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2020

Wei, M., Chiew, Y. & Cheng, N. (2020). Recent advances in understanding propeller jet flow and its impact on scour. *Physics of Fluids*, 32(10), 101303-.
<https://dx.doi.org/10.1063/5.0023266>

<https://hdl.handle.net/10356/148680>

<https://doi.org/10.1063/5.0023266>

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Cite as: Phys. Fluids 32, 101303 (2020); doi: 10.1063/5.0023266

Submitted: 28 July 2020 • Accepted: 17 September 2020 •

Published Online: 15 October 2020

View Online

Export Citation

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ABSTRACT

This paper presents an extensive review of the characteristics of a propeller jet-induced flow field and its impact on scour formation. As the driving force of scour, the jet flow behavior is first explored, including both the free and bounded jets under various boundary conditions. Accordingly, their resulting scour, namely, unconfined and confined scour, are expounded in terms of the temporal and spatial development of the scour depth. Hitherto, existing methods for predicting the scour depth are principally developed empirically, which exclude in-depth scrutiny into the mechanism governing the scouring process. With the detailed flow fields obtained in recent research, this paper aims to piece together a state-of-the-art understanding of the scouring mechanism governing confined propeller scour, that is, the combined effect of jet flow and junction flow on the scour hole development. By comparing the similarities and differences between the scouring mechanisms in open and closed quays, this paper provides a comprehensive insight into the scouring process associated with bounded propeller jets. Moreover, in terms of the near-bed flow variations during the scouring process, implications for sediment transport under highly turbulent flow are discussed. Finally, future research needs are identified.

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I. INTRODUCTION

Marine transport has formed the backbone of the growing international market and globalization ever since the Age of Discovery. To date, it is still undergoing continuous change to satisfy the ever-increasing demands of world trade. PIANC¹ reported that during the last decade, the shipping industry development was characterized by a surge in capacity, which inevitably is accompanied by the increase in engine power. Longe *et al.*² reported that the efflux velocity of a rotating propeller and the associated bed velocities could reach 11 m/s–12 m/s and 3 m/s–4 m/s, respectively. As for thrusters, Sumer and Fredsøe³ reported that the nozzle and bed velocities could also reach as high as 8 m/s–9 m/s and 3 m/s–3.5 m/s, respectively. Therefore, bed sediment can be easily eroded, causing the formation of scour holes. Although the tidal current and waves can also induce scour around the quay structures, they are insignificant when compared with that related to ship propellers.¹ 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 seabed and banks are not designed for such velocities. For this reason, the ship propeller induced jet flow is expectedly the main cause of scour. In addition to the main propeller at the rear of the ship, modern ships also are equipped with thrusters to improve maneuverability, which further aggravate the scouring problem during the mooring and unmooring process.

de Gijt and Broeken⁴ 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 located 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 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 of the propeller jet. Over the past decades, a number of case studies on propeller jet induced damages at quay structures have been reported.^{5–8} Bergh and Magnussen⁹ conducted a survey of harbors in Sweden and found that 25 quays suffered scour-damages induced by

propeller jets. Longe *et al.*² reported that propeller scour damages in 29 piers in French ports. Prosser¹⁰ and Chait⁶ also documented similar problems in the UK and South Africa, respectively. Qurrain⁷ undertook a detailed survey of British ports with reference to the propeller induced scour and reported that a total of 42% of major ports in the British Isles had encountered propeller induced scour on their seabed, and 29% of which had resulted in quay structure damages.

Tsinker¹¹ stated that the propeller induced scour should be taken into account when designing new port-related marine structures or re-evaluating 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 platform type structures with rip-rap-protected slopes. PIANC¹ also highlighted the significance of having a detailed insight into ship propeller induced flows and the resulting damage for quay structure protection. With reference to the impact of a propeller jet, Sumer and Fredsøe³ and PIANC¹ stated that the quay structures can mainly be categorized into two principal types, namely, closed and open quays, as shown in Fig. 1. In the former, a vertical solid wall is constructed in the berth front to resist the horizontal load from the landfill and other live loads. In 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 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.¹

A comprehensive understanding of the nature of propeller jet flow and its associated scouring action will provide proper guidelines for the design of quay structures to reduce and prevent failure during the mooring and unmooring of vessels. Moreover, considering the propeller jet as a typical swirling flow, its associated research findings possibly could shed light on a broader range of scientific and engineering topics, such as the flow associated with hydro/tidal turbines and its impact on the fluvial and coastal processes. This type of turbines have gained increasing attention in recent years. Regarding the characteristics of the propeller jet flow and its impact on scour, considerable research has been carried to date. Over the past decades, a number of Ph.D. theses^{7,12–19} have provided much

information on both propeller jet flows and propeller scour. Sumer and Fredsøe³ provided the first comprehensive review of propeller scour studies, based primarily on the work of Queen's University Belfast.^{7,8,14,20–23} Later, Lam *et al.*²⁴ conducted another review of the prediction equations (available then) for the velocity distribution within a propeller jet. Since then, continuous research efforts, which brought new insights into the propeller scour, have been made. At this stage, it is important to take stock of and piece together the recent advances to present an overall view of the state-of-the-art understanding of propeller flow characteristics and its associated scouring mechanism.

Since the majority of the published literature on propeller-related topics to date are experimentally based on the theoretical, numerical, and field studies receiving significantly less attention, this review paper, therefore, is mainly restricted to the experimental works and organized into six sections. In what follows, Sec. II reviews the characteristics of propeller jet flow. The associated propeller jet induced scour is subsequently discussed in Sec. III with emphasis placed on the prediction methods of the temporal and spatial development of scour. Thereafter, Sec. IV interprets the scouring mechanism in light of insights gained from the measured flow structures within the developing scour hole. Section V briefly outlines the outstanding problems and research prospects related to the propeller scour. Finally, Sec. VI summarizes the paper.

II. CHARACTERISTICS OF PROPELLER JET FLOW

As the driving force of scour, the propeller jet flow must be carefully examined with respect to the characteristics of its diffusion. Experimental studies on ship propeller jets have received much attention by both naval architects and hydraulic/coastal engineers. Naval architects aim to optimize the design of the propeller blade geometry; their main concern is related to the velocity and pressure measurements around the propeller.^{25,26} In hydraulic and coastal engineering, however, the research interests generally are related to the development of the propeller jet diffusion, which aims to better understand the propeller scour mechanisms and provide recommendations for the design of quay structures and scour prevention.²⁷ The aim of this section is to give an overview of state-of-the-art research studies of the latter, which is important toward the study of propeller induced scour.

FIG. 1. Quay structures: (a) closed and (b) open quay.

Due to the complex interactions between a rotating propeller and the fluid medium, the ensuing velocity field is highly three dimensional and turbulent. As the helicoidal blades rotate, the upstream water is drawn in, accelerated, and discharged downstream, which 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 three complex components of velocity in the axial, tangential (rotational), and radial components. With its direction along the rotation axis of the propeller, the axial velocity serves 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 conventional jets issuing from an orifice.²⁸ For a maneuvering ship, the flow field is more complicated since it is a co-flow of a swirling propeller jet, coupled with a turbulent wake from the hull.²⁴ However, Prosser¹⁰ stated 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, published studies on a propeller jet were mostly based on the consideration of the action of the propeller jet itself under the bollard pull condition only, in which the propeller jet can be generally categorized as free or bounded jets, depending on whether the jet diffusion is interfered by additional boundary conditions. Specifically, a free propeller jet refers to the case where the jet is present in a very large water body without boundary effects, while a bounded propeller jet is subjected to certain boundary conditions in practice, such as the presence of a seabed, rudder, or quay structure.

A. Free propeller jet

A propeller jet is, in the first instance, a submerged jet. In view of its resemblance to circular jets, this section reviews the characteristics of a free propeller jet in terms of the mathematical descriptions of its efflux velocity and jet diffusion. In particular, the hub and swirling effects, which are unique to propeller jets, are discussed.

1. Efflux velocity

The efflux velocity is the governing parameter used for predicting the velocity distribution of a diffusing jet. For jet scouring problems, the efflux velocity likewise is the most important indicator of the jet flow intensity, which is often incorporated in the densimetric Froude number term generally used for scour depth computations. For a jet issuing from an opening, such as an orifice or a nozzle, its efflux velocity can simply be calculated by dividing the flow rate with the cross-sectional area. However, the jet produced by a propeller is actually passing through the slots between rotating blades and influenced by the presence of the hub, which makes it difficult for one to categorically define the efflux velocity as is done with conventional jets. Ryan¹⁴ conveniently defined the efflux velocity of a propeller jet as the maximum velocity at the propeller plane. However, due to the interference of the rotating propeller blades, it is technically infeasible to experimentally measure the nominal efflux velocity at the propeller plane. Recent studies used non-intrusive velocimetry techniques, such as laser Doppler anemometry (LDA) and particle image velocimetry (PIV) for such measurements (e.g., Hsieh *et al.*,²⁹ Hamill

et al.,³⁰ and Wei *et al.*³¹). However, due to the limitation of intrusive velocimetry such as acoustic Doppler velocimetry (ADV) in some studies, the measurable efflux plane was often arbitrarily taken at a safe distance downstream of the propeller plane (e.g., Hong *et al.*³² and Tan and Yüksel³³). Thus far, there is still no general consensus on the realistic location of the efflux plane for a propeller jet. In compliance with Bernoulli’s theory, the axial jet velocity reaches its maximum value at the plane of jet contraction, i.e., vena contracta. Since the efflux velocity of a propeller jet is conveniently referred to as the maximum velocity, it is physically justifiable to take the location where the maximum jet contraction occurs as the practical efflux plane. BAW³⁴ suggested that for a non-ducted propeller, the maximum jet velocity and vena contracta form at a distance of $0.5D_p$ (D_p is the propeller diameter) downstream of the propeller plane. This hypothesis was later confirmed by Hsieh *et al.*²⁹ based on the diffusion contour of the propeller jet plotted using data obtained from PIV measurements.

