \frac{1}{2} C_L \rho c_2 d^2 u_s^2 \quad (2.51)$$

in which C_D , C_L = drag and lift coefficient, respectively; $c_1 d^3$, $c_2 d^2$ = volume and area of the particle, respectively; and u_s = flow velocity at the particle. By substituting Eqs. (2.49) - (2.51) into Eq. (2.48) and relating the critical shear stress for sloping bed τ'_c to that associated with the horizontal bed ($\phi' = 0$), they proposed the following equation:

$$\frac{\tau'_c}{\tau_c} = \cos\phi' \left(1 - \frac{\tan\phi'}{\tan\theta'}\right) \quad (2.52)$$

where τ_c = critical shear stress for horizontal bed.

Fig. 2.17 Forces acting on an individual grain lying on sloping bed (Chiew and Parker 1994)

2.2.3 Clear-Water and Live-Bed Scour

The preceding Section (2.2.2) introduces the fundamental mechanics of sediment transport, even though they are difficult to be directly applied to illustrate propeller-induced scour. The scour associated with a propeller jet could be considered as a local scour that occurred over a limited or defined area (Ryan 2002). Local scour can be categorized into two conditions as clear-water and live-bed scour. Clear-water scour takes place when there is no transport of sediment from the undisturbed upstream region into the scour hole. In other words, the average shear stress in the upstream area is less than the critical shear stress of the bed material. As the scour hole develops, the flow is concentrated, resulting in rapid erosion. As the size of the scour hole increases, the

previously concentrated flow becomes weakened and scattered. As the erosion rate decreases correspondingly, the scour tends to stabilize and reaches an equilibrium state.

On the other hand, live-bed scour occurs when the upstream average shear stress exceeds the critical shear stress, during which the upstream sediments will continuously enter the scour hole. Consequently, the scour hole will fluctuate around an equilibrium state. Fig. 2.18 illustrates the comparison of the scour process between clear-water scour and live-bed scour.

Fig. 2.18 Temporal developments of live-bed and clear-water scour (Richardson and Davis 1995)

In the case of ship propeller scour, the ship docks generally are not subjected to other disturbance causing additional sediment transport into the harbor basin. Hence, Ryan (2002) assumed that propeller scouring belongs to the case of clear-water scour. Based on this assumption, propeller-induced scour experiments can be carried out in a confined tank or flume without any other flow and sediment supply. At the end of each test, an equilibrium state is therefore supposed to be expected.

2.2.4 Scour Due to Unconfined Propeller Jet

As discussed in Section 2.1, the free expanding propeller jet without any structures obstructing the flow is known as the unconfined propeller jet. Therefore, scour induced by an unconfined jet is termed as the unconfined scour. Hamill (1987) reported that the shape of the scour holes induced by unconfined propeller jets was similar in form and nearly symmetrical along the jet centerline. The schematic diagram of propeller jet flow with a flatbed in the absence of a quay wall is shown in Fig. 2.19. Accordingly, the resulting centerline scour profile is shown in Fig. 2.20.

Fig. 2.19 Definition sketch of propeller jet flow (Sumer and Fredsøe 2002)

Fig. 2.20 Unconfined scour profile at the centerline plane (Sumer and Fredsøe 2002)

The early studies on the problem relating to propeller jet were conducted by Liou and Herbich (1976), Fuehrer and Romisch (1977), Blaauw and Kaa (1978), Fuehrer *et al.*

(1981). However, their works were mainly confined to the protection of the bottom and bank exposed to the propeller jet rather than the propeller scouring process. In addition, most of their studies were based on the simplified theories of “The Blade-Element Theory” and “Axial Momentum Theory”, in which simplified propeller model was adopted. Starting from Hamill (1987), followed by Stewart (1992), Hashmi (1993), Qurraïn (1994), McGarvey (1996), Ryan (2002) and Hong *et al.* (2013), a series of systematical studies on propeller jet scouring action have been done by using actual propeller models in their experiments.

Recently, Hong *et al.* (2013) conducted a series of experiments on unconfined propeller scour. In their study, the asymptotic scour profile was found to consist of three parts: a small scour hole, a primary scour hole and a deposition mound as shown in Fig. 2.21. The small scour hole directly beneath the propeller had not been mentioned by previous authors before them. A possible reason is that it is not the main concern in the perspective of scour protection. The maximum scour depth of the primary scour hole, by contrast, has been examined by various authors and will be highlighted in the subsequent section.

Fig. 2.21 Scour profile induced by an unconfined propeller jet (Hong *et al.* 2013)

2.2.4.1 Maximum scour depth

Rajaratnam and Berry (1977) studied the development of scour hole induced by circular turbulent wall jets and found that the scour depth was a function of the densimetric Froude number, Reynolds number, and diameter ratio. Considering the maximum scour depth ε_{max} at the asymptotic state, it can be written as:

$$\varepsilon_{max} = f(U_o, D, \rho, d_{50}, g, \Delta\rho, \nu) \quad (2.53)$$

where U_o = efflux velocity of the jet at the nozzle; D = diameter of jet at the nozzle; ρ = density of water; $\Delta\rho = \rho_s - \rho$ is difference between the sediment-grain density and water density; and g = acceleration due to gravity. Based on the Pi-theorem, the normalized maximum scour depth can be expressed as

$$\frac{\varepsilon_{max}}{D} = f_1\left(\frac{U_o}{\sqrt{gd_{50}\frac{\Delta\rho}{\rho}}}, \frac{U_o D}{\nu}, \frac{D}{d_{50}}\right) \quad (2.54)$$

$$\frac{U_o}{\sqrt{gd_{50}\frac{\Delta\rho}{\rho}}} = F_o \quad (2.55)$$

$$\frac{U_o D}{\nu} = Re \quad (2.56)$$

where F_o = densimetric Froude number, Re = Reynolds number of propeller flow. Rajaratnam (1981) showed that the effect of viscosity on the erosion induced by a plain wall jet could be neglected when Reynolds number $> 10^4$. Therefore, the normalized maximum scour depth can be re-written as,

$$\frac{\varepsilon_{max}}{D} = f_2\left(F_o, \frac{D}{d_{50}}\right) \quad (2.57)$$

Following Rajaratnam's approach, Hamill (1987) conducted a dimensional analysis in the case of the scour induced by an unconfined propeller jet, in which the effect of the clearance height between the propeller lower tip to the bed, C , has been taken into account. Therefore, the maximum depth, $\varepsilon_{m,u}$, was expressed as

$$\varepsilon_{m,u} = f_2 \left(F_o, \frac{D_p}{d_{50}}, \frac{c}{d_{50}} \right) \quad (2.58)$$

which indicates that the equilibrium scour depth induced by a propeller jet is depended on (1) the densimetric Froude number; (2) the ratio of propeller diameter to the sediment particle size; and (3) the ratio of the clearance distance to the sediment particle size.

Based on the results obtained from a series of experiments with two model propellers and two sediment sizes, Hamill (1987) proposed the following regression equation to determine the maximum scour depth,

$$\frac{\varepsilon_{m,u}}{Z_b} = 0.0467 \left[\frac{F_o}{(Z_b/D_p)} \right]^{1.39} \quad (2.59)$$

where Z_b = clearance between propeller axis and bed. This equation was deemed to be applicable for a range of grain sizes of $0.5 \text{ mm} \leq d_{50} \leq 2 \text{ mm}$, and it should be used only to give an indication of the expected scour as the author recommended.

Additional tests with a wider range of $0.5 \text{ mm} \leq d_{50} \leq 4 \text{ mm}$ were conducted by Stewart (1992), resulting in another empirical equation as follows,

$$\frac{\varepsilon_{m,u}}{Z_b} = 0.0198 \left[\frac{F_o}{(Z_b/D_p)} \right]^{2.024} \quad (2.60)$$

Moreover, Hamill *et al.* (1999) proposed an empirical equation to evaluate the longitudinal position of the maximum scour depth from the propeller face, $X_{m,u}$, in the case of unconfined propeller jet:

$$\frac{X_{m,u}}{c} = F_o^{0.94} \quad (2.61)$$

More recently, Chiew *et al.* (2012) compared the characteristics of the scour holes

induced by offset jets and unconfined propeller jets; they found that the densimetric Froude number and offset ratio are the most influential parameters on scour dimensions in these two kinds of jets. The following empirical equations were proposed to determine the maximum scour depth, length, and width at the asymptotic state for both pure offset and propeller jets.

$$\frac{\varepsilon_{m,u}}{D} = 0.265 \left[F_o - \left(4.114 \frac{Z_b}{D} \right) \right]^{0.955} \left(\frac{Z_b}{D} \right)^{-0.022} \quad (2.62)$$

$$\frac{l_{m,u}}{D} = 8.824 \left[F_o - \left(4.114 \frac{Z_b}{D} \right) \right]^{0.535} \left(\frac{Z_b}{D} \right)^{0.286} \quad (2.63)$$

$$\frac{w_{m,u}}{D} = 3.834 \left[F_o - \left(4.114 \frac{Z_b}{D} \right) \right]^{0.585} \left(\frac{Z_b}{D} \right)^{0.202} \quad (2.64)$$

where $l_{m,u}$ = maximum scour length; $w_{m,u}$ = maximum scour width; and D = diameter of nozzle, width of squared orifice or propeller diameter where applicable. The authors also noted that Eqs. (2.62) - (2.64) are valid when $Z_b/D \geq 0.5$.

2.2.4.2 Temporal development of the maximum scour depth

Besides the magnitude of the maximum scour depth, its temporal development is equally important in practice. Hamill (1987) conducted the pioneering study on the scour rate of an unconfined propeller. By measuring the maximum scour depth at different time intervals, $\varepsilon_{m,t}$, he proposed the following equation of $\varepsilon_{m,t}$ as a function of time and the same parameters in Eq. (2.58):

$$\varepsilon_{m,t} = \Omega [\ln(t)]^\Gamma \quad (2.65)$$

with

$$\Omega = 6.9 \times 10^{-4} \left[\frac{C}{d_{50}} \right]^{-4.63} \left[\frac{D_p}{d_{50}} \right]^{3.58} [F_o]^{-4.53} \quad (2.66)$$

and

$$\Gamma = 4.113 \left[\frac{C}{d_{50}} \right]^{0.742} \left[\frac{D_p}{d_{50}} \right]^{-0.522} [F_o]^{-0.682} \quad (2.67)$$

where t = time, Ω and Γ = experimental coefficient.

Following the same form of Eq.(2.65), Qurraïn (1994) proposed another set of equations by adopting a wider range of propeller models under the same free expanding experimental setup as Hamill (1987) as follows:

$$\Omega = \left[\frac{C}{d_{50}} \right]^{-4.76} \left[\frac{D_p}{d_{50}} \right]^{2.657} [F_0]^{3.517} \quad (2.68)$$

and

$$\Gamma = \left[\frac{C}{d_{50}} \right]^{0.768} \left[\frac{D_p}{d_{50}} \right]^{2.657} [F_0]^{-0.479} \quad (2.69)$$

Based on yet another study on different sediment sizes and propellers, Hamill *et al.* (1999) further updated Eq. (2.65) as follows,

$$\varepsilon_{m,t} = k_0 \Omega [\ln(t)]^\Gamma \quad (2.70)$$

where k_0 = constant taking a value of 38.97. Γ and Ω are given as,

$$\Gamma = [F_0]^{-0.53} \left[\frac{D_p}{d_{50}} \right]^{-0.48} \left[\frac{C}{d_{50}} \right]^{0.94} \quad (2.71)$$

$$\Omega = \Gamma^{-6.38} \quad (2.72)$$

It may be deduced from Eq.(2.70) that as t tends to infinity, ε_{max} tends to infinity accordingly, which is unreasonable because it indicates that a stabilized maximum scour cannot be obtained. To this end, Hamill *et al.* (1999) suggested that by attempting different time intervals and when the difference of the corresponding scour depth is reasonably small, the asymptotic scour depth could be considered to have been reached. Hamill *et al.* (1999) also commented that the above Eqs. (2.70) - (2.72) could only be used in the range $0.5D_p < C < 2.5D_p$.

Hong *et al.* (2012) found that Eq. (2.70) shows an unreasonable trend because a higher scour depth occurs at a lower speed of rotation when other parameters such as propeller

diameter, median particle size, and offset height remain constant. For this reason, they conducted a series of experiments using two uniform grains of sand with differing offset heights and propeller speeds, leading to the following dimensionless equation with $R^2 = 0.91$,

$$\frac{\varepsilon_{m,u}}{D_p} = 0.105 F_o^{0.852} \left(\frac{Z_b}{D_p} \right)^{-0.991} \left(\frac{d_{50}}{D_p} \right)^{0.315} \left(\frac{U_o t}{D_p} \right)^{0.168} \quad (2.73)$$

This equation was further modified into the following form with an improved $R^2 = 0.983$ by Hong *et al.* (2013),

$$\frac{\varepsilon_{m,u}}{D_p} = k_1 \left[\log_{10} \left(\frac{U_o t}{D_p} \right) - k_2 \right]^{k_3} \quad (2.74)$$

where

$$k_1 = 0.014 F_o^{1.120} \left(\frac{Z_b}{D_p} \right)^{-1.740} \left(\frac{Z_b}{d_{50}} \right)^{-0.170}$$

$$k_2 = 1.882 F_o^{-0.009} \left(\frac{Z_b}{D_p} \right)^{2.302} \left(\frac{Z_b}{d_{50}} \right)^{-0.441}$$

$$k_3 = 2.477 F_o^{-0.073} \left(\frac{Z_b}{D_p} \right)^{0.53} \left(\frac{Z_b}{d_{50}} \right)^{-0.045}$$

Eq. (2.74) was deemed to be valid for $0.5 < y_o/D_p < 2.87$ and $5.55 < F_o < 11.1$. Based on this equation, Hong *et al.* (2013) further derived another equation to calculate the time of initiation of propeller scour as follows,

$$\frac{t_s}{\left(\frac{D_p}{U_o} \right)} = 10^{k_2} = 10^{\left[1.882 F_o^{-0.009} \left(\frac{Z_b}{D_p} \right)^{2.302} \left(\frac{Z_b}{d_{50}} \right)^{-0.441} \right]} \quad (2.75)$$

where t_s = time to start scouring processes.

2.2.5 Scour Due to Confined Propeller Jet

2.2.5.1 In the presence of quay wall

As ships dock in a quay, the presence of berth structures will obviously affect the

development of the propeller jet in its immediate neighborhood, which may induce a significant difference in the scour profile as compared to that caused by the unconfined propeller jet. In general, local changes of the flow pattern will result in an increase of the average bed shear stress and the turbulence level (Sumer and Fredsøe 2002). Consequently, an increased scour depth is expected. In order to determine the confined propeller jet scour around port structures, the following authors investigated the influence of solid quay walls on the scouring process in the closed-type quay. According to different types of ships, the relative position between quay wall and the propeller axis may be perpendicular [Fig. 2.22(a)], parallel [Fig. 2.22(b)] or both at the same time, *i.e.*, the combined quay walls [Fig. 2.22(c)].

Fig. 2.22 Quay wall configurations (top view)

Stewart (1992) conducted a series of experiments in the presence of a perpendicular wall with different wall clearances. In his study, the asymptotic maximum scour depth was appreciably deepened when the quay wall is located between the propeller and the position of the deposited crest in the unconfined case. He also reported that this

additional scour depth is independent of densimetric Froude number. Following on his study, Hamill *et al.* (1999) proposed Eq. (2.76) (see Table 2.2) to determine the additional scour depth induced by the presence of a perpendicular quay wall, in which $\varepsilon_{m,c}$ = maximum confined scour depth; $\varepsilon_{m,u}$ = maximum unconfined scour depth; $\varepsilon_{m,u,a}$ = maximum unconfined scour depth measured from the propeller axis; and X_w = wall clearance. Based on the known $\varepsilon_{m,u}$ and $X_{m,u}$ of the unconfined case obtained by using Eq.(2.70) and Eq. (2.61), they recommended that Eq. (2.76) (see Table 2.2) can be used to estimate the additional scour at the asymptotic state due to the introduction of a quay wall into the propeller jet. The pertinent variables are defined in Fig. 2.23.

Fig. 2.23 Comparison between confined and unconfined scour (Hamill *et al.* 1999)

Hashmi (1993) investigated the propeller scouring process in the presence of a parallel quay wall and concluded that the parallel quay wall could be governed by two scouring processes, including the near and the far wall relationships. Corresponding Eq. (2.77) and Eq. (2.78) were proposed (Table 2.2), where Y_w = horizontal distance from the propeller axis to the face of the quay wall. In addition, Hashmi (1993) also presented an empirical Eq. (2.79) to determine the position of maximum scour, where Y_m = position of the maximum depth of erosion measured relative to the propeller axis.

Qurain (1994) studied the case of propeller jet scour under the effect of combined quay walls including the perpendicular quay wall as well as the parallel quay wall. Following

the form of Eq.(2.65), the empirical Eq. (2.80) for calculating the temporal development of scour at the toe of the parallel wall and Eq. (2.80) for scour at the toe of the perpendicular wall were proposed. They are applicable to sediments within the range of $1 \text{ mm} < d_{50} < 4 \text{ mm}$. Moreover, Qurrain (1994) also gave two more equations [Eq. (2.82) and (2.83), see Table 2.2] to determine the maximum asymptotic depth of scour at the face of the parallel wall and the perpendicular wall, where ε_{msw} = maximum depth of scour along the parallel wall; ε_{mfw} = maximum depth of scour along the perpendicular wall. The above-mentioned Eqs. (2.76) - (2.83) for the confined cases with quay walls are tabulated in Table 2.2.

Table 2.2 List of equations for propeller scour with quay wall

Confined case	Authors	Equations	Remark	No.
Perpendicular quay wall	Hamill <i>et al.</i> (1999)	$\left(\frac{\varepsilon_{m,c} - \varepsilon_{m,u}}{\varepsilon_{m,u,a}}\right) + 1 = 1.18 \left(\frac{X_w}{X_{m,u}}\right)^{-0.2}$	$0.6 \leq \frac{X_w}{X_{m,u}} \leq 3.27 \quad (5.74 \leq \frac{X_w}{D_p} \leq 29.5)$	(2.76)
Parallel quay wall	Hashmi (1993)	$\varepsilon_{m,t} = 540.14e^{-3.13\Gamma}[\ln(t)]^\Gamma$ $\Gamma = 13.419 \left(\frac{Y_w}{D_p}\right)^{0.325} (F_o)^{-0.872} \left(\frac{C}{d_{50}}\right)^{0.63} \left(\frac{D_p}{d_{50}}\right)^{-0.662}$	Near wall relationship $1 < Y_w/D_p < 3.05$	(2.77)
		$\varepsilon_{m,t} = 383.32e^{-3.02\Gamma}[\ln(t)]^\Gamma$ $\Gamma = 36.58 \left(\frac{Y_w}{D_p}\right)^{-0.352} (F_o)^{-0.872} \left(\frac{C}{d_{50}}\right)^{0.818} \left(\frac{D_p}{d_{50}}\right)^{-0.89}$	Far wall relationship $3.05 < Y_w/D_p < 6.1$	(2.78)
		$\frac{Y_m}{Y_w} = 2.28 \left(\frac{Y_w}{D_p}\right)^{-2.02}$	Position of the maximum scour	(2.79)
Combined quay walls	Qurain (1994)	$\Omega = 1992 \left(\frac{Y_w}{D_p}\right)^{-8.271} \left(\frac{X_w}{D_p}\right)^{-5.678} (F_o)^{3.049}$ $\Gamma = 0.016 \left(\frac{Y_w}{D_p}\right)^{2.196} \left(\frac{X_w}{D_p}\right)^{1.82} (F_o)^{-0.854}$	Scour depth at the toe of the parallel wall at any time	(2.80)
		$\Omega = 41.89 \left(\frac{Y_w}{D_p}\right)^{-0.202} \left(\frac{X_w}{D_p}\right)^{-2.839} (F_o)^{1.602}$ $\Gamma = 0.506 \left(\frac{Y_w}{D_p}\right)^{-0.327} \left(\frac{X_w}{D_p}\right)^{1.003} (F_o)^{-0.399}$	Scour depth at the toe of the perpendicular wall at any time	(2.81)
		$\frac{\varepsilon_{msw}}{\varepsilon_{m,u}} = 2.535 - 0.723 \left(\frac{Y_w}{D_p}\right) - 0.203 \left(\frac{X_w}{D_p}\right) + 1.095(F_o)$	Maximum asymptotic depth of scour at the parallel wall	(2.82)
		$\frac{\varepsilon_{mfw}}{\varepsilon_{m,u}} = 2.463 - 0.208 \left(\frac{Y_w}{D_p}\right) - 0.118 \left(\frac{X_w}{D_p}\right) - 0.022(F_o)$	Maximum asymptotic depth of scour at the perpendicular wall	(2.83)

2.2.5.2 In the presence of rudder

The above-mentioned studies are involved with unconfined or confined propeller scour in the presence of quay wall. As discussed in Section 2.1.8, the development of the propeller jet likely is affected by rudders. Therefore, the associated scour hole is also expected to be influenced. McGarvey (1996) studied ship propeller scour in the presence of a rudder and reported that the maximum scour depth was increased by approximately 25% at zero angle. Taking account of the rudder influence, he obtained the following expressions for Eq.(2.65) to estimate the rate of development of scour,

$$\Omega = 0.268 \left(\frac{C}{d_{50}} \right)^{-3.294} \left(\frac{D_p}{d_{50}} \right)^{1.494} (F_o)^{4.437} (1 + \theta)^{-1.038} \quad (2.84)$$

$$\Gamma = 0.705 \left(\frac{C}{d_{50}} \right)^{0.848} \left(\frac{D_p}{d_{50}} \right)^{-0.178} (F_o)^{-0.885} (1 + \theta)^{-0.299} \quad (2.85)$$

where θ = rudder angle in radians.

By comparing the maximum asymptotic scour depth induced by the propeller with and without a rudder, their relationship was proposed by McGarvey (1996) as follows,

$$\frac{\varepsilon_{m,r}}{\varepsilon_{m,u}} = 0.75 - 0.07(F_o) + 0.02 \left(\frac{D_p}{d_{50}} \right) - 0.15(1 + \theta) \quad (2.86)$$

where $\varepsilon_{m,r}$ = the maximum asymptotic scour depth in the presence of a rudder. Hamill and McGarvey (1997) reported that the location of maximum scour depth and that of maximum velocity show a good agreement with each other.

2.2.5.3 In the presence of rudder and quay wall

Ryan (2002) conducted an experimental investigation on the combined influence of both the parallel quay wall and a ship's rudder on the propeller scour. He found that the locations of the maximum scour depth are approximately aligned to the rudder angle,

and the scour profile along the maximum scour depth is independent on the wall clearance (Y_w), although the scour profile along the quay wall varies. To be used in conjunction with Eq.(2.65), a set of equations were proposed to determine the rate of development of erosion in the presence of a parallel quay wall, as follows:

$$\Omega = 87.045 \left(\frac{C}{d_{50}}\right)^{-3.44} \left(\frac{Y_w}{D_p}\right)^{0.225} \left(\frac{D_p}{d_{50}}\right)^{2.035} F_o^{0.498} (1 + \theta)^{-0.276} \quad (2.87)$$

$$\Gamma = 0.339 \left(\frac{C}{d_{50}}\right)^{1.249} \left(\frac{Y_w}{D_p}\right)^{-0.181} \left(\frac{D_p}{d_{50}}\right)^{-0.734} F_o^{-0.002} (1 + \theta)^{-0.172} \quad (2.88)$$

Besides, an equation for predicting the maximum scour depth at the toe of the parallel quay wall was given as follows:

$$\frac{\varepsilon_{m,r,p}}{d_{50}} = 6.47 \times 10^{-5} \left(\frac{C}{d_{50}}\right)^{-5.42} \left(\frac{D_p}{d_{50}}\right)^{6.63} \left(\frac{Y_w}{D_p}\right)^{-0.437} F_o^{2.498} (1 + \theta)^{-0.80} \quad (2.89)$$

where $\varepsilon_{m,r,p}$ = maximum scour depth in the presence of a rudder and parallel quay wall.

Ryan (2002) also studied the confined case of a perpendicular wall and a rudder. He stated that the maximum scour depth occurs at the wall and the overall shape of the scour hole is symmetrical about the maximum erosion line when rudder angle equals to zero, while as the rudder angle becomes more negative or positive the scour hole is no longer symmetrical. This study was further extended by Ryan and Hamill (2012) by investigating propeller jet scouring in the presence of both a rudder and perpendicular quay wall at the stern of the ship. Following the same form of Eq.(2.65), two sets of equations were produced based on two different propeller diameters and sediment sizes to determine the temporal development of erosion, in which the depth of scour was determined as a function of wall clearance, rudder angle and the densimetric Froude number, although the effect of propeller clearance and diameter ratio was excluded.

In the case of the 131-mm propeller with a sediment of $d_{50} = 3$ mm:

$$\Omega = \left(\frac{X_w}{D_p}\right)^{1.829} F_o^{-0.954} (1 + \theta)^{-2.22} \quad (2.90)$$

$$\Gamma = \left(\frac{X_w}{D_p}\right)^{-0.519} F_o^{-0.632} (1 + \theta)^{0.706} \quad (2.91)$$

In the case of the 76-mm propeller with a sediment with $d_{50} = 1.15$ mm:

$$\Omega = \left(\frac{X_w}{D_p}\right)^{-0.71} F_o^{1.77} (1 + \theta)^{0.145} \quad (2.92)$$

$$\Gamma = \left(\frac{X_w}{D_p}\right)^{0.473} F_o^{-0.36} (1 + \theta)^{-0.002} \quad (2.93)$$

However, the above Eqs. (2.90) - (2.93) can only be applied to the scope of their experiments, and further data are still required to enhance its applicability.

2.2.5.4 In the presence of open quay slope

As for an open quay, PIANC and IMPA (1997) reported that the scour protection for the armored slope relies on the slope angle and the coarseness of the filling materials, and the ship propeller jet threatens the stability of the lower part of the filling. Schokking *et al.* (2003) studied the bow thruster-induced damage on an armored slope with a ratio of 1:3 and reported that the maximum damage location occurred at the toe of the slope. Adopting three different slope ratios of 1:1.5, 1:2.0, and 1:2.5, Cihan *et al.* (2012) investigated the influence of slope angle on propeller scour near an open quay structure. In their study, erosion was also observed at the slope toe when there was no toe apron, and the maximum damage occurred at the steepest slope. Based on their results, they suggested that the slope steeper than 1:1.5 is not recommended for construction. Moreover, a damage level parameter and a critical densimetric Froude numbers indicating the commencement of the damage were defined in their study.

2.3 Propeller Jet Flow in and around Scour Hole

Most previous studies measured the velocities behind a propeller jet and the associated scour profile separately. Hashmi (1993) investigated the propeller jet velocities for a series of bed configuration at different scouring stages. In his study, the scour holes at the intermediate stages of 0%, 25%, 50% and 100% (the asymptotic state) of scouring process were preserved by using urea formaldehyde resin for the purpose of measuring velocities. Based on the results of centerline velocity measurement, its decay trend was related to the downstream distance from the propeller, as follows,

$$\frac{u_c}{U_o} = 0.45e^{-0.088\left(\frac{x}{D_p}\right)} \quad (2.94)$$

in which u_c = centerline velocity along the propeller axis.

Ryan (2002) continued the study on the bed-confined propeller jet in the presence of a rudder. Velocity profiles were measured at three scouring stages of 0%, 50% and 100% scour. The principal results were given as follows,

- (1) Two high velocities were also observed in his study as that reported by McGarvey (1996), *i.e.*, the upper and lower stream. In the presence of a flatbed, the lower stream was found to be the main contributor to bed scour and its associated bed velocities were obviously higher than the upper stream velocities.
- (2) The limitation of McGarvey (1996)'s Eq. (2.39) for predicting the velocity distribution with a bed boundary was noticed. The largest deviation was found in the case of the flatbed. As the scour hole developed, the lower stream was less confined, therefore the results showed some correlation with McGarvey (1996)'s equation for 50% and 100% scour.

- (3) When the scour hole reaches the asymptotic state, the bed velocities were found to be very close to the critical bed velocity for the particular sediment size under consideration.

2.4 Concluding Remarks

The present literature review has revealed that early studies on the velocity of the propeller jet were mainly focused on the unconfined propeller jet (*i.e.*, a free expanding jet), a series of equations were proposed to describe the characteristics of propeller jet, especially for the axial component of velocity. However, the other two velocity components, *i.e.*, the rational and radial velocities, which differentiate a propeller jet from the normal jet, are still poorly understood. Furthermore, due to the limitation of the earlier measurement techniques, most previous studies only present the selected velocity profile based on single-point measurement data. More importantly, limited work, if any, has been done in studying the hydrodynamic characteristics of a confined propeller jet either by a plane boundary (rigid or erodible) or an open quay slope. To bridge this research gap, it is required to undertake sufficiently detailed experiments to obtain a high-resolution picture of the confined propeller jet flow field in 3-dimensional, which will better illustrate the boundary effects on the characteristics of propeller jet.

It is also observed from the literature review that intense efforts have been concentrated on the scouring action of a propeller jet in either the unconfined case or the case of closed quay structure in the form of solid vertical walls, whether a perpendicular wall, a parallel wall or a combination of them. During the past years, a systematic study has been achieved in predicting the unconfined scour depth or the local scour depth at the toe of vertical quay walls. However, propeller scour around an open quay has not

received the same kind of attention. Only few studies related to open-quay-like structures had been conducted with the emphasis placed on the erosion of the slope itself. Qurrain (1994) conducted a survey of British ports and reported that the most common type of berth structures for Roll-on/Roll-off ships was open-piled quay. Thus, there is an urgent need to carry out extensive experiments on propeller-induced scour in the case of open quay structures in order to obtain a new insight and better understanding of the subject.

In addition, a detailed knowledge of near-bed flow and its interaction with the developing bed between the fluid-bed interface is imperative to reveal the associated scouring mechanisms. However, the characteristics of the propeller jet flow in a developing scour hole are still elusive. Therefore, a comprehensive knowledge in this aspect is also required. To meet this objective, experiments need to be conducted by measuring the flow field and the developing scour hole simultaneously.

The experimental methodology and results of the experiments that are expected to bridge the abovementioned research gap will be the main content of succeeding chapters.

CHAPTER 3

EXPERIMENTAL APPARATUS AND DATA ACQUISITION

3.1 Introduction

The experimental program comprises three phases (EP-I, EP-II, and EP-III) as indicated in Chapter 1. EP-I aims to investigate the influence of a plane boundary on the development of propeller jets by measuring the velocity field; EP-II was designed to measure the scour bed profile and thus revealing the characteristics of scouring action around an open quay; and EP-III focuses on the investigation of the scouring mechanisms, which requires the near-bed flow measurement in a developing scour hole. Accordingly, this chapter describes the experimental apparatus and data acquisition methods used in all these three experiment phases. The corresponding results are presented and discussed in Chapter 4, 5 and 6, respectively.

3.2 Experimental Apparatus

In order to comply with the different research objectives, the experiments were carried out in either a PIV flume (EP-I and EP-III) or a scour tank (EP-II) during the course of this study.

3.2.1 PIV Flume

In a recent study, Hsieh *et al.* (2013) have conducted a series of experimental studies on an unconfined propeller jet, in which a high-speed particle image velocimetry (PIV) technique was found to be capable of measuring the 3-dimensional propeller jet velocity field. In light of their work, it was decided to investigate the 3-dimensional characteristics of the confined propeller jet by employing the similar PIV technique. To

achieve this objective, a flume with glass sidewalls was required to enable optical observations. Therefore, in this study, tests involved with velocity measurements (EP-I and EP-III) were conducted in a recirculating flume (hereinafter referred to as the PIV flume) with dimensions of 11 m length, 0.6 m width and 0.7 m depth (see Fig. 3.1). The test section was located in the middle of the flume, and specific setups for the EP-I and EP-III will be discussed in later sections.

3.2.2 *Scour Tank*

The scour measurements (EP-II) were conducted in a scour tank that is 1.8 m wide, 4 m long, and 1 m deep. The size of the tank was found to be large enough for the free expanding propeller jet without sidewall effects. A sediment recess, which is 0.25 m deep, 1.8 m long and 1.2 m wide, was built on a Perspex false floor in the center of the tank. In order to simulate the propeller scouring action in an open-type quay with a slope and a vertical skirting, an armored bank was constructed by using uniform rubbles ($d_{50} = 33.2$ mm, $\sigma_g = \sqrt{d_{84}/d_{16}} = 1.2$) with a slope of 1V:1.5H on the false floor. The vertical skirting, which functions as a retaining wall, is located beneath the slope toe. It should be noted that piles are not included for the sake of simplicity because the primary objective in this study is to explore how the scour hole profile will be affected with the addition of a simple slope. Fig. 3.2 depicts the schematic of the experimental setup in the scour tank.

Fig. 3.1 PIV flume

Fig. 3.2 Scour tank

3.2.3 *Propeller Rig*

Since single-propeller propulsion systems are often equipped with larger propellers than dual-propeller propulsion, they are believed to have greater potential for scouring. Sumer and Fredsøe (2002) documented that for the ships equipped with thrusters, rudders are not necessary for maneuvering since the thrusters can turn 360 degrees and have reversible CP (controllable pitch) propellers with variable velocity. Furthermore, Hamill (1987) suggested that it may not be necessary to incorporate the ship hull, as its influence is negligible during maneuvering or at zero advance speed. Consequently, in this study, the final design of the propeller rig simply consisted of a single screw propeller model without the presence of the rudder and ship hull. Specifically, the propeller model was driven by a power assembly through a series of shafts and gear assembly (Fig. 3.3), in which the power assembly comprised a 3-phase induction motor that was connected to an inverter to gain varying rotational speeds. The entire set was mounted on an appropriately designed movable carriage that spans transversely across the flume/tank and could be moved along the longitudinal rail located on the sidewalls of the flume/tank. In addition, the propeller rig itself also allows the propeller to be moved up and down along a vertical shaft so as to ensure that the propeller could be operated at different clearance heights from the bed. In such a way, the propeller was able to run at a range of rotational speeds, clearance heights, and toe clearances, thus fulfilling the requirements of different test conditions. It should be noted that in all three experiment phases, the movement of the ships was ignored to mimic the case of maneuvering or "bollard pull condition". Following the convention adopted in the literature review, the same Right-Handed Coordinate System ($o\text{-}xyz$) was used in this thesis, in which the origin is located on the plane boundary and directly beneath the propeller face plane; the x -axis is streamwise-oriented along the bottom centerline; the

y -axis along the spanwise-oriented towards the starboard and the z -axis along the upward vertical.

Fig. 3.3 Schematic sketch of propeller rig

3.2.3.1 Propeller geometry terminology

Fig. 3.4 shows a definition sketch of the propeller model. Some pertinent terminologies used in the literature review and this thesis are listed below:

(1) Diameter	The distance across the circle made by the blade tips as the propeller rotates.
(2) Radius	The distance from the axis of rotation to the blade tip.
(3) Hub	Solid cylinder located at the center of the propeller.
(4) Rotation	When viewed from the stern: Right-hand propellers rotate clockwise to provide forward thrust. Left-hand propellers rotate counter-clockwise to provide forward thrust.
(5) Face	Defined as the surface of each propeller blade viewed from aft.

(6) Pitch	The axial distance a propeller moves in one complete angular revolution.
(7) Leading Edge	Edge of the blade that first cuts the water.
(8) Trailing Edge	Edge from which the water exits the blade.
(9) Blade Tip	Maximum reach of the blade from the center of the hub.
Separates the leading and trailing edges.
(10) Rake Angle	Angle between the rake datum line and the plane of the blade tip circle.
(11) Projected Area	Described as the area of all the propeller blades that can be projected onto a plane that is normal to the axis of rotation.
(12) Developed Area	The sum of the face areas for all the propeller blades.
(13) Blade Area Ratio	The ratio of the developed blade area to the projected blade area.

Fig. 3.4 Definition sketch of a propeller

3.2.3.2 Propeller model used in this work

The propeller rigs installed in both the PIV flume and the scour tank were essentially the same except for different propeller models mounted. Three propeller models are used in this study. All of them are left-hand propellers, which means that when looking from the stern (facing forward), it rotates counter-clockwise to provide a forward thrust. Their geometrical characteristics and features have been tabulated in Table 3.1, in which the smaller 7.5-cm propeller was used in the PIV flume for the purpose of velocity measurement and the other two larger ones were used in the scour tank for scour measurement.

Table 3.1 Characteristics of propeller geometry

No.	Propeller diameter, D_p (cm)	Hub diameter, D_h (cm)	Blade number, N	Pitch ratio, P'	Blade area ratio, β	Thrust coefficient, C_t	Experiment Phase
1	7.5	1.6	5	1.040	0.620	0.460	I, III
2	10	2.5	3	1.012	0.428	0.411	II
3	15	2.6	3	0.975	0.433	0.387	II

3.2.3.3 Propeller speed calibration

Since the rotational speed (n) of the propellers were controlled by varying the input frequency (f) of the inverter, a tachometer was used to calibrate the rotational speed of the propellers. Fig. 3.5 shows that the rotational speed exhibits a perfect linear relationship with the input frequency for all three propellers. Therefore, the input frequency could be obtained by inverse calculation from the desirable propeller rotational speed required by certain test condition.

Fig. 3.5 Calibration of propeller rotational speed:

(a) $D_p = 7.5$ cm (b) $D_p = 10$ cm (c) $D_p = 15$ cm

3.3 Sediments

Hamill (1987) recommended that a ‘single grain size’ sediment should be used in order to ensure a unique critical velocity. Otherwise within a range of grain sizes, after removing the smaller particles, the larger grains would provide an armoring effect. Subsequent authors, e.g. Stewart (1992), McGarvey (1996), Ryan (2002) and Hong *et al.* (2013), also adopted the uniform sediments in their experiments, and so does the present study.

Two different uniform cohesionless sediments are used in EP-II and EP-III in the scour tank and PIV flume, respectively. To determine the particle size distribution of the sediments, sieve tests were carried out before the commencement of any experiments. Fig. 3.6 shows the sieve test results in a semilogarithmic plot of the percentage pass versus particle size; the distribution demonstrates that the sand is well sorted.

Fig. 3.6 Particle size distribution curve

Table 3.2 summarizes the properties of the adopted sediments, in which d_{50} = the median particle size of the sand sample; σ_g = geometric standard deviation, and can be calculated as

$$\sigma_g = \sqrt{d_{84}/d_{16}} \quad (3.1)$$

where d_{84} = particle size where 84% of the particles are finer by weight; and d_{16} = particle size where 16% of the particles are finer by weight.

Table 3.2 Properties of experimental sediments

No.	Median diameter d_{50} (mm)	Geometric standard deviation, σ_g	Specific gravity	Experiment Phase	Flume/Tank
1	0.34	1.4	2.65	II	PIV flume
2	0.45	1.3	2.65	III	Scour tank

3.4 Experiment Phase I: Velocity Measurement with Plane Boundary

3.4.1 PIV System Setup

Experiment Phase I was conducted in the PIV flume (refer to Fig. 3.1). The objectives of this phase are to investigate the influence of the plane boundary on the development of the propeller jets, including the mean flow properties and turbulence characteristics. A similar high-speed PIV system as that reported in Hsieh *et al.* (2016, 2017), in which the superiority of the high-sampling-rate over traditional PIV techniques was discussed, was employed. Before the tests, the plane boundary was painted black to reduce undesirable reflections of the laser light which could reduce the accuracy of PIV measurements close to the boundary. Fig. 3.7 shows the setup of the PIV system that comprises a 5W air-cooling laser with a wavelength of 532 nm as the light source and

a high-speed camera. The beam that was emitted from the laser source passed through the optics, generating a laser light fan of 1.5 mm thickness cast down into the water. The still water depth is reasonably deep ($= 0.6$ m), and the effect of the free surface may be considered to be negligible. The high-speed camera used (Phantom Miro 120) has a maximum 1920×1200 resolution, 12-bit depth, and over 1200 fps (frame per second) sampling rate. A Sigma 105 mm $f/2.8$ prime lens was used with the aperture wide open to ensure the maximum amount of light for illuminating the seeding particles. Aluminum particles with d_{50} of $10\text{ }\mu\text{m}$ and specific density of 2.7 were used as seeding particles. The settling velocity of the aluminum particles is estimated to be $92.6\text{ }\mu\text{m/s}$ using Stoke's law, which is negligible compared with the propeller jet velocity.

In order to reconstruct the 3-dimensional propeller jet, multiple 2-dimensional planes, including both the streamwise and transverse planes, were measured. The sampling rate adopted to measure the streamwise and transverse flow field are 300 fps and 1000 fps, respectively. As for the streamwise measurement (x - z plane), the laser sheet was set to be aligned with the propeller rotation axis as shown in Fig. 3.7. In order to include the zone that covers the entire region from the propeller face to the point where the jet impinges onto the boundary and beyond, the streamwise flow field measurements are stitched from three image windows (fields of view) with at least 30% overlap between two successive windows. For the transverse measurement (y - z plane), the laser sheet was set to be perpendicular to the propeller axis, and its field of view was captured through a 45° mirror located downstream of the laser sheet as shown in Fig. 3.8. In such a way, both the streamwise (u - w) and transverse (v - w) flow field were obtained to reconstruct the 3-dimensional characteristics of a rotating jet flow. With reference to

the coordinate system adopted, the velocity components ($u-w$) correspond to ($x-z$), and ($v-w$) correspond to ($y-z$).

During the post-processing stage, the Laplacian filter function was used to reduce the scattering light by virtue of its ability to filter out low-frequency signals and enhance high-frequency signals (Hsieh *et al.* 2016). Furthermore, the image processing method proposed by Cowen and Monishmith (1997) for reducing boundary effects was also applied in this study. Thereafter, the velocity fields were determined using the analysis of cross-correlation by following the method proposed by Hsieh (2008). Specifically, a multi-pass interrogation window scheme was adopted, which begins from 32×32 pixels, then passes to 16×16 pixels and ends with 8×8 pixels. In each pass, a 50% overlap between adjacent interrogation windows was used in the cross-correlation analysis. Moreover, a multi-time interval method proposed by Hsieh *et al.* (2016) was also used to improve the measurement accuracy, especially for the turbulent jet with a large velocity gradient.

Fig. 3.7 Experimental setup of streamwise measurement: (a) top view; (b) side view

Fig. 3.8 Experimental setup of transverse measurement: (a) top view; (b) side view; (c) end view

3.4.2 Verification of PIV Measurements

Because the propeller jet is a swirling jet that comprises a complex three components of velocity, the seeding particles will have an out-of-plane velocity component. Therefore, it is imperative to verify the results obtained from the application of PIV technique in measuring a flow field that is highly 3-dimensional. In this experiment phase (EP-I), the sampling rate of the high-speed camera was carefully selected to ensure that the displacement of the captured particles is within the 1.5-mm thick laser sheet, and thus being able to measure the in-plane velocity component. Therefore, by adopting a reasonably high sampling rate, the errors caused by the out-of-plane motion would be negligible. Yoon and Lee (2002) also reported that the maximum difference in the axial velocity measurement by using a 2D PIV and stereoscopic PIV (SPIV) was less than 5%, which implies that 2D PIV and SPIV produce almost the same flow structure although bigger discrepancy could occur near the blade tip.