To estimate the efflux velocity of a propeller jet, the axial momentum theory is often applied to an ideal propeller, i.e., an actuator disc. Based on this presupposition, early studies, e.g., Fuehrer and Romisch,³⁵ obtained an analytical expression for determining the axial efflux velocity U_o of a propeller jet as follows:

$$U_o = c_o n D_p \sqrt{C_t}, \quad (1)$$

where c_o is the dimensionless coefficient (1.59), n is the propeller speed of rotation (in revolution per second), D_p is the propeller diameter (in m), and C_t is the dimensionless thrust coefficient. It must be stated that the axial momentum theory is inherently subjected to the following assumptions: (1) The propeller is represented by an infinitely thin disc, (2) the disc comprises an infinite number of blades and rotates at an infinite speed, (3) the velocity of the fluid through the disc is uniform over the entire area of the disc, (4) all energy supplied to the disc is in turn supplied to the fluid, and (5) the surrounding fluid is ideal.

Although the momentum theory provides some valuable insights into the global mechanisms of a propeller,³⁶ several researchers^{24,37} have highlighted that its underlying assumptions are inherently flawed and too crude to model an actual propeller. Fuehrer *et al.*³⁸ stated that Eq. (1) gave the prediction of efflux velocity with an error of $\pm 20\%$. Thence, significant efforts have been devoted to using semi-empirical methods by recalibrating Eq. (1) with experimental data that take into account the realistic characteristics of actual propellers in the past decades. Following the functional relationship of Eq. (1), a number of modified equations (see Table III of the Appendix) were proposed with a varying multiplicative coefficient c_o ranging from 0.89 to 1.71.^{13,17,18,33,39} In contrast to the approach founded in Eq. (1), Hamill *et al.*³⁰ modified the prediction equation by recalibrating both the multiplicative coefficient and exponents of each influencing factors, yielding

$$U_o = 1.22 n^{1.01} D_p^{0.84} C_t^{0.62}. \quad (2)$$

Equations (1) and (2) and other published equations tabulated in Table A1 yield different values of efflux velocity due to the disparity of the coefficients and exponents. In addition to the erroneous assumptions made in deriving the analytical equation [Eq. (1)], another possible reason is that the experimental data used to calibrate the equations were measured at different locations other than

FIG. 2. Schematic of a submerged free jet from an orifice (figure not drawn to scale). Re-drawn based on Albertson *et al.* (1950) (Public domain reuse).

the actual efflux plane. Furthermore, the actual efflux velocity may be closely related to the geometrical characteristic of the propeller type. Although some researchers (e.g., Stewart¹³ and Hashmi,¹⁷ see Table A1) did include such effects, their equations turn out to be overly complicated, lacking generalized applications. Additionally, Eq. (2) and the equations that propose different values of exponents are dimensionally inconsistent and therefore fundamentally flawed. It appears that in their ardent attempt to empirically fit their equations, they have overlooked the concept of dimensional homogeneity. For practical use, PIANC¹ presently recommends Eq. (1), while Eq. (2), which was calibrated with a wide range of experimental data, has been used in several laboratory studies.

2. Diffusion of propeller jet

For the sake of simplicity, the conventional circular jet without swirl was used as a surrogate for investigating the characteristics of the propeller jet flow in early studies. Albertson *et al.*⁴⁰ conducted the milestone work on submerged jet diffusion. Figure 2 shows a

schematic representation of jet diffusion given in the work of Albertson *et al.*,⁴⁰ 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). They assumed that the fluid discharged from the outlet had a constant-velocity or potential core. At the efflux section, the velocity discontinuity between the jet and the surrounding fluid causes a lateral mixing process both inwardly and outwardly, decelerating the fluid within the jet and accelerating 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) and therefore demarcating the ZFE and ZEF. Thereafter, the diffusion process continues in the ZEF without essential changes.

Due to the presence of the propeller hub in actual propeller jets, there exists a low-velocity core immediately behind it, thereby offsetting the location of the maximum axial velocity from the central axis of the jet. As a result, the velocity distribution behind a propeller features the iconic double-peak profile (see Fig. 3), which markedly differs from the potential core of the conventional circular jet (see Fig. 2). The influence of the hub decreases gradually as the high-velocity flow penetrates into the low-velocity core and the location where the double maximum velocity peaks merge into a single peak at the line of the propeller shaft axis, which demarcates the zone of flow establishment from the zone of established flow in a propeller jet. In addition, Fig. 3 shows the locus of the local maximum velocity, $u_{m,x}$. Due to the contraction effect, its radial location, albeit still off-centered, exhibits a trend of approaching the central axis at $x = 0.5D_p$, where $u_{m,x} = U_0$. Stewart¹³ reported that the transition between the two zones occurs at $x/D_p = \sim 3.25$, while Hamill and Kee²⁷ suggested a range of $3 \leq x/D_p \leq 3.5$. McGarvey¹⁵ reported that in the ZFE, the flow continues to mix with the receiving water both inwardly and outwardly, while in the ZEF, the flow will only be mixing outwardly. It should be noted that a right-handed coordinate system is adopted in Fig. 3 with the x -axis being streamwise-oriented along the propeller rotation axis, the y -axis along the lateral direction oriented toward the starboard, and the z -axis along the vertical direction. Accordingly, the corresponding velocity components along these three directions will be denoted as u , v , and w ,

FIG. 3. Schematic of a free propeller jet (figure not drawn to scale), where the blue-dotted curve represents the locus of the local maximum velocity.

hereinafter. Being in the order of ten times the magnitude of the tangential and radial velocity components,⁴¹ the axial velocity has been mostly studied by past researchers, from the early study of Blaauw and Kaa⁴² to the most recent study of Hong *et al.*⁴³ Conversely, its two counterparts, i.e., the tangential and radial velocities, have not received nearly the same kind of attention. In fact, they often have been considered insignificant in the flow analysis of propeller or thruster jets.¹ When not otherwise stated, the jet diffusion discussed below is referred to as the velocity distribution of the axial velocity component of the jet.

Based on the assumptions of hydrostatic pressure distribution, and the application of dynamic similarity of the diffusion process and normal-probability variation of the velocity distribution, Albertson *et al.*⁴⁰ proposed analytical expressions to describe the mean flow patterns within submerged jets. Albertson *et al.*⁴⁰ stated that the slipstream of a propeller jet differs little from other submerged jets. Therefore, its velocity distribution can be analyzed using the same approach. Following this rationale, continuous efforts (Hamill,¹⁸ Stewart,¹³ and McGarvey¹⁵) have proposed a number of equations for describing the velocity distribution within both the ZFE and ZEF of a propeller jet.

As the jet energy dissipates during diffusion, its velocity decays both longitudinally and radially. A complete picture that describes the velocity distribution within a diffusing jet first requires the prediction of the local maximum velocity at any longitudinal distance x from the propeller plane $u_{m,x}$, with which the radial distribution of velocity profile $u_{x,r}$ can be obtained. Specifically, the local maximum velocity $u_{m,x}$ is often normalized by the efflux velocity U_o and can be expressed as a function of the longitudinal distance x from the propeller plane, i.e.,

$$\frac{u_{m,x}}{U_o} = f\left(\frac{x}{D_p}\right). \quad (3)$$

The so-obtained local maximum velocity can therefore be used as a scaling velocity for predicting the velocity distribution profile at any longitudinal distance by adapting the Gaussian distribution function, i.e.,

$$\frac{u_{x,r}}{u_{m,x}} = e^{-\frac{r^2}{2\sigma^2}}, \quad (4)$$

where r is the radial distance within the jet and σ is the standard deviation of velocity. Note that in the ZFE, both r and σ need to be modified due to the off-center maximum velocity. As a result, Hamill¹⁸ and Fuehrer and Romisch³⁵ proposed separate equations for ZFE and ZEF. Since Lam *et al.*²⁴ have conducted a thorough review of the relevant published equations for predicting the decay of $u_{m,x}$ and distribution of $u_{x,r}$ within a propeller jet, they are summarized in Table IV of the Appendix and not repeated here. More recently, Hamill and Kee²⁷ highlighted how the decay trends of $u_{m,x}$ exhibit marked differences among different propeller models used in the experiments. Arising from this finding, they surmised that using the downstream distance x/D_p as the only parameter is inadequate in determining $u_{m,x}$, which is closely related to propeller characteristics. With this consideration, Hamill and Kee²⁷ suggested that the influence of the propeller pitch ratio (P/D_p) should also be taken into account, for which they stated that $u_{m,x}/U_o$ is linearly dependent on x/D_p and P/D_p . The corresponding equations are also included in Table IV of the Appendix.