Hsieh *et al.* (2013) compared the acoustic Doppler velocity profiler (ADVP) with 2D PIV results in measuring the same streamwise propeller jet velocity profile, which shows a good agreement between results produced by these two measurement techniques. In the current test, when measuring the flow field in the transverse plane, the axial velocity component of the streamwise flow may cause significant out-of-plane motion. Since the vertical velocity component (w) can be observed from both the streamwise (x - z) and transverse (y - z) planes, they should yield the identical value at the same location. To examine the accuracy of the transverse measurement, Fig. 3.9 shows the comparison of the vertical velocity profiles obtained from x - z and y - z planes at different locations downstream of the propeller under the test condition of $n = 500$ rpm and $Z_b = D_p$. The reasonable consistency shown in Fig. 3.9 validates the feasibility of

the present PIV application in measuring the transverse flow in this study. Furthermore, to minimize the bias that may have occurred due to the insufficient ensemble, for each field of view the mean velocities and turbulence statistics were obtained through an ensemble averaging over 20,000 frame pairs.

Fig. 3.9 Comparison of vertical velocities collected from streamwise (x - z plane) and transverse (y - z plane) measurements

3.5 Experiment Phase II: Scour Measurement

3.5.1 Scour Depth Measurement

Experiment Phase II was carried out in the scour tank (refer to Fig. 3.2). The main task was to measure the temporal and spatial development of the propeller-induced scour hole around the open quay model. An Acoustic Doppler Velocimeter (ADV) was adopted to measure the scour depth due to its capability of detecting the bottom boundary. To obtain the topographic deformation across the entire sediment recess, the ADV was mounted on a transverse system so that it could be moved to the desired position and give corresponding bottom distance. Before the test, the ADV was calibrated by manually changing the bottom distance with a 1-cm increment in still water. The result (see Fig. 3.10) shows a perfect 45° linear relationship between bottom

distance and ADV reading, which justifies its capability of giving accurate bottom distance measurement.

Fig. 3.10 Linear calibration of ADV reading

3.5.2 *Experimental Procedure*

The following experimental procedures were applied to all the tests in EP-II.

- (1) Water was first filled to the level of the false floor; the wet sand bed was then manually leveled by using a sand leveler during which the trapped air in the sand bed was removed, and total consolidation ensured.
 - (2) Water was then slowly added to the predetermined water level ($h_t = 60$ cm) without disturbing the leveled sand bed.
 - (3) The original bed level, which was set as the datum of the test, was measured.
 - (4) The propeller rig was moved to the desired position with the appropriate bed and toe clearance before the commencement of the test.
 - (5) To examine the temporal development of the scour profile, measurements were taken at predetermined time intervals until the asymptotic state was reached.
- Hamill (1987) has earlier shown that switching off and on the propeller would

not affect the overall scouring action as there are no additional flow and sediment supply in a closed tank (confirmed by the tests of Hong *et al.* 2013).

Therefore, in each test, the propeller was stopped at the predetermined time to enable measurements to be taken in still water. The centerline profile was measured at 10 mm intervals with the ADV at time intervals of $t = 0.5, 1, 2, 4, 8, 16, 32, 64, 96,$ and 128 hr.

- (6) At the end of each test, the 3-dimensional topography of the scour profile was measured using a 20 mm by 20 mm grid.

3.6 Experiment Phase III: Velocity Measurement with Erodible Boundary

3.6.1 Flume Setup

Experiment Phase III was aimed to examine the scour mechanisms during the scouring process. To achieve this, it was required to measure the scour hole profile and flow field simultaneously. Therefore, it was decided to conduct the tests in the PIV flume that was used in EP-I. In addition, a similar open quay model to that built in the scour tank in EP-II was added into the PIV flume as shown in Fig. 3.11, in which a layer of sand bed with 10-cm thickness was placed on the bottom, and an acrylic quay slope model with a vertical skirting beneath the quay slope toe was built downstream of the propeller. Moreover, the slope gradient (1V:1.5H) was kept consistent with that used in EP-II. The decision to use the simplistic acrylic slope instead of the armored slope as that used in EP-II was an attempt to initially remove as much variability as possible so as to focus on the influence of the scour profile boundary on the flow field.

Fig. 3.11 Experimental setup of PIV flume with open quay model and sand bed: (a) top view; (b) side view

A similar PIV system to that used in EP-I was also applied here. A Nikon 50mm $f/1.4$ prime lens was used to cover a rectangular field of view (FOV) in front of the quay slope (see Fig. 3.11), which is the most concerned area as per the objective of EP-III. In order to avoid refractions that may have been caused by surface fluctuations, a thin acrylic plate (= 10 mm thickness) was placed on top of the water surface to ensure a tranquil optical access for the laser light. The laser sheet was set to align with the propeller axis of rotation, which is in the vertical plane of symmetry of the flume. In this way, the streamwise flow data were collected from a sectional view of the jet central plane; meanwhile, the centerline scour profile could be identified from the illuminated line where laser sheet intersects with the sand bed as shown in Fig. 3.12(a).

3.6.2 *Image Processing and Correction*

Unlike EP-I, in which the plane boundary was painted black to reduce the boundary light scattering, in EP-III the white sand bed could produce a more severe reflection. Therefore, for image processing, in addition to the high pass filtering process adopted in EP-I, a lowered Gamma value was used to minimize the undesirable light scattering near the sand bed. A comparison of the sample image before and after the image processing is shown in Fig. 3.12, which shows the near-bed particles are almost free from the influence of the light scattering thereby ensuring the reliability of the resulting near-bed velocity.

(a) Before image processing

(b) After image processing

Fig. 3.12 Sample image before and after image processing

In normal PIV operations, the camera (or the light path) is placed perpendicular to the measuring plane (laser sheet plane), such as the setup in EP-I. However, as the scour hole develops, in particular for 3-dimensional scour holes such as those induced by a propeller jet, the sand bed and sediment deposition at the lateral sides will block optical access to the field of view inside the scour hole if the camera is still aligned at 90° to the laser sheet [see Fig. 3.13(a)]. For this reason, in order to capture a full field of view of the flow field in and around the scour hole, the camera was tilted with a depression angle in all tests of EP-III [see Fig. 3.13(b)].

Fig. 3.13 End view of the camera layout with the transverse scour profile:

(a) camera viewing at 90° ; (b) camera viewing at a depression angle

It must be noted that since the camera is not normal to the laser sheet, the captured images inevitably will be distorted. Therefore, an image correction procedure is needed before any PIV calculation is conducted. To this end, a calibration plate with a regularly spaced grid of markers was designed as shown in Fig. 3.14, in which the diameter of the circular marker is 2 mm and the vertical/horizontal distance between any two neighboring circles is 10 mm.

Fig. 3.14 Schematic diagram of calibration plate

A third-order polynomial function adopted by Soloff *et al.* (1997) was used in this study to correct the perspective distortion caused by the oblique viewing. Specifically, the

polynomial function maps the raw image pixel coordinates (x, z) to the corrected coordinates (x', z') as follows:

$$x' = \sum_{i=0}^3 \sum_{j=0}^i a_k x^{i-j} z^j \quad (3.2)$$

$$z' = \sum_{i=0}^3 \sum_{j=0}^i b_k x^{i-j} z^j \quad (3.3)$$

in which a_k and $b_k = 20$ coefficients for the third order polynomial function, where $k = \frac{i+j}{2} + j$. To obtain these 20 coefficients in order to implement the image correction, the following correction procedures were applied for all the tests in EP-III:

- (1) The laser sheet was set to align with the centerline of the propeller axis, which is similar to that of the streamwise measurement in EP-I.
- (2) The camera was adjusted to a depression angle $\alpha = 22^\circ$ from the horizontal level to obtain the desirable field of view. The lens aperture was set to $f = 5.6$ to gain a larger depth of field, which ensures the entire field of view was in focus.
- (3) Before capturing the particle seeded flow field, the calibration plate was placed at the position of the laser sheet in still water. A calibration image was obtained as shown in Fig. 3.15(a), in which the coordinates of the markers were distorted from their actual positions. This calibration image was then used to regress the 20 coefficients in Eq. (3.2) and (3.3) by fitting the distorted dots positions to the regular grid as shown in Fig. 3.15(b).
- (4) Thereafter, the calculated coefficients were applied to correct the flow field images captured in the same run of the test, during which the position of the camera was not moved. Fig. 3.16 shows the sample images of flow field seeded with particles before and after correction.

(a) Before image correction

(b) After image correction

Fig. 3.15 Calibration image before and after correction

(a) Before image correction

(b) After image correction

Fig. 3.16 Particle seeded image before and after correction

3.6.3 Error Analysis

In order to illustrate the systematic error caused by the oblique measurement, Fig. 3.17 depicts the end view of a particle displacement between a time interval from t_1 to t_2 within the thickness of the laser sheet, in which its projections on the laser sheet plane and the focal plane (image sensor) are denoted by their corresponding velocities, *i.e.*, the true velocity w_{true} , and measured velocity $w_{measured}$, respectively. The difference between these two projections is the source of the systematic error involved in the measured vertical velocity component. It must be stated that the horizontal (axial) velocity component u , on the other hand, is not affected since its direction is always parallel to both the laser sheet and focal plane for the current setup and its projections on each plane are, therefore, always the same.

Fig. 3.17 End view of particle velocity inside the laser sheet (not to scale):

(a) 90° viewing; (b) oblique viewing without out-of-plane velocity; (c) oblique viewing with out-of-plane velocity

Fig. 3.17(a) shows that when the camera is aligned normally to the laser sheet, the laser sheet plane is parallel to the focal plane. In such a situation, the measured velocity is simply the orthogonal projection of the true velocity in the laser sheet plane. In other words, $w_{true} = w_{measured}$. Conversely, Fig. 3.17(b) and Fig. 3.17(c) show that when the camera is aligned with the laser sheet plane at an angle other than 90° , the laser sheet plane is no longer parallel to the camera focal plane. Therefore, the particle displacement inside the laser sheet will generate two different projections in these two planes. Two cases should be taken into account for this situation. First, for fully 2-dimensional flows (in x - z plane), the particle displacement is perfectly parallel to the vertical laser sheet plane (y - z plane) as shown in Fig. 3.17(b). The true velocity (projection on laser plane) can, therefore, be directly calculated based on the measured velocity (projection on focal plane) as follows

$$w_{true} = \frac{w_{measured}}{\cos \alpha} \quad (3.4)$$

However, for 3-dimensional flows such as a propeller jet, which has an out-of-plane velocity component (lateral velocity, v) perpendicular to the laser sheet, the particle displacement within the laser sheet will thus have an angle with the vertical laser sheet plane as shown in Fig. 3.17(c). Consequently, the influence of this out-of-plane velocity will affect the measured velocity $w_{measured}$, causing it to be a function of the true velocity w_{true} . Based on the geometry relationship shown in Fig. 3.17(c), w_{true} can be calculated as

$$w_{true} = \frac{w_{measured}}{\cos \alpha} - v \tan \alpha \quad (3.5)$$

in which the influence of the out-of-plane velocity, *i.e.*, the systematic error is

$$err = v \tan \alpha \quad (3.6)$$

It must be noted that this error cannot be eliminated through the image correction procedure. Considering the refraction effect, the direction of light path will change as it moves from water to air (Fig. 3.18). According to Snell's law,

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \quad (3.7)$$

in which $n_1 = 1.333$ is the refractive index of water; θ_1 = incidence angle to the surface normal; $n_2 = 1$ is the refractive index of air; θ_2 = refraction angle. Therefore, the angle α in Eq. (3.6) should be substituted by θ_1 . Furthermore, Fig. 3.18 shows that θ_2 = the camera depression angle in air = 22° . Thus,

$$\theta_1 = \sin^{-1} \frac{n_2 \sin \theta_2}{n_1} = 16.3^\circ$$

Fig. 3.18 Schematic diagram of light refraction

As for the out-of-plane or the lateral velocity v , the results in EP-II show that it becomes insignificant beyond $x/D_p = 3$ since the swirling effect has decayed at this downstream location. In addition, according to Hsieh *et al.* (2013), the larger lateral velocities near the propeller mainly are restricted to a vertical range of $z = Z_b \pm D_p/2$ (where Z_b represents the position of propeller axis). Since the main interest of the current study is focused on the flow field inside the developing scour hole, the lateral velocity components due to the swirling effect likely are negligible there and the induced error may be ignored. Moreover, as mentioned earlier, the axial velocity component u , which

is the main contributor of a propeller jet and the main concern in this study, still can be accurately calibrated through the image correction procedure.

3.6.4 Verification of Oblique PIV Measurement

In order to validate the results obtained by using an obliquely viewing camera, a regular PIV measurement with the camera aligned perpendicular to the laser sheet plane was also conducted for the case of $X_t = 4D_p$ in the presence of a rigid flatbed, which mimics the initial stage of the scouring process. Accordingly, oblique measurement results for the case of $X_t = 4D_p$ at $t = 0$ hr (initial flatbed) are selected for the purpose of comparison as shown in Fig. 3.19, in which the depth velocity profiles are plotted at selected downstream locations from $x/D_p = 0.5$ to 4. The ordinate scale at $z/D_p = 1$ represents the position of the propeller axis. Fig. 3.19(a) reveals that the mean horizontal velocity u shows no significant discrepancy between the oblique and normal measurements, especially for the near-bed data, which is of particular importance for the scouring action. On the other hand, Fig. 3.19(b) shows that the swirling out-of-plane velocity v indeed causes certain influences on the vertical velocity w near the propeller axis at $z/D_p = 1$. This is consistent with the position where the swirling effect is the most significant as reported by Hsieh *et al.* (2013) and Wei *et al.* (2017). Thereafter, this influence diminishes at locations beyond $x/D_p = 2$ as the swirling effect diminishes. Furthermore, Fig. 3.19(c) shows that the profiles of resultant in-plane velocity, *i.e.*, $V_{xz} = (u^2 + w^2)^{1/2}$, essentially resemble those of the horizontal velocity. This is because the horizontal velocity u is the main contributor of the propeller jet, while the vertical w and lateral velocity v are comparably smaller in magnitude. It could, therefore, be inferred that the error involved in the vertical velocity would not affect the final flow structure, especially in locations nearer to the bed, which is more important in affecting bed scouring.

Fig. 3.19 Comparison between oblique and normal measurement:

(a) horizontal velocity, u ; (b) vertical velocity, w ; (c) resultant in-plane velocity, V_{xz}

CHAPTER 4

PLANE BOUNDARY EFFECTS ON CHARACTERISTICS OF PROPELLER JETS

4.1 Introduction

A thorough review of published literature in Chapter 2 reveals that most past studies had focused on free expanding propeller jets, *i.e.*, an unconfined jet. For a typical unconfined propeller jet, due to the presence of the hub, a low-velocity zone will be formed immediately behind the hub, causing the formation of a double-peaked velocity profile near the propeller face. In other words, the maximum axial velocity, unlike that related to a circular offset jet, is not located at the jet centerline initially. Based on its relative position to the centerline, the jet can be longitudinally divided into the zone of flow establishment (ZFE) and zone of established flow (ZEF). Because of the double-peak velocity profile feature, McGarvey (1996) opined that the propeller jet could be described as having two symmetrical streams around the centerline, namely a lower and an upper stream. A sectional view of an unconfined propeller jet is schematically depicted in Fig. 4.1(a), showing how the upper and lower off-center loci of the maximum velocity eventually join at the centerline, which signifies that the jet has entered the zone of established flow at that position. In contrast to the unconfined jet, a definition sketch of a confined propeller jet is shown in Fig. 4.1(b), in which Z_b is the clearance height measured from the propeller axis to the bed; D_p is the propeller diameter; u_m is the local maximum axial velocity, z_m is the position at u_m ; and $z_{m/2}$ is

Note: The material presented in this chapter has been published in *Experiments in Fluids*, 58(10), 141.

the position at half of u_m , *i.e.*, $u_m/2$. In previous studies concerning offset circular jets, it was reported that due to the asymmetrical entrainment on both sides of the jet, its path was found to be deflected towards the bed and finally attached to the wall, which is known as the Coanda effect (Kumar and Das 2011). In the presence of a plane boundary, the propeller jet could be qualitatively equivalent to a circular offset jet with swirl. Therefore, as the propeller jet enters a still water body at a certain clearance height, three regions are expected to form, namely (I) free jet region; (II) impingement region; and (III) wall jet region. In region I, in the vicinity of propeller face, it is not unreasonable to surmise that the boundary effect is negligible and the jet will behave like a free expanding jet with symmetrical upper and lower streams. In region II, as the jet impinges onto the bed, the boundary acts to restrict the expansion of the lower stream, forcing it to flow parallel to the bed. In region III, the jet becomes similar to a classical wall jet.

Fig. 4.1 Definition sketch of (a) unconfined propeller jet and (b) confined propeller jet with a plane boundary

When it comes to engineering concerns associated with propeller-induced scour, the propeller jet is in fact confined by at least the channel or seabed boundary. Hamill *et al.* (2009) investigated the effect of the rudder and a mobile bed on the velocity distributions and found that the two streams are not symmetrical in the presence of a mobile bed. More recently, Johnston *et al.* (2013) studied the influence of a plane boundary on the development of the axial velocity of the propeller jet and found that the lower stream expands faster in the presence of a boundary. It must be noted that their results are primarily confined to the streamwise flow field and that a thorough study of the swirling propeller jet, including all three components of the velocity, therefore, remains elusive presently. To bridge this research gap and with the aim of obtaining a better understanding of the 3-dimensional propeller jet induced flow field and scour, this chapter presents the results of EP-I which starts with the simple case of a plane bed boundary mimicking the initial state of propeller jet scour. The results particularly focus on the comparison of the mean and turbulent flow properties under three clearance heights.

4.2 Test Conditions

In a recent study, Hsieh *et al.* (2013) had conducted a series of experimental studies on an unconfined propeller jet, in which the high-speed particle image velocimetry (PIV) technique was found to be capable of measuring the 3-dimensional propeller jet velocity field. In light of their work, the 3-dimensional characteristics of the propeller jet were measured in the presence of a plane bed boundary by employing the PIV technique. To mimic the case of maneuvering or “bollard pull condition”, in which the movement of the ships is ignored, the location of the propeller model is fixed in the flume. With the primary objective to examine the boundary effect on the development of a propeller jet,

the tests were performed at two rotational speeds of $n = 300$ rpm and 500 rpm with three clearance heights, $Z_b = 2D_p$, D_p , and $0.5D_p$, which represent the high, intermediate and low clearance cases, respectively. Furthermore, it should be stated that the case of $Z_b = 0.5D_p$ is a limiting condition, in which the propeller tip is essentially touching the bottom, producing a wall jet with a swirling effect. Table 4.1 summarizes the test conditions conducted in EP-I. It was found that the flow structures of the two different rotational speeds adopted are reasonably similar. Therefore, the following discussions are only based on the results of $n = 500$ rpm, while the results of $n = 300$ rpm are attached in Appendix A.

Table 4.1 Test conditions of Experiment Phase I

Test	D_p (cm)	Z_b/D_p	n (rpm)	U_o (cm/s)	Measuring plane	Remarks	Field of view (cm ²)	Spatial resolution (cm)
1	7.5	2	500	41.5	Streamwise (x - z)	$y = 0$, central plane	49×20	0.141
2	7.5	1	500	42.4	Streamwise (x - z)	$y = 0$, central plane	49×20	0.142
3	7.5	1	500	42.4	Transverse (y - z)	$x/D_p = 0.5, 1, 2, 3, 4, 5$	18×17	0.131
4	7.5	0.5	500	39.9	Streamwise (x - z)	$y = 0$, central plane	49×13	0.135
5	7.5	0.5	500	39.9	Transverse (y - z)	$x/D_p = 0.5, 1, 2, 3, 4, 5$	18×13	0.150
6	7.5	2	300	37.4	Streamwise (x - z)	$y = 0$, central plane	49×20	0.141
7	7.5	1	300	36.7	Streamwise (x - z)	$y = 0$, central plane	49×20	0.142
8	7.5	1	300	36.7	Transverse (y - z)	$x/D_p = 0.5, 1, 2, 3, 4, 5$	18×17	0.131
9	7.5	0.5	300	35.5	Streamwise (x - z)	$y = 0$, central plane	49×13	0.135
10	7.5	0.5	300	35.5	Transverse (y - z)	$x/D_p = 0.5, 1, 2, 3, 4, 5$	18×13	0.150

4.3 Streamwise (x-z plane) Flow Properties

4.3.1 Mean Velocities

The time-averaged flow field has been widely examined to illustrate the structure of an unconfined free expanding propeller jet (Blaauw and Kaa 1978; Verhey 1983; Hamill 1987; Stewart 1992, *etc.*). The purpose of this section is to examine the mean flow structure of a confined propeller jet to obtain a better insight into the influence of boundary effects. The results with the three different clearances are shown in Fig. 4.2 in the form of the mean velocity vector map and mean streamlines, in which the magnitude and direction of the velocity vectors are $(u^2+w^2)^{1/2}$ and $\tan^{-1}(w/u)$, respectively. It should be noted that the velocity vectors are not plotted with the highest spatial resolution (equivalent to 8 pixels) as indicated in Table 4.1 because inclusion of all the measured velocity vectors in the figure would have resulted in a congested plot, rendering a rational interpretation impossible.

Fig. 4.2 Comparison of vector and streamline plots of mean velocity field under varying clearance heights:

(a1-a2) $Z_b = 2D_p$; (b1-b2) $Z_b = D_p$; (c1-c2) $Z_b = 0.5D_p$

The efflux velocity of a propeller jet is considered to be the maximum mean velocity along the efflux plane (*i.e.*, $x/D_p = 0$), which has been used as the basis for the prediction of the velocity magnitude within the propeller jet by many researchers, e.g. Hamill (1987), Ryan (2002) and Hamill and Kee (2016). It should be noted that when the propeller rotates, its blades periodically pass through the laser sheet at the efflux plane, making it difficult to extract quality data there. In this study, a geometrical mask was used to cover the propeller configuration during the PIV calculations. As a result, the measured initial efflux plane starts from the tip of the propeller hub (*i.e.*, $x/D_p = 0.24$) and the associated maximum velocity is considered to be the efflux velocity, U_o . It is found that $U_o = 41.5$ cm/s, 42.4 cm/s and 39.9 cm/s when $Z_b = 2D_p$, D_p and $0.5D_p$, respectively. Their deviations from the mean are within 3.4% of the average value of 41.3 cm/s. This minor deviation could be attributed to the bias involved in the measurement chain. Based on the measured results, one could safely surmise that the boundary effect on the efflux velocity is negligible.