Based on the assumption that the two zones are subjected to different diffusion mechanisms, different analytical methods have been applied to each of these zones to obtain the prediction equations for velocity distribution. More recently, by applying the point-source method proposed by Pani and Parameswaran,⁴⁴ Hong *et al.*⁴³ assumed that the jet flow of each infinitesimal area on the propeller efflux plane could be considered as a point source whose mean velocity distribution has a Gaussian-type profile. With this assumption, the velocity distribution at any cross section within the jet can be computed by the integration of all the differential area across the efflux plane with the exclusion of the hub area. In this way, they proposed a unified expression for the entire zone of jet diffusion without the need to differentiate the transition between the ZFE and ZEF as follows:

$$\frac{u_{x,r}}{u_m} \Big|_{r=r_p} = \left[\frac{1}{2\pi b^2} \int_0^{2\pi} \int_{\frac{1}{2}D_h}^{\frac{1}{2}D_p} e^{-(r^2+r_p^2-2rr_p\cos\theta)/2b^2} r dr d\theta \right]^{1/2}, \quad (5)$$

where r_p is the radial distance from the propeller rotational axis to an arbitrary point p , θ is the circular integration variable, and $b = cx$ with $c = (0.1822C_t + 0.0797)$ denoting the spreading factor.

The equations derived in early studies are dependent on multiple coefficients and the demarcation of the ZFE and ZEF, which were mostly empirically obtained. Therefore, their prediction capabilities are subjected to the data range from which they were originally derived. The study by Hong *et al.*⁴³ provided a theoretical description of the mean flow pattern of a propeller jet except for one single free coefficient, namely, the spreading factor that is proportional to the propeller thrust coefficient. Equation (5), which was validated with several independent datasets, including those of Hamill¹⁸ and Hamill and Kee,²⁷ besides their own measurement, is recommended to be used together with the semi-empirical equations proposed by Hamill and Kee.²⁷ A summary of the available equations for predicting the efflux velocity and jet diffusion of a free propeller jet can be found in Tables III–V of the Appendix.

3. Swirling effect

Driven by the rotating blades, the propeller jet is inherently a swirling jet in which the swirling effect transports the tangential flow momentum to the axial direction. Hong *et al.*⁴³ investigated the swirling effect in terms of the swirling number, which is defined as the tangential to axial momentum flux ratio. Their results showed that the swirling effect increases with the propeller rotational speed and decreases with the downstream distance from the propeller. The authors also argued that the swirling effect on the decay trend of the maximum velocity and the radial distribution of the axial velocity is insignificant, which in turn justifies the validity of the existing equations of jet diffusion, e.g., Eqs. (4) and (5), where the swirling effect is excluded.

B. Bounded propeller jet

Unlike the free propeller jet whose diffusion can be mathematically described by semi-empirical or analytical equations, bounded propeller jets exhibit less self-similarity due to the variability of the boundary conditions. Consequently, published studies have mainly

FIG. 4. Schematic of confinement configurations of a propeller jet: (a) horizontal boundary, (b) vertical boundary, (c) inclined boundary, and (d) rudder (plan view) (figure not drawn to scale).

focused on confinement effects on the development of flow behavior. Subsections II B 1–II B 4 cover four confinement configurations, including the horizontal, vertical, and inclined boundaries and rudder effects, as illustrated in the schematic diagrams in Fig. 4. The symbols in the figure are defined as follows: Z_b is the bed clearance, i.e., the vertical distance between the propeller axis and horizontal boundary; X_w is the wall clearance, i.e., the horizontal distance between the propeller plane and vertical wall; X_t is the toe clearance, i.e., the horizontal distance between the propeller plane and slope toe; and α is the rudder angle relative to the propeller axis.

1. Effect of horizontal boundary

Johnston *et al.*²⁸ studied the influence of a plane bed boundary on the development of the propeller jet, showing that in the presence of the 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. Besides, the plane boundary limits jet mixing with the surrounding fluid, thereby retarding energy dissipation, which eventually reduces the decay rate of the axial velocity. In terms of the development of near-bed velocities, three zones were identified 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.

Wei *et al.*³¹ investigated how the plane boundary affects the development of a propeller jet in a three-dimensional manner in which the flow patterns were presented in both the streamwise and transverse fields of view obtained through PIV measurements. Their results showed that the propeller jet exhibits a wall attachment behavior when it is placed near the plane boundary (see Fig. 5). This phenomenon, which is not unique to a propeller jet, is commonly observed in submerged offset jets and can be explained by means of the well-known Coandă effect. The authors argued that another important reason for the propeller jet attachment is related to its swirling attribute for which the presence of the boundary hinders the complete swirling rotation and confines the jet energy near the bed. Given this, one may surmise that swirling augments the wall attachment behavior, which in turn intensifies the jet scouring capability in the case of an erodible bed. Nevertheless, the swirling effect has been tacitly ignored in the current published scour prediction methods. Due to the wall attachment or Coandă effect, Fig. 6 shows the formation of three distinctive flow field regions downstream of the propeller, namely, free jet, impingement, and wall jet regions, whose extents vary under different clearance heights. In the impingement region, the transverse flow field shows that the plane boundary can

FIG. 5. Definition sketch of a confined propeller jet with a horizontal plane boundary (figure not drawn to scale).

FIG. 6. Streamwise flow patterns due to the horizontal boundary: (a) $Z_b = 2D_p$, (b) $Z_b = D_p$, and (c) $Z_b = 0.5D_p$. Reproduced with permission from Wei *et al.*, "Plane boundary effects on characteristics of propeller jets," *Exp. Fluids* **58**, 141 (2017). Copyright 2017 Springer Nature.

dramatically deform the jet rotation pattern, with the initial swirling being divided into two secondary vortices on either side of the central plane [see Figs. 7(d1) and 7(b2)]. 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.

Wei *et al.*³¹ revealed how the axial velocity profiles show a good agreement with the classical wall jet similarity function given by Verhoff.⁴⁵

Wei *et al.*⁴⁶ further examined the bed shear stress distribution within the impingement region between the swirling propeller

FIG. 7. Transverse flow patterns due to the horizontal boundary, upper row: $Z_b = D_p$ and lower row: $Z_b = 0.5D_p$. Reproduced with permission from M. X. Wei, "Propeller jet flow and its associated scour hole around open quay structures," Ph.D. thesis, Nanyang Technological University, 2018.

jet and a rigid plane bed. In their experiments, they used a left-hand propeller that rotates counterclockwise. As such, in view of the transverse flow field, Figs. 7(c1) and 7(a2) show how the swirling motion initially impinges onto the left side of the bed (with respect to the propeller axis at $y = 0$). Accordingly, when such a swirling jet approaches an erodible bed, a deeper scour depth is expected at the left side, as confirmed by Hong *et al.*³² However, in the case of a rigid bed, the measured bed shear stress result of Wei *et al.*⁴⁶ reveals that the highest shear stress, which has the highest scouring potential, forms around the upper-right region (see Fig. 8). This interesting

FIG. 8. Propeller jet induced bed shear stress distribution on a rigid horizontal bed. Note: The propeller model rotates counterclockwise when looking upstream. Reproduced with permission from Wei *et al.*, "Particle image velocimetry measurements of bed-shear stress induced by wall-bounded swirling jets," J. Eng. Mech. 146, 04020052 (2020). Copyright 2020 American Society of Civil Engineers.

discrepancy highlights the pronounced difference in flow behaviors upon jet impingement on erodible and rigid beds. In the case of a rigid boundary, the jet flow is passively deformed and deflected by the inertia force associated with the swirling motion. The rigid boundary actually "squeezes" the jet and causes an increase of the local pressure (normal stress) and a decrease of the near-bed velocity (shear stress) around the impingement region. Meanwhile, due to the swirling effect, the jet energy is diverted to the right side of the propeller, thus exerting a higher bed shear stress there (see Fig. 8). In contrast, as soon as the swirling motion impinges on an erodible bed, which essentially is a loose confinement, it will directly initiate scouring rather than being squeezed and deflected elsewhere. One may, therefore, argue that using results from fixed bed experiments as implications of erodibility, for example, by measuring the flow velocity within the scour hole by artificially fixing the scoured bed, could be misleading.

2. Effect of vertical boundary

With a simplified configuration of a closed type quay in the form of a vertical wall [see Fig. 4(b)], Wei and Chiew⁴⁷ experimentally investigated the flow behavior of a propeller jet impinging on the vertical quay wall. Due to the vertical confinement, the impinging jet exhibits a "spread-out" behavior and the original double-peak profile splits into two streams that are symmetrical about the propeller axis (see Fig. 9). With varying wall clearances, the development of the impinging jet is subjected to an interplay between two mechanisms, namely, jet diffusion and wall obstruction, which respectively govern the self-expanding and forced-spreading of the two jet streams. Based on the proper orthogonal decomposition (POD) analysis, Wei and Chiew⁴⁷ identified the coherent structures associated with the two mechanisms, thereby quantifying their relative dominance. The authors also argued that the peak frequency of jet diffusion is consistent with the propeller rotation frequency. Following this rationale, the jet diffusion mechanism could

FIG. 9. Mean flow patterns due to the vertical boundary: (a) $X_w = D_p$, (b) $X_w = 2D_p$, (c) $X_w = 3D_p$, and (d) $X_w = 4D_p$. Reproduced with permission from Wei and Chiew, "Impingement of propeller jet on a vertical quay wall," *Ocean Eng.* **183**, 73 (2019). Copyright 2019 Elsevier Ltd.

be readily singled out from a complex flow configuration, which may make it possible to study the underlying physics of different kinds of confinements on a propeller jet from a fundamental point of view.

3. Effect of inclined boundary

Qurrain⁷ reported that open-type quays are often accompanied by sloping banks as revetments under the quayside. As ships maneuver to dock near the berth, the propeller jet will impinge directly onto the inclined banks or revetments. To examine the influence of an inclined bed on the axial velocities within the propeller jet, Qurrain⁷ carried out a series of experiments in which two slope angles (7.5° and 15°) and three toe clearances ($2D_p$, $5D_p$, and $9D_p$) were adopted. His results showed that the measured efflux velocity was not evidently affected by the presence of the inclined bed, even at the nearest dock location where $X_t = 2D_p$. On the other hand, compared to free jets, the slope confinement enhanced the decay of the axial velocity, and such retarding effects of the slope on the propeller jet diffusion were proportional to the slope angle and toe clearance.

With an experimental configuration similar to that of Qurrain,⁷ Wei *et al.*⁴⁸ presented flow patterns of propeller jet diffusion in the presence of a plane bed and a quay slope ($V:H = 1:1.5$) under varying toe clearances ($X_t/D_p = 2-9$) obtained from PIV measurements. With a small toe clearance (e.g., $X_t/D_p = 2$), the bulk of the jet impinges on the slope before it can sufficiently expand to "feel" the plane bed (see Fig. 10). From the perspective of quay confinement effects, the vertical quay wall can be regarded as a slope with an angle of 90° in which the jet impinging angle is also 90° , and therefore, the vertical wall deflects the upper and lower jets symmetrically, as shown in Fig. 9.⁴⁷ In contrast, the slope quay causes an asymmetrical spread-out of the jet streams, where more jet flow (or jet energy) is deflected upwards. Note that it is the downward flow that eventually contributes to scouring in the presence of an erodible bed. One may reasonably deduce that the open quay will be subjected to less severe scouring damage than the closed quay provided that other conditions are the same. With increasing toe clearances, the slope effect decreases, while the plane bed effect dominates, as the jet flow initially attaches to the plane bed

before reaching the slope to be deflected upwards. Their results showed that at a slope of $V:H = 1:1.5$, no significant boundary layer separation and therefore large-scale vortex was formed at the junction of the slope and the plane bed (i.e., the slope toe). In this sense, a milder slope would not only ensure the stability of the slope itself but also inhibit the formation of a junction flow-induced vortex, which is often the main cause of scour damage at the slope toe in the presence of an erodible bed.

Furthermore, Wei *et al.*⁴⁸ suggested that the presence of the slope has a more pronounced influence on the turbulence intensity than the mean flow velocity at the slope toe. This is because the near-bed mean velocity profiles at the slope toe were found to be comparable among the different toe clearances tested, whereas the turbulence intensity was significantly enhanced with small toe clearances. One may surmise that in the case of an erodible bed, it is the turbulence rather than the mean flow that is more important in causing scouring at the slope toe.

FIG. 10. Mean flow patterns due to the inclined boundary (1 V:1.5 H slope): $X_t = 2D_p$. Re-drawn based on the data of Wei *et al.* (2018).

TABLE I. Summary of main findings regarding the flow field of propeller induced jets.

Type of propeller jet	Summary of finding	Limitations/remarks	References
Free propeller jet: Efflux velocity (Sec. II A 1)	<p>Defined as the maximum velocity along the propeller plane in the streamwise direction.</p> <p>Occurred at the distance $0.5D_p$ downstream of the propeller axis.</p> <p>Using analytically derived equation [Eq. (1)] with the assumption of an ideal propeller. It is presently recommended by PIANC (2015).</p> <p>Modification of Eq. (1) to numerous empirical equations with experimentally fitted multiplicative coefficients and exponents.</p>	<p>Difficult to measure experimentally due to the interference of the rotating propeller blades.</p> <p>Originally based on an arbitrary assumption but was later confirmed with actual experimental data.</p> <p>The “idealized propeller” assumption contains errors, and the computed values are different from measured data.</p> <p>The empirical equations exhibit a significant disparity in prediction. Modified exponents in Eq. (2) result in dimensional inconsistency with Eq. (1).</p>	<p>Ryan (2002)</p> <p>BAW (2010); Hsieh <i>et al.</i> (2013)</p> <p>Fuehrer and Romisch (1977); PIANC (2015)</p> <p>Hamill (1987); Hashmi (1993); Lam <i>et al.</i> (2012); Stewart (1992); Tan and Yuksel (2018); Hamill <i>et al.</i> (2015)</p>
Free propeller jet: Jet diffusion (Secs. II A 2 and II A 3)	<p>In contrast to the conventional circular jet diffusion, the presence of the propeller hub causes the formation of a low-velocity core immediately behind it and a double-peak file.</p> <p>Different values reported on the distance needed for the two peaks to merge at the propeller central axis, including $x/D_p \sim 3.25$, between 3 and 3.5, and so on.</p> <p>Because $u \gg v$ and w, most published research had concentrated on u; and the significance of v and w is considered unimportant (PIANC, 2015).</p> <p>Different equations for the streamwise velocity profiles for both the ZFE and ZEF were proposed.</p> <p>By using the point-source method for evaluating the jet axial momentum and assumption of a Gaussian distribution, the velocity profile is theoretically derived [Eq. (5)] without the arbitrary distinction between ZFE and ZEF. Equation (5) was verified using experimental data.</p> <p>Limited work on swirling effects can be found except for a recent work stating how it increases with the propeller rotational speed and decreases with the downstream distance from the propeller. Its effect on the decay of the maximum velocity and radial distribution of the axial velocity is insignificant and may be ignored.</p>	<p>The hub effect differentiates the diffusion mechanism of the propeller jet from that of the conventional circular jet. Their velocity profiles are different.</p> <p>All the data are empirical.</p> <p>More research efforts are needed to better understand the effect of v and w.</p> <p>All the equations are essentially empirically fitted, and their applicability is subjected to the data range from which they were originally derived.</p> <p>The only unknown that requires empirical fitting is the spreading factor, c, which is assumed to be proportional to the propeller thrust coefficient, C_t.</p> <p>Much more work is required in this area.</p>	<p>Albertson <i>et al.</i> (1950); Hamill (1987); Hong <i>et al.</i> (2020)</p> <p>Stewart (1992); Hamill and Kee (2016)</p> <p>PIANC (2015)</p> <p>Fuehrer and Romisch (1977); Hamill (1987); Lam <i>et al.</i> (2011)</p> <p>Hong <i>et al.</i> (2020)</p> <p>Hong <i>et al.</i> (2020)</p>

TABLE I. (Continued).