Considering a circular offset jet that discharges from an elevated opening, a vertical wall is commonly present at the inlet plane. Therefore, when the ensuing jet attaches onto the wall downstream, it will enclose a separated zone which is known as the recirculation zone (Bhuiyan *et al.* 2011). However, this is not the case for a propeller jet because an open water body is present upstream of the jet. In the right column of Fig. 4.2, the streamlines clearly indicate that due to entrainment from the upstream, no reverse eddy is formed beneath the propeller jet. Furthermore, Fig. 4.2(b2) and Fig. 4.2(c2) reveal that when the jet entrains the ambient fluid from the upper side, a backflow is formed above the jet. Although it is not explicit in Fig. 4.2(a2) due to the limitation of the field of view for $Z_b = 2D_p$, it is not unreasonable to infer that a similar

backflow also exists above the upper stream. On the other hand, as the clearance height decreases, the comparison between Fig. 4.2(a2) and Fig. 4.2(b2) reveals that entrainment below the jet has been reduced. Eventually at $Z_b = 0.5D_p$, Fig. 4.2(c2) shows how the presence of the solid boundary has completely restricted any entrainment below the jet. Meanwhile, the backflow above the jet seems to be more intense than its counterpart in the higher clearance case and even suppress the jet expansion between $x/D_p = 1 \sim 2.6$.

Since the backflow is denoted by a negative streamwise velocity, *i.e.*, $u < 0$, the upper stream boundary can be readily defined by the locus of $u = 0$ [see Fig. 4.2(b1) and Fig. 4.2(c1)], which is prevalently identified as the boundary of an unconfined propeller jet. However, in Fig. 4.2(a2), Fig. 4.2(b2) and Fig. 4.2(c2), the streamlines clearly show that the backflow is absent in the lower stream. The jet slipstream boundary is mixed with the surrounding water, invalidating the formation of a distinct jet stream boundary. In order to define an equivalent jet boundary that envelops the major jet energy so as to approximately locate its impingement point on the bed, the outer line of the jet contour plot (where $u \approx 0.05 \sim 0.06U_o$) was arbitrarily selected as the envelope curve representing the boundary of the main jet body. A similar method had been used to identify the plane shear layers in Liepmann and Laufer (1947). Using this approach, Fig. 4.2(a1) and Fig. 4.2(b1) show that the impingement points of $Z_b = 2D_p$ and $Z_b = D_p$ occur around $x/D_p = 3$ and $x/D_p = 1.2$, respectively. As for the case of $Z_b = 0.5D_p$, the jet may be assumed to have impinged onto the bed from the very beginning at $x/D_p = 0$. It should be noted that the transition zones that necessarily exist between successive regions are neglected, the impingement point defined here is for the convenience of subsequent discussion and by no means an exact demarcation.

For the high and intermediate clearance cases of $Z_b = 2D_p$ and D_p [see Fig. 4.2(a1) and Fig. 4.2(b1)], the mean velocity vector plots show that prior to their corresponding impingement points, the jet expands almost linearly, resembling that of an unconfined jet (Hsieh *et al.* 2013) with a typical feature of a double peak profile in the zone of flow establishment. This reveals that the boundary effect on the development of the jet is insignificant in this region, indicating that the jet here may be considered as the free jet region. This region is however not present in the case of $Z_b = 0.5D_p$, in which the jet enters the impingement region immediately from $x/D_p = 0$.

Upon reaching the impingement location, the jet development undergoes varying responses for the three clearances. First, since the clearance is relatively high at $Z_b = 2D_p$ [see Fig. 4.2(a1)], the impingement point is located farther downstream when compared to its counterpart with lower clearances. Based on this observation, one may surmise that a large proportion of the jet energy has already diffused before impingement on the bed. Thus, the jet behaves somewhat like an unconfined jet, and the entire shape of the jet does not deform significantly. Second, Fig. 4.2(b1) and Fig. 4.2(c1) exhibit different behavior, showing that the jet is no longer symmetrical about the propeller axis as is with an unconfined jet, or even a confined jet with a large Z_b [Fig. 4.2(a1)]. Instead, the impingement directs the entire jet towards the bed due to the Coanda effect, resembling the phenomenon that has been extensively reported in offset jets studies, e.g. Nyantekyi-Kwakye *et al.* (2015), Kumar and Das (2011) and Bhuiyan *et al.* (2011). This highlights the fact that a confined propeller jet with a plane boundary is qualitatively comparable to near-boundary offset jets, validating the existence of the wall attachment effect for a propeller jet.

Farther downstream of the impingement point, the jet development in the high clearance case ($Z_b = 2D_p$) still shows no significant difference from that of an unconfined jet. Moreover, in the downstream region, the jet velocity is expectedly weak because the jet expansion process appears to have ceased around $x/D_p = 4$. This position is consistent with the location reported by Hsieh *et al.* (2013) where the swirling effect has become negligible. On the other hand, in the intermediate and low clearance cases, the jet at the downstream location beyond the impingement point was found to behave like a wall jet [see Fig. 4.2(b1) and Fig. 4.2(c1)]. In particular, Fig. 4.2(b1) shows that after the impingement the jet even experiences a further expansion. This process could be explained by the same reason given by Beltaos (1976) for illustrating the oblique impingement jet, in which the author reported that upon impingement, the pressure inside the jet rises, resulting in significant pressure gradient that deflects the flow to be parallel to the wall. Thereafter, the pressure drops again as the wall jet region begins.

Based on the foregoing discussion, it is apparent that the extent of each region varies as the clearance height changes. In summary, it may be inferred that for the high clearance case, only Regions I and II are present; for the intermediate clearance case, all three regions are present; and for the low clearance case, only Regions II and III are observed. In the subsequent discussion, the same region demarcation will be used to examine boundary effects on the turbulence characteristics of a propeller jet.

4.3.2 Turbulence Characteristics

By using the high time-resolution PIV technique, not only are the mean velocity properties but also the turbulence characteristics are obtained, including both the

horizontal and vertical turbulence intensities, *i.e.*, $\sqrt{u'^2}/U_o$ and $\sqrt{w'^2}/U_o$ and dimensionless Reynolds stress $-\overline{u'w'}/U_o$, in which u' , w' are the horizontal and vertical velocity fluctuations, respectively. It must be stated that the turbulence discussed here only represents the in-plane component of turbulence. The results of the streamwise turbulence for different clearance heights are presented in Fig. 4.3, in which their corresponding mean velocity vector plot also is superimposed.

Fig. 4.3 Comparison of turbulence characteristics under varying clearance heights: (a1-a2) $Z_b = 2D_p$; (b1-b2) $Z_b = D_p$; (c1-c2) $Z_b = 0.5D_p$

In the left and central columns of Fig. 4.3, it is evident that the high turbulence zones in terms of $\sqrt{u'^2}/U_o$ and $\sqrt{w'^2}/U_o$, mainly are concentrated in the vicinity of the propeller face and their locations are consistent with the double peak that forms in the mean flow field. Specifically, for $Z_b = 2D_p$ and D_p , $\sqrt{u'^2}/U_o$ and $\sqrt{w'^2}/U_o$ possess a pair of symmetrical peaks with a similar magnitude and the same sign about the propeller axis, indicating that the boundary effect is insignificant in affecting the high turbulence for these two clearance heights. In contrast, for $Z_b = 0.5D_p$, due to the intense wall attachment effect, the two high turbulence peaks are no longer symmetrical, instead the lower peak is fully attached to the bed boundary. For $\sqrt{u'^2}/U_o$ and $\sqrt{w'^2}/U_o$, their respective maximum values ($\sqrt{u'^2}/U_o = 0.73, 0.78, 0.73$; $\sqrt{w'^2}/U_o = 0.78, 0.77, 0.61$) and positions for three clearance heights are shown in Fig. 4.3. It can be seen that the maximum value of $\sqrt{u'^2}/U_o$ shows no significant variation for these three clearance cases. However, Fig. 4.3(c2) shows that the maximum $\sqrt{w'^2}/U_o$ is reduced by $\sim 22\%$ for $Z_b = 0.5D_p$ compared to its counterpart for $Z_b = 2D_p$ and $Z_b = D_p$, indicating that the vertical velocity fluctuation has been suppressed by the plane boundary. One may deduce that by restricting jet expansion and thus the associated extent of jet diffusion, the total vertical turbulence intensity has been reduced. Moreover, a comparison between $\sqrt{u'^2}/U_o$ and $\sqrt{w'^2}/U_o$ for the same clearance height reveals that they have the same order of magnitude for $Z_b = 2D_p$ and D_p , complying with the isotropic turbulence characteristics. However, this is not so for $Z_b = 0.5D_p$ since the vertical velocity fluctuation level is significantly reduced although its horizontal counterpart is not, thus resulting in an anisotropic turbulence characteristic.

The right column of Fig. 4.3 shows a comparison of the equivalent Reynolds stress for different clearance heights. For $Z_b = 2D_p$ and D_p , Fig. 4.3(a3) and Fig. 4.3(b3) show a pair of high Reynolds stress wings with opposite sign due to the opposite velocity gradient of the upper and lower streams as is reflected in the superimposed mean velocity vector plot. Overall, the Reynolds stress shows a positive correlation with the horizontal velocity gradient ($\partial u/\partial z$), *i.e.*, they are both positive in the lower stream and negative in the upper stream. However, within the local area immediately around the propeller hub ($0 \leq x/D_p \leq 0.6$), it can be seen that positive and negative Reynolds stresses occur in the upper and lower streams, respectively. A reason for this difference likely is due to the higher $\partial w/\partial x$ associated with the contraction phenomenon near the propeller face (Hsieh *et al.* 2013), which is known as the vena contracta effect in the case of a stream issuing out of a nozzle or orifice. Moreover, unlike the double-peak feature observed in the $\sqrt{u'^2}/U_o$ and $\sqrt{w'^2}/U_o$ plots, the Reynolds stress's double-wing feature, which patently shows an expanding trend with the expanding shear layer, grows with the increment of the shear layer thickness. Thereafter, a significant decay is observed beyond $x/D_p = 2.7$, which is a reflection of jet energy dissipation during the expansion process. On the other hand, for $Z_b = 0.5D_p$, Fig. 4.3(c3) shows a relative smaller Reynolds stress than that of the higher clearance cases, indicating that the momentum transfer has been damped since the jet expansion is limited by the boundary effect.

4.4 Transverse (y-z plane) Flow Properties

4.4.1 Mean Velocities

The transverse flow field of an unconfined propeller jet has been reported in Hsieh *et al.* (2013), in which they found that the swirling effect was mainly concentrated within

a distance $2D_p$ downstream of the propeller. However, to the best knowledge of the authors, the transverse swirling properties of propeller flows near a boundary has rarely, if ever, been reported. Consequently, six transverse planes downstream of the propeller face were measured at $x/D_p = 0.5, 1, 2, 3, 4, 5$ with two clearance heights of $Z_b = D_p$ and $0.5D_p$. Based on the streamwise flow data associated with $Z_b = 2D_p$ [see Fig. 4.2(a1)], it may be inferred that the transverse flow field likely is similar to that associated with an unconfined jet, in that its swirling effect zone is essentially located in the free jet region. Consequently, the test with $Z_b = 2D_p$ is not conducted. The mean vector and streamline plots of the measured data with $Z_b = D_p$ and $0.5D_p$ are shown in Fig. 4.4 and Fig. 4.5, respectively, in which the counter-clockwise swirling flows are clearly presented.

Fig. 4.4 Vector (upper row) and streamline (lower row) plots of transverse mean velocity field, $Z_b = D_p$ (looking upstream)

Fig. 4.5 Vector (upper row) and streamline (lower row) plots of transverse mean velocity field, $Z_b = 0.5D_p$ (looking upstream)

Within the free jet region, Fig. 4.4(a) reveal that before the jet has impinged onto the boundary, the transverse plane exhibits a centrosymmetric swirling flow structure, causing the formation of a donut-shape shear layer around the peripheral surface of the jet. This resembles the unconfined jet published in Hsieh *et al.* (2013). However, outside the jet body, there exists a low-velocity zone between the bed and up to the lower stream of the swirling jet. In contrast, for an unconfined jet, Hsieh *et al.* (2013)'s results show that the velocity value is almost uniform around the peripheral surface of the jet since the surrounding water are equally entrained into the jet core. This difference likely is due to the presence of the bed that has restricted entrainment below the jet and eventually causes a lower velocity there. In addition, as the surrounding fluid is entrained into the jet, the swirling strength decays as its size expands with distance, x [see Fig. 4.4(b)].

In the impingement region, the swirling rotation has begun to be interrupted by the presence of the bed [see Fig. 4.4(c) and Fig. 4.5(a)] and thus its circular shape is no longer maintained. For $Z_b = D_p$, a higher velocity zone is observed in the third (lower left) quadrant [see Fig. 4.4(c)]; as the jet propagates farther downstream [see Fig. 4.4(d)], the high-velocity zone has moved away from the third quadrant, and the jet is attached to the boundary. This is particularly apparent in Fig. 4.5(a) and Fig. 4.5(b) for $Z_b = 0.5D_p$, in which the jet has impinged onto the boundary with its full swirling strength at the outset. In summary, it is evident that the jet was unable to move upward after the impingement, which may be another possible reason why the jet is directed toward the boundary.

Thereafter in the wall jet region, the experimental data show that the swirling effect has decayed to such an extent that it has become negligible, at least along the central plane ($y = 0$), although higher velocity zones still are persistent near to the boundary layer at the right side for $Z_b = D_p$ [see Fig. 4.4(e) and Fig. 4.4(f)]. For $Z_b = 0.5D_p$, the swirling is separated into two opposite secondary vortices on each side of the central plane [see Fig. 4.5(c) and Fig. 4.5(d)]. This feature confirms what was reported by Launder and Rodi (1983), in which they investigated the 3-dimensional wall jets and stated that a lateral motion was formed near the bed, diverting the jet horizontally away from the central plane, and consequently, the flow was sucked in towards the bed to satisfy flow continuity. It must be stated that in this study the lateral motions on either side of the central plane are asymmetrical due to the biased swirling nature of the propeller jet. At $x = 5D_p$, Fig. 4.5(f) shows similar low-velocity values as those in the higher clearance case, indicating that the transverse flow can be neglected at this distance and the streamwise flow could be regarded as a quasi-two-dimensional flow.

4.4.2 Turbulence Characteristics

In this section, the equivalent turbulence intensity, $I = \sqrt{v'^2 + w'^2}/U_o$ of the aforementioned transverse planes are presented (see Fig. 4.6) and discussed. A similar comparison of the data between $Z_b = D_p$ and $0.5D_p$ as in Fig. 4.6 reveals that the difference in clearance heights does not show obvious influence on the transverse turbulence intensity in terms of its order of magnitude. The maximum turbulence intensity near the propeller was not significantly reduced in the low clearance case ($Z_b = 0.5D_p$) as that observed in the streamwise plane. A possible reason is that in the transverse plane, the swirling effect is the dominant source of turbulence and its intensity is mainly dependent on the propeller rotational speed. Therefore, the

turbulence intensity is expected to decay along with the decreasing swirling effect as the jet propagates downstream. This is exactly what is observed in Fig. 4.6.

Moreover, Fig. 4.6 shows that the shapes of the turbulence intensity field are basically consistent with their corresponding mean flow patterns shown in Fig. 4.4 and Fig. 4.5. The left two columns of Fig. 4.6 show that since the swirling effect is still strong up to $x = D_p$, the high turbulence zone indicated by the red color scale can be observed in both $Z_b = D_p$ and $0.5D_p$ although in the latter case, the wall attachment effect deforms the swirling circle and causes significant diffusion of the turbulence. Thereafter, at $x = 2D_p$, since the swirling flow is either interrupted or completely split apart by the boundary, as was discussed in the preceding section, the high turbulence intensity is rapidly dissipated along with jet diffusion. Beyond $x = 3D_p$, for $Z_b = D_p$, the turbulence intensity is found almost evenly distributed in the measured field of view; for $Z_b = 0.5D_p$, however, the turbulence is mainly attached to the boundary because vertical jet diffusion is limited, as was discussed earlier.

Fig. 4.6 Comparison of equivalent turbulence intensity: (a-f) $Z_b = D_p$; (g-l) $Z_b = 0.5D_p$

4.5 Characteristic Profiles

4.5.1 Depth Velocity Profiles

To better understand boundary effects on the three velocity components $u(x)$, $v(y)$ and $w(z)$ individually, their vertical profiles at selected downstream locations in the central plane are plotted in Fig. 4.7 - Fig. 4.9, respectively, in which the propeller axis positions are denoted by the horizontal dash line.

Fig. 4.7 shows the evolution of the mean axial velocity u profile at different downstream distances. It may be inferred from Fig. 4.2 and Fig. 4.7 that the axial component of the flow dominates the propeller jet configuration, as was reported by previous researchers based on experimental measurements of the initial 3-dimensional flow, e.g., Lam *et al.* (2010), who stated that the axial velocity component represents the main contributor of the velocity of a propeller jet. By aligning the sub-figures in Fig. 4.7 vertically, it can be observed that in the vicinity of the propeller face up to $x = 0.5D_p$, the u -profiles of all the three clearance heights show a comparable double-peak shape and similar magnitude. Farther downstream, different development trends can be observed. For $Z_b = 2D_p$, Fig. 4.7(a) shows that the symmetrical double peak profile, or in another word, the free jet region, persists up to $x = 2D_p$ before boundary effects kick in to reduce it to a single peak profile. This is supported by the plot in Fig. 4.2(a1), in which the double peaks merge into an off-center single peak located below the propeller axis at $x \approx 2D_p \sim 3D_p$. As the clearance height decreases, the jet enters the impingement region earlier. For $Z_b = D_p$, Fig. 4.7(b) shows that the symmetrical double peak profile in the free jet region has become asymmetrical at $x = 2D_p$, with the lower peak having a higher magnitude. Farther downstream from this location, the off-center single peak moves

down to the boundary, somewhat resembling that of a wall jet. Furthermore, for $Z_b = 0.5D_p$, Fig. 4.7(c) shows that within the impingement region, the double peak profile is asymmetrical and maintained only up to $x = D_p$. At $x = 2D_p$, the wall jet region is already reached, and the jet profile develops a typical wall jet thereafter.

Fig. 4.7 Mean axial velocity at different downstream locations in which regions I, II, III represent free jet, impingement and wall jet regions, respectively. (a) $Z_b = 2D_p$ (b)

$Z_b = D_p$ (c) $Z_b = 0.5D_p$

Fig. 4.8 shows the vertical distribution of the mean vertical velocity w at different downstream distances, which is of great interest due to the presence of the lateral motion in 3-dimensional turbulent jets. In general, in the vicinity of the propeller, Fig.

4.8(a) ($x \leq 2D_p$) and Fig. 4.8(b) ($x \leq D_p$) show that the vertical velocity in the upper and lower streams are negative and positive, respectively, indicating that the ambient water is entrained from both above and below the jet. However, Fig. 4.8(c) shows that the vertical velocities are almost all negative in both the upper and lower streams. This is attributed to the fact that when $Z_b = 0.5D_p$ the ambient water can only be entrained from the upper side. Upon reaching the impingement region, Fig. 4.8(a) ($x = 3D_p$) and Fig. 4.8(b) ($x = 2D_p$) show that the vertical velocities in the lower stream have reduced to almost zero. Farther downstream, in all three clearance cases, Fig. 4.8(a) ($x \geq 4D_p$), Fig. 4.8(b) ($x \geq 3D_p$) and Fig. 4.8(c) ($x \geq 2D_p$), show that the vertical velocities below the propeller axis are negative with increasing absolute values from high to low clearance cases, which quantitatively verifies that the jet is directed downward with increasing attachment effect.

Fig. 4.8 Mean vertical velocity at different downstream locations in which regions I, II, III represent free jet, impingement and wall jet regions, respectively. (a) $Z_b = 2D_p$

(b) $Z_b = D_p$ (c) $Z_b = 0.5D_p$

Fig. 4.9 presents vertical distributions of the mean lateral velocities for $Z_b = D_p$ and $0.5D_p$. When $x \leq D_p$, both Fig. 4.9(a) and Fig. 4.9(b) show that the lateral velocity profiles exhibit an inverse S-shape function due to the swirling nature of the flow. Approaching the impingement region, Fig. 4.9(a) ($x = 2D_p$) shows how the lateral velocity profile is suppressed near the bed. Thereafter, the swirling strength decreases gradually, meanwhile the vertical position of the local maximum v shows a wall attachment effect up to $x = 5D_p$, which is similar to the behavior of its axial counterparts.

However, for $Z_b = 0.5D_p$, Fig. 4.9(b) shows that from $x = 2D_p$ the swirling strength disappears somewhat abruptly as the lateral velocity profile almost overlaps with zero. This is because the main swirling rotation has been separated into two secondary vortices on either side of the central plane [see Fig. 4.5(d)], rendering the streamwise flow on the central plane approaching a 2-dimensional flow.

Fig. 4.9 Mean lateral velocity at different downstream locations in which regions I, II, III represent free jet, impingement and wall jet regions, respectively. (a) $Z_b = D_p$ (b) $Z_b = 0.5D_p$

4.5.2 Longitudinal Profiles

To further examine the jet development under different clearance heights, selected characteristic curves are plotted in Fig. 4.10, in which Fig. 4.10(a) depicts the loci of the local maximum axial velocity from both the upper and lower streams; Fig. 4.10(b) shows the decay of the magnitude of the maximum axial velocity u_m ; and Fig. 4.10(c) illustrates the evolution of the velocity along the centerline of the propeller axis, u_c .