Type of propeller jet	Summary of finding	Limitations/remarks	References
Bounded propeller jets:		Horizontal boundary effects	
(i) Effect of the horizontal boundary (Sec. II B 1)	The effects of a horizontal boundary (i.e., a plane bed) are as follows: (a) The jet below the propeller axis expands faster; (b) due to limited mixing with the surrounding jet, the decay rate of the axial velocity decreases; and (c) in terms of the development of near-bed velocity, three zones were identified in their study, namely, (i) the zone before jet impact, (ii) the zone of boundary layer development, and (iii) the zone of developed boundary layer flow.	Earlier works were mostly based on point-wise velocimetry measurements and lacked a global view of the jet development. In addition, the results obtained from non-erodible plane bed experiments are unlikely to be applicable to an erodible bed when a scour hole forms.	Johnston <i>et al.</i> (2013)
	Similar to submerged offset jets, the Coandă effect also causes a propeller jet to attach to the bed. This attachment is augmented by the swirling effect.	The wall attachment behavior, which likely will intensify the jet scouring capacity, is ignored in most scour prediction equations.	Wei <i>et al.</i> (2017)
	Three distinctive flow field regions (see Fig. 6) were identified downstream of the propeller, namely, free jet, impingement, and wall jet regions.	The present research shows that the division of the flow field regions is only related to the clearance heights. This inference requires additional verification because other factors, such as the Reynolds number effect may also be important.	Wei <i>et al.</i> (2017)
	In the wall jet region, the axial velocity profiles show a good agreement with the classical wall jet similarity function.	This similarity is important but requires additional data for verification.	Verhoff (1963); Wei <i>et al.</i> (2017)
	The incessant swirling of the propeller causes an asymmetrical distribution of the near-bed shear stress distribution on a rigid plane bed. The phenomenon likely will be quite different in an erodible bed where scouring could take place.	An overall understanding of the effect of swirling on bed erosion still requires additional works, both experimentally and numerically.	Wei <i>et al.</i> (2017)
		Vertical boundary effects	
(ii) Effect of vertical boundary (Sec. II B 2)	The effect of vertical boundary (e.g., a vertical quay wall) is characterized by confinement of the longitudinal development of the jet. Upon impingement, the jet is symmetrically split into two streams in the streamwise plane. Under varying wall clearances, the overall jet configuration is subjected to a trade-off interaction between jet diffusion and wall obstruction, whose individual contributions can be identified by POD analysis.	The current finding is obtained based on the flow field measurement conducted along the sectional streamwise plane along the propeller axis. The flow properties and pressure distribution along the transverse plane (i.e., the impinging plane along the vertical boundary) still remains elusive.	Wei and Chiew (2019)

TABLE I. (Continued).

Type of propeller jet	Summary of finding	Limitations/remarks	References
Inclined boundary effects			
(iii) Effect of inclined boundary (Sec. II B 3)	<p>The inclined boundary (e.g., open quay slope) shows no evident effects on the efflux velocity. However, an increase in the slope angle (and/or decrease in toe clearance) enhances the decay of the jet axial velocity. The jet splits asymmetrically upon impingement on an inclined boundary as the greater bulk of jet energy is deflected upwards with respect to an adverse slope.</p> <p>Compared with the near-bed mean velocity, turbulence is more sensitive to the toe clearance. Therefore turbulence effect is surmised to be the main cause in initiating the scour in the case of an erodible bed.</p>	<p>The current inference of an insignificant inclined boundary effect on the efflux velocity is confined to a minimum toe clearance of $2D_p$.</p> <p>The fraction of downward-deflected jet energy, which would eventually contribute to scouring, has not been quantitatively investigated in terms of its dependence on the inclined slope.</p> <p>A detailed examination of turbulence effects on sediment transport during the scouring process is important in the future research.</p>	<p>Qurraïn (1994)</p> <p>Wei <i>et al.</i> (2018b)</p> <p>Wei <i>et al.</i> (2018b)</p>
Rudder effects			
(iv) Effect of rudder (Sec. II B 4)	The rudder splits the propeller jet into two jets, namely, surface and bottom jets.	Further numerical and experimental efforts are needed to obtain a topological and quantitative description of the jet flow behavior in the presence of a rudder.	Robakiewicz (1966); McGarvey (1996)

4. Effect of rudder

The rudder, which is a steering device located in front of the propeller, is used for ship maneuvering.³ Most research studies dealing with the velocity distribution behind a ship's propeller were conducted without a rudder. As a navigational device with a rudder angle of 35° as the practical limit for effective steering,³ the rudder will generate a different flow field. Robakiewicz⁴⁹ suggested that the propeller jet would be split into two jets, namely, surface and bottom jets, in the presence of a rudder in a central position of a propeller jet, with the former directed upwards to the surface and the latter directed downwards to the seabed. More recently, McGarvey¹⁵ conducted a series of experiments involving propeller flows in the presence of a rudder whose angle, α , varied in a range of -35° to $+35^\circ$. Note that the positive angle refers to the rudder position directing to the portside, while the negative angle is designated to the starboard side.⁵⁰ McGarvey¹⁵ reported that negative angles produced the bottom jet and positive angles produced the surface jet for right-hand propellers, which rotate clockwise to provide forward thrust. Clearly, the amount of works conducted thus far relating to rudder-effects on propeller jets is still limited. Additional research studies, both experimentally and numerically, are needed to obtain a better topological and quantitative description of the jet flow behavior in the presence of a rudder.

For easy reference, the main findings and remarks regarding the propeller flow related research covered in this section are summarized in Table I.

III. PROPELLER JET INDUCED SCOUR

Propeller jet induced scour may be considered to be a localized scour that occurs over a limited or defined area.¹⁴ As ships approach the port in a harbor basin, they generally are not subjected to significant hydrodynamic forces that cause general sediment transport, and therefore, the propeller scour is commonly considered as a case of clear-water scour. An implication of this low energy environment is that the effect of the ambient flow field often is ignored in past studies. Early studies on propeller scour were conducted by Liou and Herbich,⁵¹ Fuehrer and Romisch,³⁵ Blaauw and Kaa,⁴² and Fuehrer *et al.*⁵² 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 a simplified propeller model was adopted. Later, more realistic propeller models were used by Hamill¹⁸ and subsequent researchers, e.g., Stewart,¹³ Hashmi,¹⁷ Qurraïn,⁷ McGarvey,¹⁵ Ryan,¹⁴ Hong *et al.*,³² Tan and

Yüksel,³³ Wei,¹² and Penna *et al.*⁵³ To date, significant efforts have been devoted to predicting the dimension of the scour hole profile, in particular, the maximum scour depth, which is of particular significance to practical design and maintenance. It should be stated that due to the overwhelming amount of published prediction equations, this review only covers the most typical ones with emphases placed on their functional relationships. A summary of existing equations, which may not be exhaustive, is provided in Tables VI–IX of the Appendix.

Following the framework of the propeller jet classifications in Sec. II, an unconfined scour is defined as that forms on the seabed due to a propeller without a rudder or/and in the absence of any vertical boundary such as quay walls, while a confined scour is that forms with a vertical or/and inclined boundary subjected to a propeller with or without a rudder. In the latter, the seabed is also present. The terminology used here generally follows the definition customarily adopted in the published literature.

A. Unconfined scour

This section evaluates existing studies on the prediction methods of the maximum scour depth of the unconfined scour hole and its temporal development.

1. Prediction of maximum scour depth

A systematic study on the unconfined propeller scour was conducted by Hamill,¹⁸ who carried out a series of well-designed experiments with different combinations of the influential parameters, e.g., propeller diameter, rotation speed, bed clearance, sediment size, and so on. Thereafter, this type of propeller scour remains an active research topic and has been extensively studied by Stewart,¹³ Hong *et al.*,³² Tan and Yüksel,³³ and Penna *et al.*⁵³

Based on visual observations, Hamill¹⁸ reported that the shape of the scour holes induced by free propeller jets is similar in form and nearly symmetrical along the jet centerline, although the lateral depositions exhibit a slight asymmetry. Accordingly, most published scour equations are related to the computation of the maximum scour depth along the jet centerline. On the other hand, Hong *et al.*³² showed that the equilibrium scour profile comprises three parts: a small scour hole, a primary scour hole, and a deposition mound, as shown in Fig. 11. Since the maximum scour depth of the primary scour hole is the most important design parameter, many researchers had focused their attention on its estimate. On a side note, Wei *et al.*⁵⁴ suggested that the small scour hole directly beneath the propeller is attributed to the ground vortex, which is

FIG. 11. Unconfined propeller scour profile.

a phenomenon that has been extensively studied in the field of aerodynamics associated with aircraft propellers.⁵⁵

Considering the primary scour hole, the maximum scour depth $\varepsilon_{m,u}$ at the equilibrium state can be written functionally as

$$\varepsilon_{m,u} = f(U_o, D_p, C, \rho, d_{50}, g, \Delta\rho, \mu), \quad (6)$$

where U_o is the efflux velocity, D_p is the propeller diameter, C is the clearance between the propeller lower tip and undisturbed bed, ρ and μ are the density and viscosity of water, respectively, $\Delta\rho = \rho_s - \rho$ is the difference between the sediment-grain density ρ_s and water density, d_{50} is the median sediment size, and g is the acceleration due to gravity. Based on the Buckingham pi theorem, the normalized maximum scour depth can be expressed as

$$\frac{\varepsilon_{m,u}}{D_p} = f\left(F_o, Re, \frac{D_p}{d_{50}}, \frac{C}{d_{50}}\right), \quad (7)$$

where $F_o = \frac{U_o}{\sqrt{g d_{50} \frac{\Delta\rho}{\rho}}}$ is the densimetric Froude number and $Re = \frac{\rho U_o D_p}{\mu}$ is the Reynolds number of the propeller flow. Rajaratnam⁵⁶ showed that the effect of viscosity on the erosion induced by a plane wall jet could be neglected when $Re > 10^4$, which is the condition for most prototypes and even experimental conditions. Therefore, the normalized maximum scour depth can be re-written as

$$\frac{\varepsilon_{m,u}}{D_p} = f\left(F_o, \frac{D_p}{d_{50}}, \frac{C}{d_{50}}\right), \quad (8)$$

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

Given that the propeller axis clearance $Z_b = D_p/2 + C$, Z_b may be used as an alternative length scale that incorporates both the effects of the propeller diameter D_p and clearance distance C . Moreover, since the effect of the sediment size is inherently included in the densimetric Froude number, Verhey⁵⁷ suggested that the normalized scour depth could be expressed as a function of F_o and Z_b/D_p as follows:

$$\frac{\varepsilon_{m,u}}{Z_b} = c_1 F_o^{c_2} \left(\frac{Z_b}{D_p}\right)^{c_3}, \quad (9)$$

where the dimensionless coefficients $c_1 = 0.0041$, $c_2 = 2.9$, and $c_3 = -2.9$ are calibrated with experimental data. Following the same form as Eq. (9), Hamill¹⁸ recalibrated the coefficients by using his own experimental data, giving $c_1 = 0.0467$, $c_2 = 1.39$, and $c_3 = -1.39$.