Fig. 4.10 Longitudinal profiles of (a) loci of local maximum axial velocity, z_m ; (b) decay of the maximum axial velocity, u_m and (c) evolution of the centerline velocity,

$$u_c$$

In Fig. 4.10(a), the propeller axis is referred to as the centerline and is denoted by the horizontal dash line where $z_m/Z_b = 1$. The data show that for all three clearance heights, both the upper and lower loci of u_m initially move toward the centerline until $x/D_p = 0.6$, where the vena contracta is assumed to occur. Thereafter, because of jet expansion, they are found to depart from the centerline, causing the formation of the typical double peak profile, as is seen in Fig. 4.7. For an unconfined propeller jet, the upper and lower loci

of u_m will finally return to the centerline and enter the zone of established flow [see Fig. 4.1(a)]. Fig. 4.10(a) shows that this is generally true for the upper stream for all three clearance heights. However, for the lower stream, the loci of u_m do not meet its upper stream counterpart at the centerline for all three cases, although for $Z_b = 2D_p$ and D_p they did show an attempt towards the centerline within a range of $x/D_p = 2.2 \sim 2.6$ and $2.5 \sim 3.2$, respectively. Farther downstream, the loci of u_m for $Z_b = 2D_p$ seem stable in the vertical direction after $x/D_p = 2.6$ but are located slightly lower than the propeller axis, confirming that the wall attachment effect is still present in this high clearance case. For $Z_b = D_p$, the loci of u_m show a turning point around $x/D_p = 3.2$ and start falling towards the bed thereafter. Finally, the loci of u_m for $Z_b = 0.5D_p$ fall all the way towards the bed and are almost attached to the bed beyond the vena contracta until the jet expands again.

Since a rotating propeller draws the upstream water through its blade slot, the efflux velocity may be theoretically maximum at the blade plane. Once the ambient fluid is entrained into the high-velocity region of the jet, the decay of the maximum axial velocity is expected. However, Fig. 4.10(b) shows that the normalized values of u_m in all three cases show no obvious decay within $1D_p$ distance downstream the propeller, instead a slight increase around $x = 0.6D_p$ is detected. This is probably due to the effect of the vena contracta.

In general, Fig. 4.10(b) shows the data for three clearance heights although it only exhibits two distinct trends of decay as the low clearance case of $Z_b = 0.5D_p$ shows a totally different scenario from that of the two higher clearance cases. On the one hand, for the high and intermediate clearance cases of $Z_b = 2D_p$ and D_p , their respective u_m –

value exhibits an almost identical decay rate up to $x/D_p = 1$, which is located within their respective free jet region. Thereafter, for $Z_b = D_p$, within a range of $x/D_p = 1 \sim 3$, u_m shows a marginally higher decay rate than that for $Z_b = 2D_p$, which likely is attributed to the energy loss caused by impingement. Beyond this, the decay rate progressively decreases until it reaches $x/D_p = 3.2$, and appears to stop altogether around $x/D_p \geq \sim 4$. For $Z_b = 2D_p$, u_m appears to adopt two distinctive decay rates all the way down to the far downstream region, with the change occurring at $x/D_p = \sim 3$, with the earlier decay rate being larger than that of the later. This result confirms Johnston *et al.* (2013)'s inference that the confinement of the jet limits the mixing intensity of the lower stream by restricting entrainment of the ambient water inwards the jet, consequently reducing the decay rate of the maximum axial velocity.

On the other hand, u_m for $Z_b = 0.5D_p$ only decays very marginally up to $x/D_p = \sim 2.5$ since jet expansion is confined. However, beyond this location, it is found to decay quickly, probably attributable to energy dissipation due to mixing associated with wall jet expansion. Launder and Rodi (1983) suggested that in a typical wall jet, the outer-region shear stress due to mixing is larger than the wall stress itself; moreover, the latter decays faster than its counterpart in the outer region. From the results presented in this study, one may surmise that in the wake of a propeller jet, energy dissipation is mainly due to the mixing effect with the surrounding fluid where larger shear stress occurs, although the impingement with the boundary, to a certain extent, indeed would cause some energy loss. Consequently, due to the presence of the bed boundary, the overall mixing intensity dwindles and thus slowing down the decay of the maximum velocity.

Fig. 4.10(c) shows that in all three clearance heights, the centerline velocity u_c undergoes a similar acceleration from the low-velocity zone behind the propeller hub to reach their respective peak value at almost the same location of $x = 0.6D_p$. By aligning Fig. 4.10(a) and Fig. 4.10(c) vertically, it is found that this location is, in fact, consistent with the one where the contraction effect has occurred (denoted by the red dotted line). Beyond this location, u_c in $Z_b = 2D_p$ and D_p show a similar monotonic decreasing trend, although its magnitude is slightly higher in the former than the latter, possibly due to its jet path being directed downward to the bed. Another interesting feature is in the case of $Z_b = 0.5D_p$ in which u_c decreases rapidly in the impingement region, to be followed by another increase in the wall jet region as the jet expands again. This is because as u_c decreases, the pressure inside the jet increases. Then as the wall jet region develops the pressure drops back to its ambient value, resulting in the increases of u_c as shown in Fig. 4.10(a) after $x/D_p = 3$.

4.5.3 Wall Jet Similarity Profiles

In this section, the discussion is focused on the wall jet region of the intermediate and low clearance cases ($Z_b = D_p$ and $0.5D_p$). According to Verhoff (1963), by introducing proper velocity and length scales with an error function, the velocity profiles of a plane turbulent wall jet can be expressed by a universal similarity function with the following form

$$\frac{u}{u_m} = A \left(\frac{z}{\delta} \right)^{1/7} \left[1 - \operatorname{erf} \left(B \frac{z}{\delta} \right) \right] \quad (4.1)$$

in which, A and B are constants, and δ is the characteristic length scale of the jet profile. As mentioned earlier, for $Z_b = D_p$ and $0.5D_p$, there exists a wall jet region following the impingement region, in which the jet expands with a wall jet shape. By taking the velocity half height $z_{m/2}$ (the height where $u_m/2$ occurs) as the characteristic length scale,

an attempt is made to fit the present data with the classical wall jet similarity function. It is found that the confined propeller jet data of this study also exhibit self-similarity and show a reasonable agreement with Verhoff (1963)'s fitted curve (see Fig. 4.11) with $A = 1.48$, $B = 0.68$.

$$\frac{u}{u_m} = 1.48 \left(\frac{z}{z_{m/2}} \right)^{1/7} \left[1 - \operatorname{erf} \left(0.68 \frac{z}{z_{m/2}} \right) \right] \quad (4.2)$$

Fig. 4.11 Self-similarity of streamwise velocity in the wall jet region

Although a sharp demarcation between impingement and wall jet region cannot be easily identified in the figure, the location where the velocity profile starts to collapse with Verhoff's proposed equation may be considered as an approximate value. In the current study (EP-I), they are $x/D_p = 3.2$ and 1.8 for $Z_b = D_p$ and $0.5D_p$, respectively. It can be seen that since the case of $Z_b = 0.5D_p$ shows a more intense wall attachment, its

$z/z_{m/2}$ have a lower vertical position, resulting in its similarity profile $z/z_{m/2}$ to be higher in the vertical direction in Fig. 4.11. Meanwhile, evident deviation occurs when $u/u_m < 0$ and $z/z_{m/2} > 2$. This could be attributed to the presence of backflow where $u/u_m < 0$ because Eq. (4.2) does not allow negative values of u/u_m . As for the case of $Z_b = D_p$, deviation also exists in the upper profile where $z/z_{m/2} > 1$. However, as x/D_p increases, this deviation shows a decreasing trend as the associated similarity profile approaches the fitted curve. In general, within the range of $z/z_{m/2} < 1$, it may be surmised that the clearance height does not affect the shape of the wall jet profile as long as the jet already has entered the wall jet region. With reference to the transverse flow field, it should be noted that in the wall jet region, the transverse flow on the central plane is essentially small and the streamwise flow could be considered to be quasi-two-dimensional. This may explain why a confined swirling jet possesses a wall jet region in which the classical wall jet similarity function can be applied.

4.6 Concluding Remarks

In this chapter, the 3-dimensional flow field and turbulence characteristics of confined propeller jets in the presence of a plane boundary are presented. The boundary effect was examined by comparing results obtained from three clearance heights. The following findings are drawn from the study:

1. In the presence of a plane boundary, the flow field downstream of the propeller can be divided into three regions, namely free jet, impingement and wall jet regions.
2. The streamwise vector plots show that the jet is directed towards the bed. The phenomenon can be explained by the well-known Coanda effect, similar to that related to jet attachments observed in the classical 3-dimensional offset jet.

Another reason for the propeller-jet attachment is related to the transverse flow in which the presence of the boundary hinders the complete swirling rotation and confines the jet energy near the bed.

3. In the impingement region, the transverse flow field shows that the boundary can dramatically deform the rotation pattern, especially when $Z_b = 0.5D_p$, with the initial swirling being separated into two secondary vortices on either side of the central plane. As a result, the streamwise flow at the central plane becomes quasi-two-dimensional in the wall jet region.
4. For $Z_b = 0.5D_p$, the presence of the boundary significantly restricts the vertical velocity fluctuation and the associated turbulence intensity in the streamwise plane, causing the turbulence characteristics to become anisotropic. However, the magnitude of the equivalent turbulence intensity in the transverse plane does not change much. A possible reason is that it is mainly dependent on the swirling strength that is controlled by the rotational speed.
5. The decay of the maximum velocity reveals how the presence of the bed boundary slows down jet energy dissipation through a reduced mixing intensity with the surrounding fluid.
6. In the wall jet region, the jet exhibits a behavior that resembles a wall jet, and the axial velocity profile shows a good agreement with the classical wall jet similarity function.

CHAPTER 5

INFLUENCE OF TOE CLEARANCE ON PROPELLER SCOUR AROUND AN OPEN-TYPE QUAY

5.1 Introduction

Chapter 2 reveals that most research studies on propeller-induced scour were restricted to either unconfined propeller scour or confined propeller scour associated with a closed quay; researches on propeller scour in the open-type quay have rarely been reported. This chapter presents the results of EP-II, which comprises a series of laboratory tests on scouring action induced by a ship propeller jet in an open berth quay with an armored slope and vertical skirting. The objective is primarily to investigate the influence of the toe clearance on the scouring process under different test conditions. The centerline profile and characteristic dimensions, including the maximum asymptotic scour depth, width, and length under different test conditions are measured and compared to obtain an improved understanding of the subject.

5.2 Test Conditions

The Experiment Phase II was conducted in the scour tank as introduced in Chapter 3. Table 5.1 summarizes the test conditions adopted in this phase. The test conditions (Test A0) of Hong *et al.* (2013) are also included because their data are used for comparison in this chapter. According to Verhey (1983), in order to avoid the scale effects due to viscosity, the Reynolds number of the jet flow and propeller should be greater than

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3×10^3 and 7×10^4 , respectively. Following Verhey (1983)'s method, these two Reynolds numbers can be calculated by using $Re_{flow} = \frac{U_o D_p}{\nu}$ and $Re_{prop} = \frac{n D_p L_m}{\nu}$, in which L_m is the characteristic length dependent on the propeller geometry defined as $L_m = \beta D_p \pi \left[2N \left(1 - \frac{D_h}{D_p} \right) \right]^{-1}$. Hamill *et al.* (2015) suggested that the efflux velocity, U_o , can be obtained by using $U_o = 1.22 n^{1.01} D_p^{0.84} C_t^{0.62}$ [*i.e.*, Eq. (2.10)], an equation that is used in some current design guideline (Hamill and Kee 2016).

In this chapter, the Reynolds number of the jet flow varies from 6.8×10^4 to 14.2×10^4 , all of which are found to be greater than 3×10^3 . On the other hand, the Reynolds number of the two propellers used in this study (EP-II) varies from 2.0×10^4 to 4.0×10^4 , which are lower than the limiting value suggested by Verhey (1983). However, Blaauw and Kaa (1978) and Verhey (1983) have stated that the scale effects due to the non-compliance of the viscous effects likely are not significant, an issue that was later confirmed by Lam *et al.* (2010) and Hamill and Kee (2016). Consequently, the scale effects, if any, related to the lower propeller Reynolds number is ignored.

Table 5.1 Test conditions of Experiment Phase II

Test ^a	D_p (cm)	d_{50} (mm)	Z_b/D_p ^b	X_t/D_p ^c	n (rpm)	U_o (m/s)	F_o	Type of scour	Remark
A1-A8 ^d	10	0.34	1	2, 3, 4, 5, 6, 7, 8, 9	450	0.778	10.5	Confined	Present study
B1-B9	10	0.34	1	2, 3, 4, 5, 6, 7, 8, 9, 11	600	1.040	14.0	Confined	Present study
C1-C9	15	0.34	1	2, 3, 4, 5, 6, 7, 8, 9, 10	450	1.053	14.2	Confined	Present study
A0	10	0.34	1	∞	450	0.778	10.5	Unconfined	Hong <i>et al.</i> 2013
B0	10	0.34	1	∞	600	1.040	14.0	Unconfined	Present study
C0	15	0.34	1	∞	450	1.053	14.2	Unconfined	Present study

^aTest numbers A1-A8 are referred to as Series A in this paper, and A0 is the corresponding unconfined case. The rest follows in the same manner.

^b Z_b/D_p is clearance height ratio.

^c X_t/D_p is toe clearance ratio.

^dTests A1-A8 adopted the same propeller model and bed sediment as that used in Test A0 conducted by Hong *et al.* (2013).

The definition sketch of a typical scour profile (side and end views) in an open-type quay is shown in Fig. 5.1, where the maximum scour depth ε_m is expected to be affected by the following variables, *viz.*, propeller diameter D_p ; speed of rotation, n ; median sediment size d_{50} ; bed clearance Z_b ; toe clearance X_t ; slope gradient; and tail water depth h_t . In this chapter, the influence of toe clearance is systematically examined under various test conditions as tabulated in Table 5.1. Ryan (2002) has stated that the typical distance from the propeller face to a perpendicular quay wall, which is dependent on the ship and pier design, varies from $3D_p$ to $5D_p$ and upwards. It must be stated that due to the limitation of the tank size, the present experimental setup allows the toe clearance to vary from $2D_p$ to $11D_p$ for the 10-cm propeller, and $2D_p$ to $10D_p$ for the 15-cm propeller.

Fig. 5.1 Definition sketch of typical scour profile in the presence of a quay slope

5.3 Temporal Development of Scouring Process

Fig. 5.2(a) shows the evolution of the centerline profile for Test A4 ($D_p = 10$ cm; $n = 450$ rpm; $X_t = 5D_p$) from time, $t = 0.5$ to 128 hr, in which z is the scour depth and x is the longitudinal distance measured from the propeller face. The data reveal that the upstream section of the scour profile near the propeller reaches the asymptotic state earlier than the downstream part near the skirting. Similar trends are found in all the

other tests conducted in EP-II with different propeller diameters, rotational speeds, bed and toe clearances. Corresponding results are attached in Appendix B.

Fig. 5.2 Temporal development of (a) centerline profile and (b) maximum scour depth
(Test A4)

Because the centerline profile was measured at geometric time intervals, the absolute equilibrium state is difficult to ascertain. Recognizing that the maximum scour depth at the asymptotic state is an important parameter needed for designing the depth of the vertical skirting in terms of scour damage, it is assumed that when the average rate of the development of the maximum scour depth in the last 64 hours of the test is less than

0.3 mm/h (in the same order of magnitude of d_{50} per hour), the asymptotic state is considered to have been reached and the test can be terminated. Based on this definition, all tests conducted in EP-II are found to have reached the asymptotic state at 128 hr. The maximum scour depth at different time intervals ($\varepsilon_{m,t}$) were collected from the centerline profiles in Fig. 5.2(a) and plotted against time in Fig. 5.2(b). The data reveal that the temporal development of the propeller scouring process may be divided into four phases, which are similar to those observed by Zanke (1978) and confirmed in Hoffmans and Verheij (1997) and Hong *et al.* (2013), as follows:

- I. Initial phase: The initial scour hole profile was formed, and the maximum scour depth deepens rapidly, $t = 0 \sim 8$ hr;
- II. Development phase: The overall scour hole profile does not change much, although the maximum scour depth continues to increase, $t = 8 \sim 32$ hr;
- III. Stabilization phase: The erosion rate of the maximum scour depth reduces with time until $t = 64$ hr; and
- IV. Asymptotic phase: The scouring process almost ceases altogether, $t = 64 \sim 128$ hr.

It must be stated that the timescales stated above are deduced from Test A4. They may be marginally different for tests conducted with the other test conditions although the four phases are observed in all the tests.

5.4 Comparison with the Unconfined Propeller Scour

5.4.1 Three-Dimensional Scour Hole Comparison

Hong *et al.* (2013) conducted a series of experiments on unconfined propeller scour in the same tank with the same sediments ($d_{50} = 0.34$ mm) and propeller model ($D_p = 10$ cm) as that used in this study (EP-II). In their work, the asymptotic scour profile was

found to consist of three parts: a small scour hole, a primary scour hole and a deposition mound. By using the same variables, *i.e.*, bed clearance ratio (Z_b/D_p), propeller diameter (D_p) and rotational speed (n), the results of the present confined propeller scour conducted with different toe clearances are compared with their experimental data. The confined scour profiles obtained from this study reveal that the small scour hole and primary scour hole are also present in all the cases with different toe clearances. However, because of the presence of the armored slope and vertical skirting at the downstream location, many of the primary scour holes are abruptly curtailed at the toe of the slope with sediment deposition occurring on their transverse sides instead of at the downstream location [see Fig. 5.3(a)], as is in the unconfined scour case [see Fig. 5.3(b)]. It should be mentioned that if the propeller is located far away from the quay structures, *i.e.*, large X_i/D_p ratios, the deposition mound is observed to form downstream of the primary scour hole, similar to that formed with an unconfined scour hole, although some sediment particles are still found on its transverse sides. All the other 3-dimensional scour hole plots for Series A, B, and C are attached in Appendix B.

(a) Confined propeller scour (Test A4)

(b) Unconfined propeller scour (Test A0, Hong *et al.*, 2013)

Fig. 5.3 Three-dimensional asymptotic scour hole of (a) confined and (b) unconfined propeller scour, plotted based on data of Hong *et al.* (2013)

5.4.2 Centerline Profile Comparison

In the absence of a quay structure, *i.e.*, the unconfined case, the propeller-induced scour is primarily dependent on propeller jet diffusion. When the propeller moves toward a quay, it is postulated that a deflected flow will be formed in front of the quay structures due to the obstruction, wherein the final scour hole is the result of the combined action of the propeller jet and deflected flow. In other words, two scouring processes, namely, the jet diffusion and quay obstruction mechanisms would influence the development of scour hole in the presence of the armored slope and vertical skirting. Similar processes were observed by Chin *et al.* (1996), who reported that the development of local scour around a vertical pile subjected to a 3-dimensional offset jet was governed by the pile obstruction and jet diffusion mechanisms.

In order to illustrate how these two scouring mechanisms influence the development of the scour profile, the asymptotic centerline profiles of the confined case (Series A of

the present study, EP-II) are plotted together with the published centerline profile of the unconfined case (Test A0, Hong *et al.* 2013) in Fig. 5.4. The data clearly highlight how the propeller-induced scour profile is significantly influenced by the presence of the armored slope and vertical skirting, causing different profiles to form with different toe clearances.

Fig. 5.4 Comparison between the centerline profile of confined and unconfined scour hole at asymptotic state (Series A): (a) $X_t = 2D_p$; (b) $X_t = 3D_p$; (c) $X_t = 4D_p$; (d) $X_t = 5D_p$; (e) $X_t = 6D_p$; (f) $X_t = 7D_p$; (g) $X_t = 8D_p$; (h) $X_t = 9D_p$

For X_t equals $2D_p$ to $5D_p$, Fig. 5.4(a)-(d) show that both the small and primary scour holes of the confined cases are shallower than those of the unconfined case reported in Hong *et al.* (2013). A possible reason is that the armored slope has prevented further enlargement of the scour hole and the entrained bed sediment particles from being transported downstream. As a result, the entrained particles are either redeposited back into the scour hole or transported sideward to be deposited on its transverse sides. Another important observation is that the maximum scour depth is always found to form at the toe of the slope. When the toe clearance reaches a distance of $5D_p$, both the location and magnitude of the maximum scour depth on the centerline profile are the same as those of the unconfined case.

Because the propeller is farther away from the slope when X_t equals $6D_p$ to $7D_p$, it is found that a discernable small toe scour hole with a steep slope forms immediately in front of the vertical skirting [see Fig. 5.4(e)-(f)]. This phenomenon confirms the presence of the deflected flow and shows how the obstruction mechanism is beginning to produce a more visible effect in shaping the final scour profile when compared to those associated with X_t equals $2D_p$ to $5D_p$. When $X_t = 8D_p$, the small toe scour hole is no longer present [see Fig. 5.4(g)], which is a reflection that the influence of the quay obstruction has reduced, allowing the propeller jet to have more space to expand. Therefore, the centerline profile exhibits a trend that resembles the unconfined case, even though there still exists a distinct difference between them.

When the toe clearance reaches a distance of $9D_p$, both the small and primary scour profiles are found to be very close to those of the unconfined case [see Fig. 5.4(h)]. Therefore, it may be surmised that beyond this position, the effect of the slope is

negligible and may be neglected, and the associated scour may be regarded as an unconfined scour.

5.4.3 Classification of Scour Profiles

Based on the development of the centerline profiles, a clear inference may be deduced. It relates to the important influence that toe clearance plays in affecting both the aforementioned scour mechanisms. In light of this, the scour profiles that form in the vicinity of an open quay at different toe clearances may be classified into three types as per their toe clearance fields (it should be noted that the specific demarcations of X_t noted in the following parentheses are based on the results of Series A for easy reference to the descriptions and figures in the preceding section), namely:

I. Near toe clearance field ($X_t = 2D_p \sim 5D_p$)

Because the propeller is still close to the quay, the propeller jet purportedly has not been sufficiently diffused when it reaches the slope and skirting. At this juncture, the strong jet flow directly impinges onto the slope and skirting thus resulting in the final scour profile as a truncated primary scour hole (or in another word, a toe scour hole) with the maximum scour depth at the slope toe.

II. Intermediate toe clearance field ($X_t = 6D_p \sim 8D_p$)

As the toe clearance increases, the propeller jet is now more diffused when it reaches the quay structure. The final scour profile is thus the result of the combination of the jet diffusion and obstruction mechanisms, which produce the upstream primary scour hole and the downstream toe scour hole immediately in front of the skirting, respectively. In addition, during this field the maximum scour depth shifts from the toe scour hole to the primary scour hole as the toe clearance increases.

III. Far toe clearance field ($X_t = 9D_p$ and greater)

The propeller jet is fully expanded as is in the case of an unconfined jet; the scouring process is solely governed by the jet diffusion mechanism.

Finally, it must be stated that the above classification, which is primarily based on the toe clearance, is not absolute because the flow field clearly will also play an important role in affecting the classification. Because of the limited data, it is impossible to include the combined effects of both the toe clearance and flow field in a precise demarcation of the scour field. This could only be achieved with additional data collected in a wider range of propeller size and speed of rotation.

5.5 Swirling Effect

Hamill (1987) stated that the scour profile induced by an unconfined propeller jet is nearly symmetrical along the jet centerline with a slight asymmetrical deposition on its transverse sides, a similar phenomenon can also be observed in the result [see Fig. 5.3(b)] from Hong *et al.* (2013). However, in the present study, the scour profiles at the asymptotic state are found to be highly asymmetrical, especially for the deposition mound at the transverse sides of the scour hole. This is because the propeller jet is inherently a swirling jet, which is centrosymmetric when looking upstream toward the propeller as shown in Chapter 4 (refer to Fig. 4.4). As introduced in Chapter 3, in this study, left-hand propellers are used, which means that it rotates in the counterclockwise direction when looking upstream toward the propeller. Therefore, the formation of a deeper scour hole on its left side and a higher deposition mound on its right side are

expected. This is exactly what is observed from the measured transverse scour profile in this study.

Fig. 5.5 Longitudinal (thalweg and centerline) and transverse profiles of the asymptotic scour hole (Series A): (a1-a2) $X_t = 2D_p$; (b1-b2) $X_t = 3D_p$; (c1-c2) $X_t = 4D_p$; (d1-d2) $X_t = 5D_p$

Fig. 5.6 Longitudinal (thalweg and centerline) and transverse profiles of the asymptotic scour hole (Series A): (a1-a2) $X_t = 6D_p$; (b1-b2) $X_t = 7D_p$; (c1-c2) $X_t = 8D_p$

Fig. 5.7 Longitudinal (thalweg and centerline) and transverse profiles of the asymptotic scour hole (Series A): (a1-a2) $X_t = 9D_p$

The longitudinal and transverse scour profiles of the asymptotic scour hole for Test A1-A8 have been plotted side by side in Fig. 5.5 - Fig. 5.7, in which the left column shows

the comparison between the thalweg and centerline profiles, and the right column shows the corresponding transverse profiles (looking upstream) at the location of the maximum scour depth. The transverse location of the maximum scour depth on either the thalweg or centerline has been denoted by the horizontal reference lines. In the right columns of Fig. 5.5 - Fig. 5.7, the transverse profiles clearly reveal that the maximum scour depth does not necessarily occur on the centerline due to the swirling effect. Accordingly, in the left columns, the comparison between the thalweg and centerline profiles exhibit the extent of the deviation in longitudinal direction. For the near toe clearance field ($2D_p \leq X_t \leq 5D_p$), Fig. 5.5 shows that the thalweg generally shows a good agreement with the centerline profiles except for the height of the ridge between the small and primary scour hole. A possible reason is that since the axial velocity is more dominant than its lateral counterpart (*i.e.* the swirling component), a vortex tube may be generated in front of the skirting wall as the jet impinges on it, which would weaken the swirling effect and thus resulting in a relatively symmetrical scour hole. Meanwhile, outside the scour hole, the lateral depositions above the original bed level are still quite asymmetrical.

When the toe clearance increases from $6D_p$ to $8D_p$, *i.e.*, the intermediate toe clearance field, Fig. 5.6 reveals a distinct deviation occurs between the thalweg and centerline profile with the scour depth associated with the latter being significantly lower than the former. Furthermore, it is interesting to note that the deviations in Fig. 5.6(a1), Fig. 5.6(b1) and Fig. 5.6(c1) are all starting from the same longitudinal location around $x = 280$ mm (as denoted by the vertical reference line), which may represent the location where the swirling jet body impinges onto the sand bed.

However, this deviation disappears in Fig. 5.7 when $X_t = 9D_p$, *i.e.*, the far toe clearance field, at which the thalweg and centerline profiles essentially overlap, indicating that the asymptotic scour hole tends to become nearly symmetrical when the toe clearance is large enough. This is because the far toe clearance provides sufficient downstream space that allows the jet to be fully expanded. As a result, the entrained sediments could be either transported to farther downstream or deposited on lateral sides, which eventually induces a rather flat bottom around the transverse centerline ($y = 0$) although the lateral deposition is still slightly asymmetrical [see Fig. 5.7(a2)]. This may lend credence to why the centerline profile was used as the maximum scour line by previous researchers such as Hamill (1987) and Hong *et al.* (2013).

5.6 Geometrical Characteristics of Scour Hole

Besides investigating the development of the scour profile, the characteristic dimensions at the asymptotic state, namely the maximum scour depth $\varepsilon_{m,c}$, width $w_{m,c}$, and length $l_{m,c}$ were also obtained from the measured asymptotic scour profile. In this thesis, $\varepsilon_{m,c}$ is defined as the maximum scour depth along the thalweg of the primary scour hole. $w_{m,c}$ is the maximum transverse distance between the two locations at which the primary scour profile intersects with the original bed; and $l_{m,c}$ is the maximum longitudinal distance between the propeller face and the downstream end of primary scour hole (Fig. 5.1). Their counterparts in the unconfined propeller scour are denoted as $\varepsilon_{m,u}$, $w_{m,u}$, and $l_{m,u}$, respectively. By normalizing the maximum scour depth, width, and length in Series A, B and C by their counterparts in the corresponding unconfined cases A0, B0 and C0, respectively, Fig. 5.8 - Fig. 5.10 show their relationship with the normalized toe clearance $X_t/X_{m,u}$, in which $X_{m,u}$ is the horizontal distance between the

propeller face and the location of the maximum scour depth in the unconfined case. The corresponding data are tabulated in Table C.1 (see Appendix C).

Fig. 5.8 Normalized maximum scour depth with $X_t/X_{m,u}$ (Series A: $D_p = 10$ cm, $n = 450$ rpm; Series B: $D_p = 10$ cm, $n = 600$ rpm; Series C: $D_p = 15$ cm, $n = 450$ rpm)

Fig. 5.9 Normalized maximum scour width with $X_t/X_{m,u}$ (Series A: $D_p = 10$ cm, $n = 450$ rpm; Series B: $D_p = 10$ cm, $n = 600$ rpm; Series C: $D_p = 15$ cm, $n = 450$ rpm)

Fig. 5.10 Normalized maximum scour length with $X_t/X_{m,u}$ (Series A: $D_p = 10$ cm, $n = 450$ rpm; Series B: $D_p = 10$ cm, $n = 600$ rpm; Series C: $D_p = 15$ cm, $n = 450$ rpm)

Generally, the maximum scour depth and width plots reveal similar wavelike functions as shown in Fig. 5.8 and Fig. 5.9, respectively. Through a point-by-point comparison of the data, it is shown that the maximum scour depth and width follow an almost synchronous development with the normalized toe clearance. Therefore, it may be surmised that the developments of the maximum scour depth and width are closely related to the three toe-clearance fields discussed earlier. In the case of Series A, for example, when the toe clearance increases from $X_t/X_{m,u} = 0.4$ to 1 (or $X_t/D_p = 2$ to 5, *i.e.*, the near field), the maximum scour depth increases almost linearly with increasing toe clearance. On reaching the peak at $X_t/X_{m,u} = 1$ (or $X_t/D_p = 5$), it decreases until $X_t/X_{m,u} \approx 1.4$ (or $X_t/D_p = 7$) before increasing again thereafter (*i.e.*, the intermediate field). When the toe clearance is far enough such that the influence of the slope has become negligible (*i.e.*, the far field), one may surmise that the maximum scour depth will remain unchanged and equal to that of the unconfined case. In light of this finding, it is presumed that there may exist a generic demarcation between each of the fields.

Fig. 5.8 and Fig. 5.9 show that in all the three series, the maximum scour depth and width reach their turning point at $X_t/X_{m,u} = 1$. More specifically, the maximum scour depth and width occurs at $X_t = 5D_p$ for Test series A and $X_{m,u} = 5D_p$ for Test A0; Similarly, they occur at $X_t = 6D_p$ and $X_{m,u} = 6D_p$ for Test B and Test B0, respectively; as well as Test Series C and Test C0, respectively. It is interesting to note that the toe clearance associated with these turning points is also the threshold that distinguishes between the near and intermediate toe clearance fields. Therefore, it may be inferred that for a given confined propeller scour in the open quay, the threshold between the near and intermediate fields can be quantified as the location of the maximum scour depth in the corresponding unconfined case, *i.e.*, $X_t/X_{m,u} = 1$. Considering a given unconfined propeller jet, the location where the maximum scour depth occurs may be determined by using the empirical equation proposed by Hamill *et al.* (1999) as follows:

$$X_{m,u} = F_o^{0.94} C \quad (5.1)$$

where $F_o = U_o / \sqrt{(\frac{\rho_s - \rho}{\rho}) g d_{50}}$ is the densimetric Froude number; ρ_s = density of sediment, ρ = density of water, g = gravitational acceleration, and C is the bed clearance measured from the lower tip of the propeller (see Fig. 5.1).

In contrast to the scour depth and width plots, Fig. 5.10 shows that the maximum scour length exhibits a linear relationship trend with increasing toe clearances, in which all three series are found to collapse together. This is because, in the near and intermediate fields, the primary scour hole was truncated by the slope toe, which means that in those cases, the maximum scour length $l_{m,c}$ is actually equivalent to the toe clearance X_t . Therefore, as long as the primary scour hole stops at the slope toe, there will be a linear

relationship between $l_{m,c}/l_{m,u}$ and $X_t/X_{m,u}$. To this end, a linear equation is fitted to the experimental data with an R^2 value of 0.989 as follows:

$$\frac{l_{m,c}}{l_{m,u}} = 0.523 \frac{X_t}{X_{m,u}} + 0.0118 \quad (5.2)$$

It must be stated that the linear relationship clearly will not be valid when the far field is reached because $l_{m,c}$ will remain unchanged and equal to $l_{m,u}$ regardless of any increment in X_t . Accordingly, the threshold of the far toe clearance field can be predicted as $X_t/X_{m,u} = 1.9$ when $l_{m,c}/l_{m,u} = 1$.

5.7 Scouring Mechanisms

As discussed earlier, two scouring mechanisms, namely jet diffusion and quay obstruction, play different roles in shaping the scour profile. In this section, an attempt is made to illustrate how the scouring mechanisms produce the specific geometrical characteristics in the three stated fields.

5.7.1 Near Toe Clearance Field

At the asymptotic state, for a given propeller jet, the location of the maximum scour depth ($X_{m,u}$) in an unconfined scour hole may be regarded as the point where the velocity of the propeller jet slipstream is equal to the critical shear velocity for bed sediment entrainment. In other words, it is the limit of the downward jet diffusion, beyond which the jet slipstream cannot expand anymore because it no longer can entrain the bed sediment. If this location is considered to be the target point [see Fig. 5.11(a)], then in its corresponding confined counterpart, the target point of the jet diffusion mechanism must occur at $x = X_t$ in the near field where $X_t \leq X_{m,u}$. This is because before the jet can expand to a distance of $X_{m,u}$, it is blocked by the skirting so that the jet is forced to impinge there, *viz.*, X_t is now considered to be the target point [see Fig. 5.11(b)]. Since

the propeller jet expands at an angle of $13^\circ \sim 15^\circ$ (Steward 1992), when the toe clearance increases, the target point will also move down to a deeper depth. It may be surmised that if the effect of jet diffusion is considered singly, as long as the velocity at the jet slipstream is greater than the critical velocity of the bed sediment, the magnitude of the maximum scour depth in front of the skirting will increase in proportion to the increasing toe clearance, which is exactly what is observed in the near toe clearance field in this study (see Fig. 5.8). Therefore, it may be inferred that in this field jet diffusion plays a more dominant role in affecting the scour depth.

Fig. 5.11 Schematic of propeller jet's target point

On the other hand, if one were to consider the obstruction mechanism on its own; since the deflected flow is formed just in front of the skirting, its target point will always form at that location where a toe scour hole is expected to develop. As a result, in the near toe clearance field, the target points of the propeller jet and deflected flow are one of the same. They combine to excavate the scour hole causing the maximum scour depth to occur in front of the skirting. This explains why it is the very location where the

maximum scour depth always occurs in this field (see Fig. 5.5), and therefore the longitudinal location of the maximum scour depth $X_{m,c}$ shows a linear relationship with X_t (see Fig. 5.12). Thus, it may be concluded that in the near toe clearance field, both the jet diffusion and quay obstruction mechanisms play a positive role in inducing the maximum scour depth at the skirting.

Fig. 5.12 Normalized maximum scour location with $X_t/X_{m,u}$ (Series A: $D_p = 10$ cm, $n = 450$ rpm; Series B: $D_p = 10$ cm, $n = 600$ rpm; Series C: $D_p = 15$ cm, $n = 450$ rpm)

Hamill *et al.* (1999) reported that in a closed-type quay, the presence of a perpendicular wall would considerably increase the scour depth near the quay wall. This is, however, not always the case in an open-type quay as is shown in Fig. 5.8, in which the maximum scour depth is found to be no greater than its counterpart in the unconfined case of Series A and B. As for Series C, where a larger propeller was used, the maximum scour depth is found to increase only at $X_t/X_{m,u} = 0.8 \sim 1.2$ (or $X_t/D_p = 5 \sim 7$). This is because, in the closed quay, much of the jet is deflected downwards onto the sediment bed, causing the formation of a deeper scour hole. In the open quay, on the other hand, the jet has the tendency to be deflected upwards and away from the sediment bed due to

the inclination of the slope. Consequently, comparatively less energy will be directed onto the bed, resulting in the formation of a smaller scour hole. With respect to the maximum scour depth, it may, therefore, be concluded that when compared to the closed quay, the open quay could dissipate rather than concentrate the jet energy on the sediment bed.

5.7.2 *Intermediate Toe Clearance Field*

In the intermediate field, because $X_t > X_{m,u}$, the target point will remain unchanged as is in the unconfined case, *i.e.*, $x = X_{m,u}$ and it is located upstream of the skirting [see Fig. 5.11(c)]. Thus, the target points of the propeller jet and deflected flow generally do not coincide with each other as they do in the near field. Fig. 5.8 and Fig. 5.9 show that within the intermediate field, the maximum depth and width decrease from $X_t = X_{m,u}$ to a local minimal around $X_t \approx 1.5X_{m,u}$, and then increase again when $X_t > 1.5X_{m,u}$. For the former ($X_t < 1.5X_{m,u}$), it may be surmised that the deflected flow may have transported some eroded sediment particles, which are eroded by the jet diffusion, upstream back into the scour hole, resulting in a reduced scour depth and therefore a declining trend from $X_t/X_{m,u} = 1 \sim 1.5$. In other words, due to the departure of the two target points, the effect of the propeller jet and deflected flow in causing erosion are actually opposing to each other. However, for the latter ($X_t/X_{m,u} > 1.5$), the obstruction mechanism and its concomitant deflected flow appear to have decreased, as is reflected by the increase in the scour depth and width. This is also consistent with the deduction drawn from the centerline profile comparison discussed earlier. A possible reason may be given in terms of the erosion capacity (or energy) of the jet and the deflected flow. The maximum scour depth and width are actually a reflection of the combined erosion capacity at the target point of the propeller jet. Beyond $X_t/X_{m,u} = 1$, the erosion effect of

the deflected flow decreases as the toe clearance continues to increase. In fact, it reaches zero when the toe clearance is far enough. Consequently, the overall energy is maximum at $X_t/X_{m,u} = 1$ (jet energy + deflected energy) and equal to the jet energy alone when the deflected energy becomes zero at high values of $X_t/X_{m,u}$. Between them, the overall energy will reach a local minimum where the total erosive energy is the difference between the jet energy and a certain amount of deflected energy. One may deduce from the empirical scour data of this study that this local minimum occurs at $X_t/X_{m,u} = 1.5$. In other words, the location of $X_t/X_{m,u} = 1.5$ represents the threshold beyond which the jet diffusion once again starts to dominate the magnitude of maximum scour depth.

Additionally, Fig. 5.12 shows that from $X_t/X_{m,u} \approx 1.5$, the location of the maximum scour depth in a confined case exhibits a tendency to approach the target point of their corresponding unconfined counterpart, asymptoting toward the horizontal line of $X_{m,c}/X_{m,u} = 1$. This observation supports the inference that jet diffusion plays a more dominant role when $X_t/X_{m,u} > 1.5$.

5.7.3 Far Toe Clearance Field

When the far toe clearance field is reached, all the characteristic dimensions will remain unchanged and equal to that of the unconfined case because the influence of the obstruction has become negligible. At this point, both the scour profile and characteristic dimension of the scour hole have become the same as those associated with the unconfined case, as shown in Fig. 5.8 - Fig. 5.10.

The experimental data in Fig. 5.8 show that the maximum scour depth for both Series A and C ($n = 450$ rpm) are close to or have reached the horizontal line of $\varepsilon_{m,c}/\varepsilon_{m,u} = 1$, while that for Series B ($n = 600$ rpm) still falls somewhat below it. A likely reason for this is attributed to the fact that because a higher rotational speed will diffuse the propeller jet to a longer distance, a larger toe clearance ratio X_t/D_p is required to ensure that the far toe clearance field is reached. In contrast, Fig. 5.9 and Fig. 5.10 show that the maximum scour width and length of Series B are already very close to the limiting condition associated with the unconfined case.

5.8 Concluding Remarks

This chapter presents the results of Experiment Phase II, illustrating the influence of toe clearance on propeller jet scour in the presence of an armored slope and a vertical skirting located downstream of the propeller. The following findings are drawn from this chapter:

1. The overall temporal development of a propeller-induced scour hole around an open-type quay is found to be similar for different toe clearances. The scouring process follows four phases, namely, the initial, development, stabilization, and asymptotic phases. All tests conducted in EP-II reach the asymptotic state at 128 hr.
2. The scour profile is significantly influenced by the toe clearance. Based on the evolution of centerline profile and the swirling effect, the scour profiles may be classified into the near, intermediate and far toe clearance fields. The characteristic dimensions of the asymptotic scour hole confirm such a classification.

3. Based on the test conditions in EP-II, the generic demarcation between the near and intermediate field can be quantified by the longitudinal location of the maximum scour depth in the corresponding unconfined case, *i.e.*, $X_t/X_{m,u} = 1$. The threshold of the far toe clearance field occurs at $X_t/X_{m,u} = 1.9$.
4. The scouring process is governed by the jet diffusion and quay structure obstruction mechanisms. In the near field, jet diffusion dominates the development of the scour hole. In the intermediate field when the toe clearance increases, the influence of the obstruction mechanism becomes more important initially; however, its effect dwindles when $X_t > 1.5X_{m,u}$. In the far toe clearance field, the scouring process is solely dependent on the jet diffusion mechanism.

CHAPTER 6

CHARACTERISTICS OF PROPELLER JET FLOW WITHIN DEVELOPING SCOUR HOLES AROUND AN OPEN QUAY

6.1 Introduction

Chapter 2 reveals that most of the published studies were focused on the unconfined propeller jet or confined propeller jet in the presence of a fixed boundary. However, limited published studies have been found in measuring the propeller jet flow field in a developing scour hole. Since the scour test and velocity measurements often were conducted separately, it has always been challenging to directly relate the flow field to the scouring process in order to better understand the underlying physics. Hill and Younkin (2006) stated that the main obstacle in understanding the scouring mechanism governing the developing scour hole is that the high-resolution details of the interaction between the flow field and the sediment at the water-bed interface have been technically inaccessible to the researcher. This chapter presents the results of EP-III, which is an attempt to measure the flow field and developing scour hole simultaneously by employing the high-speed PIV technique and thus providing an improved understanding of the scouring mechanisms.

In Chapter 5, EP-II investigated the propeller-induced scour holes around an open-type quay model in the form of a slope with a vertical skirting beneath it. The results reveal that the asymptotic scour profile formed in front of the quay slope can be classified into

Note: The material presented in this chapter has been accepted for publication in *Journal of Hydraulic Engineering*.

three fields associated with the toe clearance (X_t), namely near, intermediate and far toe clearance fields. More specifically, the near toe clearance field was characterized by a toe scour hole (or a truncated primary scour hole) around the quay slope toe [Fig. 6.1(a)]; the intermediate field features a primary scour hole followed by a local toe scour hole immediately in front of the skirting [Fig. 6.1(b)]; and the far field exhibits a single completed formed primary scour hole that resembles the unconfined scour profile, which is denoted by the dash line in Fig. 6.1(c). However, Chapter 5 (EP-II) was primarily focused on the evolution of the scour profile as the toe clearance changes, while the underlying scouring mechanisms that cause the difference in the scour profile associated with these three fields remains unexplored due to the lack of velocity and turbulence data. For this reason, EP-III adopted a similar experimental configuration in the PIV flume as that used in EP-II in the scour tank, by which means, it was managed to measure the propeller jet flow in and around the developing scour holes by employing PIV measurement as introduced in Chapter 3.