Based on the observation that the scouring process initiates at a critical condition, Chiew *et al.*⁵⁸ introduced a critical densimetric Froude number $F_{o,c}$ (for the initiation of a propeller scour) to Eq. (9), yielding

$$\frac{\varepsilon_{m,u}}{D_p} = c_1 (F_o - F_{o,c})^{c_2} \left(\frac{Z_b}{D_p}\right)^{c_3}, \quad (10)$$

where $F_{o,c} = c_4 \frac{Z_b}{D_p}$. Noting that the scour induced by a pure water jet without swirl is, in fact, subjected to the same factors, i.e., the densimetric Froude number and offset ratio (clearance ratio) as that

of the propeller induced scour, Chiew *et al.*⁵⁸ made an attempt to unify the prediction of scour dimension induced by propeller and pure water jets. Using the experimental data of circular jets,⁵⁹ square jets,⁶⁰ and propeller jets,^{18,58} they obtained $c_1 = 0.265$, $c_2 = 0.955$, $c_3 = -0.022$, and $c_4 = 4.114$. Following the same form as Eq. (10), Tan and Yüksel³³ further calibrated the coefficients with an extensive dataset to obtain yet another equation with $c_1 = 0.57$, $c_2 = 0.33$, $c_3 = -1.1$, and $c_4 = 2.1$. It is apparent that the values of the coefficients obtained in these studies exhibit large disparity (up to two orders of magnitude) because the data used in their calibration were obtained from different experimental configurations and have diverse ranges. Nevertheless, the signs of the coefficients consistently reflect the physical trends that the scour depth is positively correlated with F_o , while negatively correlated with $F_{o,c}$ and $\frac{Z_b}{D_p}$. In other words, most studies on submerged offset and propeller jets had reached a consensus that the most influential factors in determining the unconfined scour depth are the densimetric Froude number and the clearance (or offset) ratio. Penna *et al.*,⁵³ on the other hand, argued that the effect of $\frac{Z_b}{D_p}$ on the formation of scour is much lower than that of F_o , even suggesting that the scour dimension is a function of F_o alone, i.e., $\frac{\varepsilon_{m,u}}{Z_b} = c_1 F_o^{c_2}$, where $c_1 = 0.57$ and $c_2 = 0.33$. Their disagreement with other researchers is likely due to the fact that in their experiments, $\frac{Z_b}{D_p}$ was limited in a narrow range of 0.83–1.17, whose effects were therefore overwhelmed by F_o that varied in a comparatively wider range of 3.65–9.54. Their inference is unlikely to be physically correct because one would intuitively recognize that the scour depth with a propeller located near the bed will exceed that with large Z_b . In fact, when Z_b approaches infinity (very high), the scour depth should approach zero. Notwithstanding this, Penna *et al.*⁵³ conducted a detailed three-dimensional scanning of the equilibrium scour profile, which allows them to obtain the global maximum scour depth with respect to the entire scour profile (i.e., the scour depth from the thalweg) other than that collected from the centerline profile, as was done by other researchers. By doing so, the scour asymmetry due to the swirling effect is taken into account in their equations. According to Penna *et al.*⁵³ data, the maximum scour depth of the thalweg is up to 6.7% higher than that at the centerline. Accordingly, prediction with the equations based on the scour depth at the centerline would have underestimated the maximum value, albeit with a discrepancy of not more than ~7%.

In addition to the maximum scour depth, the location where it occurs is also of great interest to practical design. Hamill *et al.*⁸ stated that the longitudinal position of the maximum scour depth from the propeller face, $X_{m,u}$, can be expressed as a function of F_o and propeller tip clearance C as follows:

$$X_{m,u} = F_o^{0.94} C. \quad (11)$$

The above-mentioned equations that are applicable to the unconfined propeller scour for the computation of the magnitude and location of the maximum scour depth are not only important indicators of unconfined scour, but these values also serve as physically justifiable length scales when predicting the scour hole

dimension in the corresponding confined case, as will be discussed in Sec. III B.

2. Temporal development of maximum scour depth

Besides the magnitude and location of the maximum scour depth, its temporal development is equally important in practice. Rajaratnam⁵⁶ showed that for a plane jet induced scour, the temporal development of the scour depth $\varepsilon_{m,t}$ follows a linear relationship with the logarithm of time. For a propeller induced scour, Hamill¹⁸ proposed a nonlinear functional relationship between $\varepsilon_{m,t}$ and $\ln(t)$, i.e.,

$$\varepsilon_{m,t} = \Omega [\ln(t)]^\Gamma, \quad (12)$$

where t is the time, and Ω and Γ depend on $\frac{C}{d_{50}}$, $\frac{D_p}{d_{50}}$, and F_o . The form of Eq. (12) has been adopted by subsequent studies^{7,8} in which the expression of Ω and Γ was fine-tuned with extensive experimental data, e.g., different propeller models and sediment sizes (see Table VII of the Appendix). It is noted that Eq. (12) is not dimensionally consistent, which consistently remains a drawback of some equations proposed by the group in Belfast. In contrast to the dimensional approach, Hong *et al.*³² proposed a different functional relationship to describe the temporal development of the maximum scour depth in a dimensionless manner as follows:

$$\frac{\varepsilon_{m,t}}{D_p} = k_1 \left[\log_{10} \left(\frac{U_o t}{D_p} \right) - k_2 \right]^{k_3}, \quad (13)$$

where k_1 , k_2 , and k_3 depend on F_o , $\frac{Z_b}{D_p}$, and $\frac{Z_b}{d_{50}}$. Note that Eq. (13) was not only fitted using their own data but also validated against the propeller jet scour data of Hamill¹⁸ as well as the square jet scour data of Karki *et al.*⁶⁰ To this end, it generalizes the temporal development of scour induced by three-dimensional water jets with or without swirl. More recently, both Eqs. (12) and (13) were further refined by Tan and Yüksel,³³ who carried out a series of experiments having a relatively larger range of F_o and $\frac{Z_b}{D_p}$ than those of Hamill¹⁸ and Hong *et al.*³² (see Table VII of the Appendix).

A close examination of the available equations derived from Eqs. (12) and (13) reveals that the calibrated exponents of F_o provided by these studies are inconsistent in their ($\pm$) signs (see Table VII of the Appendix). This implies that neither Eq. (12) nor (13) can unequivocally identify the individual effect of each parameter as their exponents are collectively regressed via Ω and Γ or k_1 – k_3 . This finding in turn indicates that the empirical equations, even though with a high correlation coefficient, could be physically misleading and unjustifiable. Moreover, as their mathematical forms indicate, both Eqs. (12) and (13) render an infinite scour depth when t tends to infinity, which is unreasonable because it implies that a stabilized maximum scour cannot be obtained,³ although both equations show that the scouring rate significantly slows down with time.

B. Confined propeller scour

When a ship is equipped with a rudder or docks at a quay, the presence of the rudder and berth structure will obviously affect the development of the propeller jet in its immediate neighborhood, which will expectedly induce a significant difference in the scour profile as compared to that caused in the unconfined propeller scour case (as discussed in Sec. III A). In terms of the confinement configurations, this section, as was done with propeller jet developments, reviews effects of typical types of quays (i.e., a closed quay with a vertical quay wall and an open quay with a slope bank) and a rudder on the scour development.

1. Effect of quay wall

In the presence of a quay structure, local changes in the flow pattern will generally result in an increase in the average bed shear stress and turbulence level.³ Consequently, an increased scour depth is expected. Depending on the types of ships, the relative position between the quay wall and propeller axis may be perpendicular [Fig. 12(a)], parallel [Fig. 12(b)], or both at the same time, i.e., the combined quay walls [Fig. 12(c)], where X_w and Y_w are the distances between the propeller (plane or rotation axis) and the perpendicular and parallel quay walls, respectively.

FIG. 12. Quay wall configurations (plan view).