Fig. 6.1 Definition sketch of the toe clearance fields

6.2 Test Conditions

Since the primary objective of EP-III was to examine the scouring mechanisms in each aforementioned toe clearance fields observed in EP-II, experiments were conducted at four toe clearances of $X_t = 2D_p$, $4D_p$, $5D_p$, and $6D_p$. For each case, PIV measurements were carried out during the entire scouring process from the beginning to the asymptotic state at predetermined time intervals ranging from $t = 0$ to $t = 48$ hr. The other variables were kept as constant: clearance height $Z_b = D_p$, and propeller rotational speed $n = 300$ rpm. It should be stated that to ensure better PIV measurements, the propeller rotational speed adopted here is smaller than that ($n = 450 \sim 600$ rpm) used in EP I and II. The purpose was to obtain a moderate scour hole so that the camera oblique angle could be made as small as possible (as discussed in Chapter 3). Table 6.1 summarizes the test conditions adopted in EP-III.

The uniformly distributed cohesionless sediment with median grain size, $d_{50} = 0.45$ mm and geometric standard deviation, $\sigma_g = \sqrt{d_{84}/d_{16}} = 1.3$ was used in EP-III. Consequently, with the careful selection of the smaller rotational speed (lower flow intensity) and the bigger bed sediment size (higher critical shear velocity) than those used in EP II, visual observations during the experiment reveal that the sediment particles were mainly transported as bed load. This ensures that the PIV analysis, which was based on cross-correlations of the moving particles, was not interfered with suspended sediment particles that would have occurred in the case of scouring with finer sediments. The velocity fields were determined using the same analysis of cross-correlation as that used in EP-I, in which a multi-pass iteration process was adopted, as the interrogation windows start from 32×32 pixels, 16×16 pixels and end with 8×8 pixels. The FOV size for each test and the corresponding spatial resolution that is

equivalent to 8 pixels are also given in Table 6.1. A sampling rate of 300 fps was used to ensure that the particle displacement was within 50% overlap between adjacent interrogation windows for cross-correlation analyses. The final time averaging was based on an ensemble images without noticeable bed boundary change, whose time window lasted from several seconds to tens of minutes for the initial and the asymptotic phases of the scouring process, respectively. Accordingly, the amount of the captured images used for time averaging was ranged from ~850 to ~4,000 for the first 0.5 hr. As time increases, the scouring rate decreases and the total images used for time averaging for the remaining time intervals were ~17,000.

Table 6.1 Test conditions of Experiment Phase III

No.	D_p (cm)	d_{50} (mm)	h_t (cm)	n (rpm)	Z_b/D_p	X_t/D_p	U_o (cm/s)	F_o	t (h)	Field of view (cm ²)	Spatial resolution (cm)	Remarks
1	7.5	0.45	50	300	1	2	36.4	4.31	0 ~ 48	$\sim 26 \times 17$	0.11	Near field
2	7.5	0.45	50	300	1	4	36.4	4.31	0 ~ 48	$\sim 32 \times 21$	0.13	Intermediate field
3	7.5	0.45	50	300	1	5	36.4	4.31	0 ~ 48	$\sim 26 \times 17$	0.11	Intermediate field
4	7.5	0.45	50	300	1	6	36.4	4.31	0 ~ 48	$\sim 29 \times 19$	0.12	Far field

6.3 Scouring Process

6.3.1 Temporal Development of Centerline Profiles

Fig. 6.2 depicts the temporal development of the centerline profiles at four toe clearances, *i.e.*, $X_t = 2D_p$, $4D_p$, $5D_p$, and $6D_p$, in which the centerline profiles were deduced from PIV images obtained at selected time intervals from $t = 0$ to 48 hr during the scouring process. It should be noted that due to the limited size of the field of view of the PIV measurements, Fig. 6.2(c) and Fig. 6.2(d) only cover the downstream scour profile in front of the quay slope, which is the location of primary concern relating to scour. Generally, for all the toe clearances conducted in EP-III, Fig. 6.2 exhibits similar scouring phases as those reported in Chapter 5 (EP-II), namely, (I) initial phase, (II) development phase, (III) stabilization phase, and (IV) asymptotic phase. Although the exact time demarcation between these phases may vary marginally at different toe clearances, it could generally be summarized that the scour hole develops rapidly during the initial phase in the first 2 hours; During the development phase the bed scour profile continues to evolve until ~ 12 hr; thereafter, the scour rate decreases and the bed scour profile shows no significant change in shape until ~ 48 hr. Eventually, the scour profile reaches the asymptotic state beyond 48 hr.

Fig. 6.2 Temporal development of centerline profiles:

(a) $X_t = 2D_p$, (b) $X_t = 4D_p$, (c) $X_t = 5D_p$, and (d) $X_t = 6D_p$

6.3.2 Toe Clearance Fields

As discussed in the introduction section, according to the results of EP-II, the confined propeller scours around an open quay can be classified into three toe clearance fields based on their asymptotic scour profile geometries (refer to Fig. 6.1). In Chapter 5, it was concluded that the demarcation between the near and intermediate fields could be quantified by using the longitudinal location of the maximum scour depth in the corresponding unconfined case, *i.e.* $X_{m,u}$. For the sake of comparison, the corresponding unconfined case with the same rotational speed and clearance height was also conducted in EP-III. Besides, in order to obtain the entire centerline profiles for tests with $X_t = 5D_p$ and $6D_p$, the upstream portion of the scour profile (not previously measured using the PIV due to the limited FOV) also was measured by using a point gage at the asymptotic state. Fig. 6.3 shows the comparison of the asymptotic centerline

profiles between the unconfined and confined cases conducted in EP-III. The data reveal that the effect of the toe clearance on the scour profile is similar to that found in EP-II. Specifically, $X_t = 2D_p$ [Fig. 6.3(a)] belongs to the near toe clearance field since $X_t < X_{m,u} (= \sim 2.6D_p)$; $X_t = 4D_p$ and $5D_p$ [Fig. 6.3(b) and Fig. 6.3(c)] reasonably falls into the intermediate field as $X_t > X_{m,u}$; finally $X_t = 6D_p$ [Fig. 6.3(d)] evidently reaches the far field case as its centerline scour profile almost overlaps with its counterpart in the unconfined case. In general, since the asymptotic scour profiles in these four toe clearance cases exhibit reasonable geometrical similarities to those in EP-II, it may be inferred that it is the same scouring mechanisms that govern the final scour profile. Therefore, these four toe clearances ($X_t = 2D_p$, $4D_p$, $5D_p$, and $6D_p$) are selected as the representatives of the aforementioned fields and their associated scouring mechanisms in terms of the flow structure will be discussed in the following sections.

Fig. 6.3 Comparison between confined and unconfined centerline scour profiles at asymptotic state: (a) $X_t = 2D_p$, (b) $X_t = 4D_p$, (c) $X_t = 5D_p$, and (d) $X_t = 6D_p$

6.4 Mean Flow Patterns

The mean flow fields at selected time intervals of $t = 0, 0.5, 2, 12$, and 48 hr are plotted in the form of mean velocity vectors and streamlines in Fig. 6.4 - Fig. 6.7 for four different toe clearances tested. Since only a single clearance height of $Z_b = D_p$ is adopted here, the ordinate value at $z/D_p = 1$ represents the vertical position of propeller rotational axis, and the abscissa value at $x/D_p = 0$ represents the longitudinal position of propeller face. It must be stated that the abscissa values are not started from $x/D_p = 0$ in Fig. 6.6 and Fig. 6.7 because the propeller is out of the field of view during PIV measurements for the cases of $X_t = 5D_p \sim 6D_p$ as mentioned earlier (in Section 6.3.1). In the vector plots, the magnitude and direction of the velocity vectors are $(u^2 + w^2)^{1/2}$ and $\tan^{-1}(w/u)$, respectively. It should be noted that velocity vectors are not plotted in the highest resolution to avoid data congestion.

6.4.1 Near Toe Clearance Field

In Chapter 5, it was stated that the asymptotic maximum scour depth in the near toe clearance field always occurs at the toe of the quay slope and its magnitude increases with the increase of toe clearance. It can, therefore, be inferred that amongst all the toe clearances in this field, the scouring mechanisms that determine the final scour profiles are similar and can be illustrated by using any single case as long as $X_t < X_{m,u}$. Fig. 6.4 shows the different mean velocity fields as the scour profile develops from the initial flat bed to its asymptotic stage for the case of $X_t = 2D_p$. In the left column of Fig. 6.4, the velocity vector plots reveal that the high-velocity zone is concentrated within the zone of $z/D_p = 1 \pm 0.5$ and $x/D_p < \sim 1.7$ and the typical double-peak velocity profile resembling that of the unconfined propeller jet case (see Hsieh *et al.* 2013). In other words, neither the change of the scour profile nor the presence of quay slope at $x = X_t$

$= 2D_p$ has significantly influenced the flow field around the propeller. Additionally, the efflux velocity was obtained as $U_o = 36.4$ cm/s. Furthermore, in the right column of Fig. 6.4, the streamlines are approximately horizontal and parallel to each other within $z/D_p = 1 \pm 0.5$ up to $x/D_p = 2$ as the upstream water is drawn into the propeller disc to be discharged downstream. Beyond $x/D_p = 2$, the data show how the jet flow impinges onto the quay slope. Fig. 6.4(a2) reveals that the streamlines above the quay slope are deflected upwards to be approximately parallel to the slope face.

What dictates the development of the scour profile clearly is related to the flow field below the propeller and around the sediment bed. In Chapter 4, EP-I investigated the characteristics of the propeller jet in the presence of a plane boundary, in which it was reported that due to the asymmetrical entrainment from above and below the jet, there exists a pressure reduction between the jet body and the bed, which deflects the jet towards the bed. However, since the current study (EP-III) is carried out with an erodible bed, the pressure reduction becomes an agent to cause erosion of the bed sediment, facilitating the subsequent formation of the scour hole. A closer observation of the streamline plots in the right column of Fig. 6.4 shows that a reversal flow prevails near the scoured bed in front of the quay slope, indicating the formation of a vortex there. Due to the uniform scale used in preparing the vector plots (left column of Fig. 6.4), the velocity vectors in and around the toe scour hole are difficult to be deciphered when compared with those near the propeller. However, the growth of the vortex is more visually explicit in the streamline plots in the right column of the figure. At the commencement of the test ($t = 0$ hr), Fig. 6.4(a2) shows the formation of a small vortex at the quay slope toe on an otherwise flatbed. As a result of this vortex, the toe scour hole develops rapidly in the initial phase ($t = 0.5$ hr). Fig. 6.4(b2) shows that the vortex

has descended into the toe scour hole and evolved into a well-formed vortex at this stage, which probably is due to flow separation that occurs near the quay slope toe. This vortex is responsible for further entrainment of sediment particles from the scour hole in front of the vertical skirting, eventually being swept by the jet flow to either downstream or lateral side of the hole. During the scouring process from $t = 2$ to 48 hr, the shape of the vortex exhibits a self-preserving feature and expands to fill the developing scour hole. Meanwhile, the center of the vortex progressively moves upstream and stabilized around $x/D_p = \sim 1.74$ at $t = 48$ hr [denoted by the vertical dash line in Fig. 6.4(e2)]. In summary, it may be deduced from the experimental data associated with the near toe clearance field that, upon impingement onto the quay slope and skirting, the main jet flow develops into a strong vortex flow inside the toe scour hole, which eventually shapes the final scour profile and causes the formation of the maximum scour depth in front of the vertical skirting.

Fig. 6.4 Measured data of mean velocity vectors (left column) and streamlines (right column), $X_t = 2D_p$ (Near toe clearance field)

6.4.2 Intermediate Toe Clearance Field

Within the intermediate toe clearance field, the final scour profile comprises both primary scour and toe scour holes. In Chapter 5, EP-II's results show that as the toe clearance increases, the location of the overall maximum asymptotic scour depth will move from the toe scour hole to the upstream primary scour hole. In view of this, the intermediate field can be further sub-divided into two stages, depending on whether the overall maximum scour depth occurs at the downstream toe or upstream primary scour hole. This behavior clearly is observed in the present study (EP-III) when the toe clearance changes from $X_t = 4D_p$ to $5D_p$. Their mean velocity vectors and streamlines are shown in Fig. 6.5 and Fig. 6.6, respectively. Because of the larger toe clearance for $X_t = 4D_p$ compared to $X_t = 2D_p$, the main jet flow is less restricted spatially, allowing it to expand and impinge onto the initial flatbed before reaching the quay slope. Fig. 6.5(a1) and Fig. 6.5(a2) show that at the commencement of the test ($t = 0$ hr), the near-bed flow generally exhibits an upward direction, indicating that the bed sediment particles can be picked up to be carried along by the on-coming main jet flow. Thereafter, at $t = 0.5$ hr, Fig. 6.5(b2) shows that the original flatbed has developed into a primary scour hole (albeit a very shallow one), together with the formation of a small dune just upstream of the quay slope. The latter presumably is due to the eroded sediment particles from the primary scour hole. Up to $x/D_p = \sim 0.7$, the near-bed streamlines show a downward direction, indicating that the jet flow tends to attach onto the undisturbed sediment bed. Upon entering the primary scour hole, the upstream end of the scour hole induces flow separation around $x/D_p = \sim 1.2$ and the streamlines rise obliquely from the bed and a flow reversal (or vortex) is formed along the bed between the separation point (at $x/D_p \sim 1.2$) and the trough of the primary scour hole (at $x/D_p \sim 2.2$), somewhat similar to that observed in the lee of a sand dune. In this way, the

sediment particles are entrained by the vortex to be carried along by the oncoming flow. Thereafter, the main jet flow impinges onto the downstream portion of the scour hole, where sediment transport is driven by the local flow field along the slope of the scour hole. This flow pattern is consistent with the observations of Guan *et al.* (2013) in their weir-scour study and that of Hill and Younkin (2006) in their planar jet scour study. As the scouring process continues to $t = 2$ hr, the downstream edge of the primary scour hole is now pushed nearer to the quay slope as its depth increases; meanwhile the small dune (near to quay toe) observed at $t = 0.5$ hr has diminished altogether. Fig. 6.5(c2) shows that the flow field inside the primary scour hole resembles that in Fig. 6.5(b2). At $t = 12$ hr, the longitudinal development of the primary scour hole is truncated by the presence of the quay slope, whence its influence clearly is manifested by the formation of the toe scour hole in front of the skirting due to the vortex that forms there. It can be inferred that from here the main jet flow and vortex that forms at the quay slope govern the formation of the primary scour hole and the toe scour hole, respectively. Finally, when the scouring hole has reached the asymptotic state at $t = 48$ hr, the near-bed velocity becomes very weak (less than the critical velocity for bed sediment motion) and no perceptible flow separation in the primary scour hole is observed [Fig. 6.5(e2)] and further scouring ceases. Meanwhile, the main jet flow simply attaches onto the scoured bed until it reaches the skirting, inducing the formation of a significant vortex that causes the formation of a larger toe scour hole. Therefore, it may be concluded that at $X_t = 4D_p$, or the first stage of the intermediate field, it is the vortex near to the quay slope that dominates the scour process, resulting in the overall maximum asymptotic scour depth to form at the toe scour hole although both the main jet flow and vortex are responsible in shaping the overall bed scour profile.

Fig. 6.5 Measured data of mean velocity vectors (left column) and streamlines (right column), $X_t = 4D_p$ (Intermediate toe clearance field)

For $X_t = 5D_p$, only the downstream flow fields beyond $x/D_p = 1.9$ are shown in Fig. 6.6, because the main jet flow along the upstream portion of the scour hole essentially is the same as that of its counterpart for the case of $X_t = 4D_p$. At $t = 0$ hr, similar to that observed in Fig. 6.5(a2), Fig. 6.6(a2) shows that the downstream near-bed flow also exhibits an upward direction along the initial flat bed. At $t = 0.5$ hr, upon the initiation of scouring, the initial flat bed develops into the primary scour hole followed by the formation of a dune downstream, as was also observed with $X_t = 4D_p$. Fig. 6.6(b2) reveals how the main jet flow attaches well along the scoured bed boundary, and flow separation is observed at the dune crest. With time, the primary scour hole continues to grow, eventually reaching the quay slope. During this stage (at $t = 2$ hr), Fig. 6.6(c2) shows that the streamlines in the primary scour hole are directed parallel to the sloping bed and a vortex evidently forms in the lee of the dune due to flow separation. Since the main jet flow is confined to the upstream section of the dune, the downstream vortex is supposedly not strong enough to induce a toe scour hole. At $t = 12$ hr, Fig. 6.6(d2) reveals a similar behavior of the streamlines in the primary scour hole when the dune has moved farther downstream, beyond the current field of view. However, as the primary scour hole continues to enlarge ($t = 48$ hr), the influence of the quay slope finally emerges when the downstream end of the primary scour hole reaches the skirting so that the main jet flow can directly impinge onto it, causing the formation of a vortex there [see Fig. 6.6(e2)]. Here, the toe scour hole, attributable to the vortex induced in front of the skirting, is finally formed.

Fig. 6.6 Measured data of mean velocity vectors (left column) and streamlines (right column), $X_t = 5D_p$ (Intermediate toe clearance field)

It is evident that during the entire scouring process for $X_t = 5D_p$, the main jet flow plays a more dominant role in shaping the overall scour profile, causing the maximum asymptotic scour depth to be found within the primary scour hole. In comparison to that in $X_t = 4D_p$, the intensity of the vortex in front of the skirting is weak even though both these scenarios belong to the intermediate flow clearance field.

6.4.3 Far Toe Clearance Field

It was noted in Chapter 5 that when the toe clearance is sufficiently far, the influence of the quay slope will become negligible. Therefore, the jet flow alone will govern the final scour profile. Fig. 6.7 shows the mean flow vectors and streamlines for $x/D_p \geq 2.8$ for the case of $X_t = 6D_p$. In general, the figure depicts similar characteristics of the jet flow in the primary scour hole and the vortex in the lee of the dune as those observed for the case of $X_t = 5D_p$ before the influence of the quay slope is felt. However, Fig. 6.7(e1) and Fig. 6.7(e2) show that before the scour hole has reached the asymptotic state, the downstream edge of the scour hole is still sufficiently far from the quay slope leaving the skirting buried in the sediment deposition. In this way, the main jet flow could not directly impinge onto the skirting, thus no vortex and toe scour hole could be induced there, corroborating to the fact that the influence of the quay slope is insignificant in shaping the final scour profile. With reference to Fig. 6.5 and Fig. 6.6 in the intermediate field, it could be inferred that the formation of the toe scour hole is dependent on whether the main jet flow is strong enough to wash away the sediment in front of the quay slope and able to directly impinge onto the skirting. With the increasing toe clearance, the erosion capacity of the main jet flow is expected to be lower upon reaching the quay slope, resulting in the formation of a smaller scour hole when one moves from the 1st to 2nd stage of the intermediate field. With the far clear

toe clearance field, a deposition mound is formed near the quay slope, resembling the unconfined scour hole reported in Hong *et al.* (2013). From an engineering perspective, the deposition mound that formed downstream of the scour hole is equally important when compared with scouring because it will reduce the local water depth, which will endanger the safe under-keel clearance close to the docking area. In addition, the velocity vectors and streamlines in Fig. 6.7 reveal that throughout the scouring process, the main jet flow in the scour hole attaches well to the scoured bed boundary, which again confirms the premise that the underlying scouring mechanism along the downstream edge is closely related to the local flow field in this toe clearance field.

Fig. 6.7 Measured data of mean velocity vectors (left column) and streamlines (right column), $X_t = 6D_p$ (Far toe clearance field)

6.5 Turbulence Characteristics

The intermediate field case of $X_t = 4D_p$ is selected to illustrate the turbulence characteristics in and around the developing scour hole since both the primary and toe scour holes are present with this toe clearance. The horizontal and vertical turbulence intensities are normalized by the efflux velocity as $\sqrt{u'^2}/U_o$ and $\sqrt{w'^2}/U_o$, in which u' , w' are the horizontal and vertical velocity fluctuations, respectively. Fig. 6.8 shows their distribution plots in the developing scour hole from $t = 0$ to $t = 48$ hr. In Chapter 4, EP-I's results show that the high-turbulence zone associated with a propeller jet mainly is concentrated in the vicinity of the propeller face and its intensity decays as the jet flow mixes with the receiving fluid. A similar trend is observed in EP-III, showing no significant changes to the high-turbulence zone as the scour hole deepens. Consequently, Fig. 6.8 only covers the field of view below the propeller lower tip ($z/D_p = 0.5$) to better focus on the turbulence field in and around the scour hole, and the contour line of 0 represents the boundary of the scoured bed.

Fig. 6.8 Development of the horizontal and vertical turbulence intensities, $X_t = 4D_p$

The left column of Fig. 6.8 shows the development of the horizontal turbulence intensity. In general, the near-bed turbulence intensity progressively decreases as the scour hole enlarges. Initially, when the scour bed remains as a flatbed at $t = 0$ when the sediment bed is still flat at $t = 0$ hr [see Fig. 6.8(a1)], the confining effect of the bed on

jet expansion is very significant. As the jet impinges onto the sand bed, Fig. 6.8(a1) reveals that the contour lines of 0.1 and 0.2 are clustered to the bed boundary, indicating the presence of high near-bed turbulence intensity. It may be inferred therefrom that the high near-bed turbulence plays an important role in causing sediment mobility and scour. With the formation of the primary scour hole beyond the initiation of scouring [Fig. 6.8(b1) and Fig. 6.8(c1)], the contour lines of 0.1 and 0.2 move apart from each other and descend into the just-formed primary scour hole as the jet flow expands to fill the scour hole. Additionally, it is evidently clear that inside the primary scour hole, the high turbulence intensities are mainly concentrated at the downstream section due to the main jet flow impingement there. At $t = 12$ hr and beyond, since the toe scour hole has formed in front of the skirting, Fig. 6.8(d1) and Fig. 6.8(e1) show that the higher turbulence has further expanded into the toe scour hole due to the flow separation and vortex formation there. Meanwhile, the near-bed turbulence intensity across the entire scour profile has reduced to and stabilized at a low magnitude of less than 0.05, confirming an asymptotic state of the scouring process.