Hamill *et al.*⁸ conducted a series of experiments in the presence of a perpendicular wall [Fig. 12(a)] with different wall clearances, showing that the equilibrium maximum scour depth is deepened appreciably (see Fig. 13) when the wall clearance is small (for example, $X_w/X_{m,u} = 0.636$ and 0.909 in their experiments). Their results also showed that the wall effect persisted even for a considerably large wall clearance, although no quantified limit was given. They stated that compared to the corresponding unconfined scour depth, the augmented scour depth can be expressed as a function of $X_w/X_{m,u}$ as follows:

$$\left(\frac{\varepsilon_{m,c} - \varepsilon_{m,u}}{Z_b + \varepsilon_{m,u}} \right) + 1 = 1.18 \left(\frac{X_w}{X_{m,u}} \right)^{-0.2}, \quad (14)$$

in which $\varepsilon_{m,c}$ is the maximum confined scour depth, and $\varepsilon_{m,u}$ and $X_{m,u}$ can be obtained by using Eqs. (9) and (11). Equation (14) shows that when $X_w/X_{m,u} = \sim 2.3$, the augmented scour depth approaches zero, that is, the confined scour depth at the wall equals to the unconfined maximum scour depth. More recently, Yüksel *et al.*⁶¹ further investigated the confined propeller scour around the perpendicular quay wall. Their results revealed two different types of scour profiles as the wall clearance increases, with the location of the maximum scour depth moving from the toe of wall to the upstream of wall. However, no clear demarcations between the two types of profiles were obtained. In addition, following the form similar to that of the unconfined scour equation [i.e., Eq. (9)], Yüksel *et al.*⁶¹ proposed yet another equation for predicting the scour depth at the quay wall by including the normalized wall clearance ($X_w/X_{m,u}$) as an additional multiplicative parameter (see Table VIII of the Appendix).

Following a similar approach, Hashmi¹⁷ and Qurain,⁷ respectively, investigated the propeller scouring process in the presence of parallel quay [Fig. 12(b)] and combined quay [Fig. 12(c)] walls. Their results revealed a consistent effect associated with the perpendicular and parallel quay walls, showing that when normalized by $\varepsilon_{m,u}$, the confined scour depth at the quay wall is inversely proportional to the wall clearance (X_w/D_p or Y_w/D_p) and directly proportional to F_0 , which can be expressed by a linear functional relationship. In addition, following the form of Eq. (12), Hashmi¹⁷ and Qurain⁷ also proposed the corresponding equations for predicting the temporal development of the confined scour depth at the toe of the quay walls by incorporating X_w/D_p or Y_w/D_p into the expression of Ω and Γ (see Table IX of the Appendix). Meanwhile, the mentioned drawback of Eq. (12), i.e., dimensional inconsistency, is therefore naturally carried-over.

FIG. 13. Confined scour at the closed quay wall, where the red-solid and black-dashed lines represent the confined and unconfined scour profiles, respectively.

Moreover, compared to the unconfined case, any additional influential parameter related to the confined condition would bring a geometric growth of data requirement for a rigorous multiple regression analysis. However, for the sake of experimental feasibility, the datasets used for calibrating the empirical equations are often confined to a limited range. For this reason, the so-obtained equations are yet to be validated using prototype data and should be considered only as a background for understanding the functional relationship governing the scouring process. The same limitations are also applicable to other confined cases that are subjected to multiple confined conditions.

2. Effect of rudder

As discussed earlier, the development of the propeller jet is affected by rudders; therefore, the associated scour hole should also be similarly influenced. McGarvey¹⁵ studied the ship propeller scour in the presence of a rudder and reported that the maximum scour depth $\varepsilon_{m,r}$ was observed to be increased by $\sim 25\%$ when the rudder angle is zero compared to its unconfined counterpart. As the rudder angle increases, the normalized maximum scour depth ($\varepsilon_{m,r}/\varepsilon_{m,u}$) exhibits a linearly decreasing trend (see Table VIII of the Appendix). Moreover, the thalweg of the scour hole was found to be well in line with the rudder angle. Following Eq. (12) and taking into account the rudder angle for Ω and F , the corresponding equations for describing rudder effects on the temporal development of scour were given by both McGarvey¹⁵ and Hamill *et al.*⁶² (see Table IX of the Appendix).

3. Combined effects of rudder and quay wall

Ryan and Hamill⁶³ conducted an experimental investigation on combined effects of a rudder and a parallel quay wall on the propeller scour. Furthermore, the same authors, Ryan and Hamill,⁵⁰ examined the combined effects of a rudder and a perpendicular quay wall. Similar to the results of McGarvey,¹⁵ this research showed that the loci of the maximum scour depth of the scour hole are approximately aligned to the rudder angle. Moreover, in both cases, the scour depth at the wall decreases with increasing wall clearance, either Y_w or X_w . On the other hand, the rudder effect differs with respect to different wall configurations. For the parallel wall configuration, Ryan and Hamill⁶³ reported that when the rudder angle increases, the jet axis is directed to the wall, thereby causing an increase in the scour depth and a decrease in the overall length of the scour hole along the parallel wall. For the perpendicular wall configuration, Ryan and Hamill⁵⁰ reported that when the rudder angle is zero, the scour hole is symmetrical about the axis of the propeller. In other words, the propeller jet impinges onto the perpendicular wall at an angle of 90° . As the rudder angle increases, the scour depth at the wall decreases. This is because a larger rudder angle tends to deflect the jet to be more aligned to the wall (i.e., with a smaller impinging angle), which in turn weakens the jet scouring capacity. For both the parallel and perpendicular wall configurations, empirical equations (see Tables VIII and IX of the Appendix) were proposed to determine the magnitude of the scour depth and its temporal development by taking into account the combined effects of the wall clearance and rudder angle. However, it must be stated that due to the complexity of the combined effects, these equations were only calibrated with very limited experimental data, and their general application is uncertain. In other words, no reliable equations are hitherto available, and any

extrapolation using the existing equations should be carried out with caution. Consequently, Ryan and Hamill^{50,63} suggested that the computed values should be used only as an initial guide for practicing designs.

4. Effect of open quay slope

Regarding the open quay, PIANC¹ reported that the scour protection of an armored slope is dependent on the slope angle and coarseness of the fill materials, with the ship propeller jet threatening the stability of the lower part of the fill. Schokking⁶⁴ studied bow thruster-induced damages on an armored slope with a ratio of 1:3 (V:H) and reported that the maximum damage location occurred at the toe of the slope. By using three different slope ratios of 1:1.5, 1:2.0, and 1:2.5, Cihan *et al.*⁶⁵ investigated the influence of slope angles on the 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 the results, they suggested that the slope steeper than 1:1.5 is not recommended for construction.

Wei and Chiew⁶⁶ experimentally investigated the propeller jet induced scour around an open quay with a constant slope angle of 1:1.5, and the research focus was placed on the influence of the toe clearance. Their results show that the characteristics of the scour profile at the equilibrium state differ significantly with varying toe clearances. Based on this observation, they classified the final scour profiles into three types in terms of the toe clearance, namely, near (Type N), intermediate (Type I), and far (Type F) toe clearance fields (see Fig. 14). Specifically, Type N has the form of a truncated primary scour hole around the slope toe, while Type I is characterized by a primary scour hole followed by a toe scour immediately in front of the quay slope. Finally, Type F is simply a primary scour hole that resembles the unconfined scour profile. Using the longitudinal location of the maximum scour depth in the corresponding unconfined case (i.e., $X_{m,u}$) as the scaling parameter, they demarcated these three types in terms of $X_t/X_{m,u}$. Based on their experimental data, the demarcation between Types N and F was given by $X_t/X_{m,u} = 1$, and the threshold of Type F occurred at $X_t/X_{m,u} = 1.9$. Such a demarcation was later confirmed by Wei and Chiew.⁶⁷ With varying toe clearances, their studies reveal that the maximum scour depth may occur in either the primary or the toe scour holes. A similar phenomenon was also observed by Ryan and Hamill⁵⁰ and Yüksel *et al.*⁶¹ in their study of propeller scour with a perpendicular quay. It essentially may be surmised from the absence of the scour profile similarity amongst these three toe clearance field types that they are subjected to distinct scouring mechanisms, which makes it difficult to achieve a unified prediction equation in terms of wall or toe clearances. Following the classification of Wei and Chiew,⁶⁶ Wei *et al.*⁵⁴ proposed a set of equations for predicting the maximum scour depth for each individual type of scour profile (see Table VIII of the Appendix). It must be stated that their study primarily focused on the toe clearance influence on the development of scour, while other influential factors, e.g., the bed clearance ratio and densimetric Froude number, are implicitly incorporated in $\varepsilon_{m,u}$ and $X_{m,u}$, which are used as scaling parameters in the proposed equations. In addition, the effect of the angle of the open slope, which should be included in the prediction model, has not been quantitatively examined.

FIG. 14. Scour types at an open quay: (a) near field (Type N), (b) intermediate field (Type I), and (c) far field (Type F), where the red-solid and black-dashed lines represent the confined and unconfined scour profiles, respectively.