The right column of Fig. 6.8 principally depicts a similar development of the vertical turbulence intensity with the scouring process as that of its horizontal counterpart. A comparison between the horizontal and vertical turbulence intensity plots reveals an anisotropic characteristic of the turbulence field inside the scour hole. Taking the contour of 0.05 for example, the data show that it is located farther from the bed in Fig. 6.8(e2) than that in Fig. 6.8(e1). In other words, the near-bed horizontal turbulence intensity is greater than its counterpart in the vertical direction at the same location and time. This presumably may be attributed to the bed playing a more important role in restricting vertical velocity fluctuations.

6.6 Near-Bed Reynolds Stress

With the turbulence measurement available, the local bed shear stress often was estimated by extrapolating the Reynolds stress distribution to the bed (Chen and Chiew 2003, Dey 2014). By virtue of the high-speed PIV measurement, one could extract near-bed flow field data with a higher resolution than the point based measuring technique, such as the Acoustic Doppler Velocimetry (ADV). Therefore, in order to better understand the near-bed sediment incipient bed sediment during the scouring process, the temporal development of the near-bed Reynolds stress $\tau_b (= -\rho \overline{u'w'})$ distribution along the scoured bed profile for the case of $X_t = 4D_p$ is summarized in Fig. 6.9, in which the critical bed shear stress is also superimposed as a reference. Since the sign of the Reynolds stress could be negative along the upward scour bed where the vertical velocity gradient is dominant, the absolute value of the negative Reynolds stress is also plotted as red circle in Fig. 6.9 for easy comparison with the critical bed shear stress. It must be stated that the measured near-bed Reynolds stress values are extracted at a location of 5 mm above the scoured bed boundary to avoid the possible boundary reflection influence on the data quality. The critical shear stress on a sloping bed τ'_c is calculated by using the equation proposed in Chiew and Parker (1994):

$$\frac{\tau'_c}{\tau_c} = \cos\varphi' \left(1 - \frac{\tan\varphi'}{\tan\theta'}\right) \quad (6.1)$$

in which τ_c = critical shear stress for a horizontal bed (calculated as 0.23 Pa based on Shields diagram); φ' = bed angle (is positive/negative for the upstream/downstream edge, respectively); θ' = sediment angle of repose (measured as 36° in this study).

Generally, Fig. 6.9 shows that the critical bed shear stress τ'_c does not change much during the entire scouring process, especially for the primary scour hole portion where

the slope of the scoured bed is rather mild. Conversely, the near-bed Reynolds stress τ_b experiences a significant decrease from the initial to the asymptotic phase. Specifically, at $t = 0$ hr, as the jet impinges onto the sand bed, Fig. 6.9(a) clearly shows that τ_b generally exceeds τ'_c between $x/D_p = 1.2 \sim 3.5$, resulting in sediment mobility there. This zone is consistent with the location of the initial primary scour hole at $t = 0.5$ hr [Fig. 6.9(b)]. The measured near-bed Reynolds stress in Fig. 6.9(a) clearly supports the previously proposed scour mechanism during the initial scouring phase. At $t = 0.5$ hr, Fig. 6.9(b) reveals that τ_b is dramatically reduced compared to that at $t = 0$ hr, especially for the upstream edge of the scour hole where τ_b has dropped below τ'_c ; at the downstream edge, as the main jet flow impinges onto the bed, $|\tau_b|$ shows an increasing trend such that it exceeds τ'_c around $x/D_p = 3$. As a result, the downstream edge of the scour hole experiences a faster scouring rate than the upstream edge as is shown in Fig. 6.9(b). This observation is also in conformity with the results of Wei and Chiew (2017). Thereafter, at $t = 2$ hr, Fig. 6.9(c) shows that $|\tau_b|$ undergoes a further increment beyond $x/D_p = \sim 3$, which is the reason that the downstream edge continues to undergo erosion. As a result, when the downstream edge is pushed over the skirting at $t = 12$ hr, Fig. 6.9(d) reveals that the influence of the quay slope on the scour hole profile has emerged. As the toe scour hole forms in front of the skirting, the sudden change of the bed boundary causes a steep decrement on τ'_c , before τ'_c increasing again as the bottom of the local scour becomes mild. Meanwhile, all τ_b has fallen below τ'_c across the entire scoured bed to be $\approx \tau'_c$. However, since the near-bed turbulence intensities also contribute to the scouring process as discussed in the former section, scouring still continues until $t \sim 48$ hr. At $t = 48$ hr, Fig. 6.9(e) shows that the relationship between τ_b and τ'_c resembles that at $t = 12$ hr as the scouring process transits from the stabilization phase to asymptotic phase.

Fig. 6.9 Comparison of near-bed Reynolds stress and critical shear stress, $X_t = 4D_p$

6.7 Concluding Remarks

The propeller jet flow field within a developing scour hole around an open quay with different clearances fields is measured by using high-speed PIV technique in EP-III. The experiments adopted an oblique PIV measurement approach to determine the turbulence flow field in the 3-dimensional propeller-induced scour hole, recognizing the systematic errors inherent in the set-up. The results relating to the scouring development, mean flow patterns, turbulence characteristics and near-bed Reynolds stress are presented and discussed in this chapter. The main findings are summarized as follows:

1. A comparison with results obtained from a normally executed PIV measurement approach reveals that the systematic error caused by the oblique PIV measurement is negligible after going through the image correction approach. The insignificance is especially apparent in the lower stream of the propeller jet and therefore important in the context of this study. This is because the lower propeller jet stream plays a more direct role in affecting bed sediment transport and scour, which is the main objective of the present study.
2. The three toe clearance fields identified in EP-II (Chapter 5), namely near, intermediate and far toe clearance fields are confirmed in this chapter. The temporal and spatial development of the mean flow patterns and their impact on the development of the scour hole are discussed for each of these fields.
3. For the near field, the main jet flow induces the formation of a sizable and well-defined vortex that fills the toe scour hole and governs the final scour profile, causing the maximum scour depth to form at the toe of the quay slope.
4. For the intermediate field, the main jet flow and vortex that forms at the quay slope govern the formation of the primary and toe scour hole, respectively. The

measured data reveal that when the toe clearance increases, the intensity of the vortex decays, and the relative importance of the vortex and main jet flow in causing scour reverses. As a result, the maximum asymptotic scour depth moves from the toe scour hole to the primary scour hole.

5. For the far field, the influence of the quay slope in causing scour becomes negligible. The main jet flow, which is found to attach to the boundary of the scoured bed, dominates the formation of the scour profile.
6. The case of $X_t = 4D_p$ is selected as a representative for illustrating the turbulence characteristics in a developing scour hole. The data show that the near-bed turbulence intensity generally decreases as the scour hole enlarges, and a region of high turbulence is observed at the downstream edge of the scour hole due to jet impingement.
7. For the case of $X_t = 4D_p$, the near-bed Reynolds stress τ_b was extracted to estimate the bed shear stress. The results show that the critical bed shear stress τ'_c is significantly exceeded at $t = 0$ hr, resulting in a rapid scouring during the initial phase. As the scouring process approaches the asymptotic phase, τ_b progressively decreases to be less than τ'_c .

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

Based on the state of the art literature review given in Chapter 2, it was found that a number of investigations were carried out to study the characteristics of the propeller jet and its associated scour hole. However, they mainly focused on the hydrodynamic characteristics of an unconfined propeller jet (*i.e.*, the free expanding jet) or the local scour issue in the case of a closed-type quay that featured by the presence of vertical quay walls. Only limited studies related to the open-quay-like structures (e.g. a sloping bank or quay slope) had been conducted, among which the emphasis was placed either on the influence of the sloping bank on the development of the velocity profiles or the erosion of the slope itself. Hitherto, a completed and detailed picture of the characteristics of a confined propeller jet and its interaction with a developing scour hole around an open-type quay is still unclear. To this end, the principal objective of this study was to provide an insight of the flow behaviors of a confined propeller jet (either by a rigid or mobile boundary) and its associated scouring mechanisms around an open-type quay. In light of the high-resolution measurement, the results of this study are also expected to provide laboratory reference for relating numerical models, which could then be used in more extensive engineering applications after verifications.

The experiments were designed and performed in three experiment phases (EP-I, EP-II, and EP-III), whose results have been presented in Chapters 4, 5, and 6, respectively. In EP-I (Chapter 4), focusing on the velocity measurement in the presence of a plane boundary, the effects of clearance height on the development of the flow field of

propeller jets were discussed and the associated flow regions were identified. In EP-II (Chapter 5), focusing on the scour measurement around the quay slope, the characteristics of the confined scour holes were compared with the unconfined ones and classified into three toe clearance fields. In EP-III (Chapter 6), the velocity and scour measurements were managed to implement simultaneously by employing a new experimental technique (*i.e.*, the oblique PIV measurement). In such a way, the temporal development of the flow field within the developing scour holes were measured in each toe clearance fields defined in Chapter 5. The key findings drawn from these three phases are highlighted in the following sections.

7.1.1 Experiment Phase I

The main task of EP-I was the velocity measurement of a plane boundary confined propeller jet, in which both the streamwise (central plane) and transverse (selected transverse planes) flow field have been measured by using PIV technique. The comparison of streamwise and transverse results validates the applicability of planar PIV in measuring the highly 3-dimensional propeller jet. In this point of view, EP-I also serves as a technical preparation for the application of the oblique PIV technique adopted in EP-III.

The boundary effects were studied by comparing results obtained from three clearance heights. As the clearance height decreases, a significant behavior of the streamwise flow is that the jet is directed towards the bed. This phenomenon can be explained by the well-known Coanda effect, similar to that related to jet attachments observed in the classical 3-dimensional offset jet. Another particular reason for the propeller-jet attachment is related to the transverse flow in which the presence of the boundary hinders the complete swirling rotation and confines the jet energy near the bed.

Due to the wall-attachment effect (or the Coanda effect), by changing the clearance height between the propeller axis and the plane boundary, three regions in the flow field downstream of the propeller have been recognized, namely free jet, impingement and wall jet regions. In the impingement region, the transverse flow field shows that the boundary can dramatically deform the jet rotation pattern, especially when $Z_b = 0.5D_p$, with the initial swirling being separated into two secondary vortices on either side of the central plane. As a result, the streamwise flow at the central plane becomes quasi-two-dimensional in the wall jet region, where the jet exhibits a behavior that resembles a wall jet, and the axial velocity profile shows a good agreement with the classical wall jet similarity function. The comparison of depth velocity profiles of u , v , and w shows how the plane boundary influence the individual velocity components and presents a more distinct difference between different flow regions than the global flow field does. In addition, the decay of the maximum axial velocity reveals how the presence of the bed boundary slows down jet energy dissipation through a reduced mixing intensity with the surrounding fluid.

The maximum turbulence intensity occurs near the propeller face and shows an isotropic characteristic for $Z_b = 2D_p$ and $Z_b = D_p$. However, for $Z_b = 0.5D_p$, the presence of the boundary significantly restricts the vertical velocity fluctuation and the associated turbulence intensity in the streamwise plane, causing the turbulence characteristics to become anisotropic. Nevertheless, the magnitude of the equivalent turbulence intensity in the transverse plane does not change much among the three clearance heights. A possible reason is that it is mainly dependent on the swirling strength that is controlled by the rotational speed.

7.1.2 Experiment Phase II

In EP-II, the propeller-induced scour holes around an open quay (simplified as a combination of an armored slope and a vertical skirting) have been measured under different test conditions. Particularly, the influence of toe clearance on the temporal and spatial developments of the scour hole has been examined systematically.

Generally, the overall temporal development of a propeller-induced scour hole around an open quay is found to be similar for different toe clearances. The scouring process exhibits four phases, namely, the initial, development, stabilization, and asymptotic phases. However, the experiment results show that the final bedform is significantly altered by varying the toe clearance. Based on the evolution of centerline profile with the increasing toe clearance, the scour profiles have been classified into the near, intermediate and far toe clearance fields. The characteristic dimensions of the asymptotic scour hole confirm such a classification. In addition, based on the current experimental range, the generic demarcation between the near and intermediate field has been quantified by the longitudinal location of the maximum scour depth in the corresponding unconfined case, *i.e.*, $X_t/X_{m,u} = 1$. The threshold of the far toe clearance field occurs at $X_t/X_{m,u} = 1.9$.

In terms of the geometrical characteristics of the scour profile at the asymptotic state, the underlying scouring mechanisms have been discussed for the stated three fields. It was inferred that the scouring process around an open quay is governed by the jet diffusion and quay structure obstruction mechanisms. In the near field, jet diffusion dominates the development of the scour hole. In the intermediate field when the toe clearance increases, initially the influence of the obstruction mechanism becomes more

visible in shaping the final scour profile; however, its effect dwindles when $X_t > 1.5X_{m,u}$. In the far toe clearance field, the scouring process is solely dependent on the jet diffusion mechanism. The inference of EP-II was then used as a guideline for the design of the case study in EP-III.

7.1.3 Experiment Phase III

In EP-II, the propeller-induced scour hole around an open quay has been measured, in which the associated scouring mechanisms were discussed indirectly based on the asymptotic bed form. To reveal the direct scouring mechanisms, the detailed flow field within the developing scour hole was measured by the oblique PIV measurement in EP-III. By comparing with the normal PIV measurement results, the systematic error caused by the oblique PIV measurement has been rectified as insignificant after image correction.

Based on the PIV results, the temporal and spatial development of the mean flow patterns and the associated scouring mechanisms have been discussed respectively in the three toe clearance fields defined in EP-II. For the near field, the main jet flow inside the scour hole evolves into a sizable vortex which fills the scour hole and governs the final bedform, causing the maximum scour depth at the slope toe. For the intermediate field, in general, the main jet flow and the vortex govern the primary and local (toe) scour hole, respectively. Within the intermediate field, as the toe clearance increases the vortex flow decays, and the relative importance of the local vortex and the main jet flow are reversed. As a result, the maximum scour depth shifts from the local scour hole (*i.e.*, the toe scour hole) to the primary scour hole. For the far field, the influence of the slope/skirting has become negligible. The main jet flow was found to attach to the boundary of the scoured bed and dominate the bedform during the scouring process.

The turbulence data show that the near-bed turbulence intensity generally decreases as the scour hole deepens, and the high turbulence gradient was observed on the downstream edge of the scour hole. Thanks to the high-resolution PIV measurement, the near-bed Reynolds stress was extracted and used to estimate the near-bed shear stress. Comparison between the near-bed Reynolds stress τ_b with the critical shear stress τ'_c shows that τ'_c was significantly exceeded at $t = 0$ hr, thus resulting in a rapid scouring during the initial phase. Afterward, τ_b progressively falls below τ'_c , and their longitudinal variations across the scoured bed are reasonable similar as the scouring process approaches the asymptotic phase.

Overall, backed up by the methodical analyses in image correction and error analysis, EP-III demonstrates an innovative application of the oblique PIV measurement in measuring the complex interaction between fluid and bed at a micro level, which has traditionally been inaccessible to the past researchers. The so obtained results provide a better understanding of the intricate mechanisms of the formation of scour hole in virtue of the simultaneously measured velocity field. Further application and improvement of the methodology presented in EP-III is expected to be of great importance to the researchers and engineers in the context of both laboratory and field applications.

7.2 Recommendations

Based on the experience and results obtained from this study, the following topics are recommended here for possible future research.

7.2.1 Transverse Flow Measurement Within the Scour Hole

The transverse flow field of a propeller jet in the presence of plane boundary has been measured through a 45° mirror placed far downstream the propeller in EP-I of this study. However, the transverse flow field within the scour hole remains inaccessible in this way since the downstream deposition and quay model will obstruct the optical path. For future study, a possible experimental method is to employ the 3-dimensional Stereo PIV (SPIV) technique, by which means the lateral velocity component could be obtained from the streamwise measurement.

7.2.2 Scour Test

The scour tests in this study (EP-II and EP-III) were primarily focused on the influence of toe clearance (X_t). However, a wider range of variables that may affect the scouring process is required to make a reasonable prediction of the final scour dimension. It is recommended that future study should further examine the influence of clearance height (Z_b), rotational speed (n) and angle of the quay slope. For instance, by adopting a wider range of slope angle, it may be possible to reveal a complete picture of the evolution of the scouring process during the transition from the open-type quay to the closed-type quay. In addition, the present study was conducted in the presence of a stable quay slope, while in practice the armored slope may be damaged due to the instability of the armored material upon the impingement of propeller jet. Further investigations should be necessary for the case where the armored stone is allowed to be entrained and dislodged so as to reveal the failure mechanism of the quay slope. This may provide a complementary understanding of quay structure design.

7.2.3 *Near-bed Flow Measurement*

In the present study (EP-III), the state-of-the-art high-speed PIV measurement has been shown to be capable of capturing the flow field above a mobile bed thanks to its high sampling rate and data transfer speed. In order to reduce the near-bed light scattering, a lower Gamma value was adopted during the image processing in EP-III. The compromise is the concentration of the illuminated seeding particles was also decreased by doing so. To better solve this problem, the fluorescent PIV is recommended in future studies.

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APPENDIX A FLOW FIELD RESULTS (EP-I)

Fig. A.1 Comparison of vector plots and streamlines of mean velocity field under varying clearance heights ($n = 300$ rpm):

(a1-a2) $Z_b = 2D_p$; (b1-b2) $Z_b = D_p$; (c1-c2) $Z_b = 0.5D_p$

Fig. A.2 Vector (upper row) and streamline (lower row) plots of transverse mean velocity field, $Z_b = D_p$ ($n = 300$ rpm, looking upstream)

Fig. A.3 Vector (upper row) and streamline (lower row) plots of transverse mean velocity field, $Z_b = 0.5D_p$ ($n = 300$ rpm, looking upstream)

APPENDIX B SCOUR MEASUREMENT RESULTS (EP-II)

Fig. B.1 Temporal development of centerline profiles of Series A (EP-II):

Test A1 – A8

Fig. B.1 (Continued)

0.5h 1h 2h 4h 8h 16h 32h 64h 96h 128h

Fig. B.1 (Continued)

Fig. B.2 Temporal development of centerline profiles of Series B (EP-II):

Test B1 – B9

—●— 0.5h —●— 1h —●— 2h —●— 4h —●— 8h —●— 16h —●— 32h —●— 64h —●— 96h —●— 128h

Fig. B.2 (Continued)

0.5h 1h 2h 4h 8h 16h 32h 64h 96h 128h

Fig. B.2 (Continued)

—●— 0.5h —●— 1h —●— 2h —●— 4h —●— 8h —●— 16h —●— 32h —●— 64h —●— 96h —●— 128h

Fig. B.3 Temporal development of centerline profiles of Series C (EP-II):

Test C1 – C9

0.5h 1h 2h 4h 8h 16h 32h 64h 96h 128h

Fig. B.3 (Continued)

0.5h 1h 2h 4h 8h 16h 32h 64h 96h 128h

Fig. B.3 (Continued)

A1

A2

A3

Fig. B.4 Three-dimensional asymptotic scour holes of Series A (EP-II):

Test A1 - A8

A4

A5

A6

Fig. B.4 (Continued)

A7

A8

Fig. B.4 (Continued)

B1

B2

B3

Fig. B.5 Three-dimensional asymptotic scour holes of Series B (EP-II):

Test B1 – B9

B4

B5

B6

Fig. B.5 (Continued)

B7

B8

B9

Fig. B.5 (Continued)

Fig. B.6 Three-dimensional asymptotic scour holes of Series C (EP-II):

Test C1 – C9

C4

C5

C6

Fig. B.6 (Continued)

C7

C8

C9

Fig. B.6 (Continued)

APPENDIX C SCOUR TEST DATA SHEET (EP-II)

Table C.1 Experimental data of geometrical dimensions of scour hole

Test no.	Maximum scour depth (mm)	Maximum scour width (mm)	Maximum scour length (mm)	Longitudinal location of maximum scour depth (mm)
	ε_m^a or $\varepsilon_{m,u}^b$	w_m or $w_{m,u}$	l_m or $l_{m,u}$	X_m or $X_{m,u}$
A0	97	433	913	500
A1	43	293	200	200
A2	60	335	300	300
A3	82	404	400	400
A4	97	493	500	500
A5	74	386	600	600
A6	69	411	700	480
A7	78	397	774	480
A8	93	423	823	500
B0	157	548	1175	600
B1	53	337	200	200
B2	63	426	300	300
B3	104	493	400	400
B4	113	552	500	500
B5	118	596	600	600
B6	111	566	700	700
B7	94	454	800	800
B8	88	491	900	620
B9	123	560	1100	600
C0	203	954	1613	900
C1	97	560	300	300
C2	189	856	450	450
C3	189	886	600	600
C4	222	1052	750	750
C5	248	1212	900	900
C6	219	1043	1050	1050
C7	187	846	1200	700
C8	186	848	1350	830
C9	200	897	1500	900

^aThe maximum scour depth data for confined cases (A1-A8, B1-B9, and C1-C9) are collected from the thalweg profile, which is the actual maximum scour depth of the scour hole.

^bThe maximum scour depth data for unconfined cases (A0, B0, and C0) are collected from the centerline profile, which is considered to overlap the thalweg profiles in such cases.