IV. SCOURING MECHANISM

The propeller scour studies discussed above mainly aim at developing empirical equations for scour depth estimation for scour protection needs. While of significant practical value, empirically obtained equations shed limited light on the fundamental scouring mechanism. The scouring process essentially is a sediment transport phenomenon in which the flow-bed interaction holds the key to understanding the underlying physics. Although a number of equations describing the jet diffusion are available, most of them are exclusive to the free propeller jet and cannot be directly related to the scouring process. In terms of scour prediction, the efflux velocity has been routinely used as the sole parameter for representing the flow intensity. However, a complete picture that depicts how the jet flow evolves and interacts with a developing scour hole hitherto remains elusive. Due to the lack of detailed flow field data, the understanding of the scouring mechanism was often qualitatively inferred from visual observations of the evolution of the scour hole. More often than not, what is presented as a reason of scour is merely a corollary of the scour hole dimension. To provide a better quantitative account of the propeller scour mechanism, Wei¹² proposed an oblique-PIV (OPIV) measurement method, which allows for a concurrent measurement of the flow field and scour hole development during the scouring process. By applying the OPIV technique, Wei and Chiew⁶⁷ and Wei *et al.*⁶⁸ investigated the scouring mechanisms associated with the confined propeller scour at open and closed quays, respectively.

A. Similarity of scouring mechanisms at open and closed quays

Figures 15 and 16 exemplify the experimentally obtained mean flow patterns within the equilibrium scour holes at open (1 V:1.5 H slope) and closed (vertical) quays, respectively. The flow field reveals how the scour hole that forms at either the slope toe or the quay wall is essentially attributed to the junction flow induced by flow separation associated with the jet impingement. In a 2D sectional perspective, this phenomenon is analogous to the iconic horseshoe vortex that forms in a pier-scour hole in the uniform open channel flow. In contrast to the mean flow properties of uniform flows that remain unchanged in the longitudinal direction by definition, the jet flow diffuses both radially and longitudinally when it mixes with its surrounding fluid, causing the jet velocity to decay with the downstream distance, as discussed earlier (see Sec. II A 2). Consequently, compared to pier-scouring in the uniform flow, the confined propeller scour is subjected to an additional variable, namely, the clearance distance between the jet efflux and the obstruction structure, which is referred to as the toe (or wall) clearance in the context of an open (or closed) quay.

Based on the geometrical characteristics of the scour profiles (see Types N, I, and F in Sec. III B 4), Wei and Chiew⁶⁶ hypothesized that the scouring process around an open quay is governed by the jet diffusion and quay obstruction mechanisms. Wei and Chiew⁶⁷ flow field data confirmed these two previously inferred mechanisms as a self-expanding jet flow and an obstruction-deflected junction flow, respectively. Specifically, in the near field (Type N), Fig. 15(a)

FIG. 15. Mean flow pattern within the equilibrium scour hole at an open quay (1 V:1.5 H slope): (a) $X_t = 2D_p$, (b) $X_t = 4D_p$, and (c) $X_t = 6D_p$. Reproduced with permission from Wei and Chiew, "Characteristics of propeller jet flow within developing scour holes around an open quay," *J. Hydraul. Eng.* **144**, 04018040 (2018). Copyright 2018 American Society of Civil Engineers.

FIG. 16. Mean flow pattern within equilibrium scour holes at a closed quay: (a) $X_w = 1D_p$, (b) $X_w = 2D_p$, (c) $X_w = 3D_p$, and (d) $X_w = 4D_p$. Reproduced with permission from Wei *et al.*, "Vortex evolution within propeller induced scour hole around a vertical quay wall," *Water* **11**(8), 1538 (2019); licensed under a Creative Commons Attribution (CC BY) License.

clearly shows the flow separation and the formation of a sizable vortex that fills the scour hole, which is the flow feature that governs the final scour profile. For the intermediate field (Type I), Fig. 15(b) shows that the jet flow first attaches to the bed and excavates a primary scour hole before it impinges onto the slope toe, where the junction flow and a secondary scour hole (i.e., the toe scour hole) are formed. The figure highlights a combined effect of the jet and junction flows in affecting the final scour hole. For the far field (Type F), Fig. 15(c) shows that the jet flow exclusively dominates the scour profile that resembles its unconfined counterpart in which the slope toe is buried by incoming sediment particles that are eroded from the primary scour hole on the upstream bed and no junction flow occurs.

Since the vertical quay walls and slope quay both function as a kind of obstacle that facilitates the formation of the junction flow upon jet impingements, the scouring mechanism at these two structures is expected to be similar, which encompasses the interaction between the jet and junction flows. In vertical quay walls with small wall clearances when $X_w = D_p$ and $2D_p$, it is the junction flow in the form of a well-established vortex that dominates the scour hole [see Figs. 16(a) and 16(b)]. When the wall clearance increases, the wall confinement effect gradually decreases, during which the relative dominance of the jet flow and junction flow eventually reverses. Such a flow behavior and the associated scouring process

resemble that observed in the open quay case (see Fig. 15), and therefore, their resulting scour profiles are generally similar, albeit with different scour depths. Moreover, to better understand the interaction between the flow structure and the scoured bed, it is useful to refer to Fig. 9, which depicts the effect of the vertical wall on the impinging jet in the absence of a scour hole. Clearly, compared to Fig. 9, Fig. 16 reveals significant changes in the flow structure due to the presence of a scour hole on the bed. In particular, Figs. 16(a) and 16(b) show a vortex system comprising three vortices (V1, V2, and V3) instead of a pair of symmetric vortices, as that shown in Fig. 9(a). This finding highlights that when the flow has excavated a scour hole, the overall flow structure is significantly re-configured.

B. Junction flows at open and closed quays

With varying toe or wall clearances, the above discussion has underscored how the jet and junction flows collaboratively shape the final scour profile. However, the maximum scour depth immediately at the quay structure, which is of interest to practical design, is dominated by the junction flow. This section therefore puts particular emphasis on the characteristics of the junction flow and its dependence on the type of the quay structures.

Considering that the jet energy dissipates with the longitudinal distance, the junction flow intensity and its associated scour depth are expected to be inversely related to the toe (or wall) clearance. This is apparently true for the case of the closed quay, as confirmed by the data of Hamill *et al.*⁸ and Wei *et al.*⁶⁸ However, the open quay case exhibits an opposite trend, where the maximum scour depth at the slope toe was found to increase with increasing toe clearance in the near field.⁶⁶ This difference manifests the slope angle effect associated with the open quay, which is prone to deflect the impinging jet upwards rather than downwards to formulate the junction flow at the toe (as discussed in Sec. II B 3). Figures 10 and 15(a) evidently indicate that with a small toe clearance of $X_t/D_p = 2$, where the jet has not fully expanded before it impinges onto the

quay slope, the majority of the jet flow is deflected upwards along the quay slope. A more expanded jet with a relatively larger toe clearance (within the extent of near field) would, therefore, allow a larger portion of the jet to be felt by the slope toe, thereby facilitating the formation of junction flow and eventually contributing to scour there.

Furthermore, Fig. 17, which is plotted based on the work of Wei and Chiew⁶⁷ and Wei *et al.*,⁶⁸ shows the comparison of the temporal development of the junction flows at open and closed quays during the entire scouring process. From the perspective of vortex evolution, it can be observed from Fig. 17 that in the case of the open quay (upper row), only one primary vortex is formed around the slope toe as the sharp edge of the slope toe fixes the flow separation point

FIG. 17. Comparison of vortex evolution between open [(a1)–(e1)] and closed [(a2)–(e2)] quays, where the open quay has a 1 V:1.5H slope and the closed quay has a vertical quay wall. Note: [(a1)–(e1)] and [(a2)–(e2)] are reproduced with permission from Wei and Chiew, “Characteristics of propeller jet flow within developing scour holes around an open quay,” *J. Hydraul. Eng.* **144**, 04018040 (2018). Copyright 2018 American Society of Civil Engineers and Wei *et al.*, “Vortex evolution within propeller induced scour hole around a vertical quay wall,” *Water* **11**(8), 1538 (2019). Copyright 2019 Author(s), licensed under a Creative Commons Attribution 4.0 License, respectively.

FIG. 18. Temporal development of near-bed (a) turbulent kinetic energy (TKE) and (b) average kinetic energy (AKE) in a developing scour hole around the closed quay wall. Re-drawn based on the data of Wei *et al.* (2019).

TABLE II. Summary of main findings regarding the propeller induced scour.

Type of propeller scour	Summary of finding	Limitations/remarks	References
Unconfined scour (Sec. III A)	Both the magnitude and location of equilibrium maximum scour depth are functionally dependent on the densimetric Froude number and bed clearance. Empirical prediction equations are available.	Most studies overlooked the swirling effect that causes the final scour hole asymmetric. As a result, the so-obtained equations based on the measured scour depth from the centerline may yield underestimated estimations (up to ~7%).	Hamill (1987); Stewart (1992); Hong <i>et al.</i> (2013); Tan and Yuksel (2018); Penna <i>et al.</i> (2019)
	The temporal development of maximum scour depth follows a non-linear functional relationship with the logarithm of time [Eqs. (12) and (13)].	Equation (12) is dimensionally inconsistent. Both Eqs. (12) and (13) are inapplicable for predicting the time scale when scour reaches equilibrium as their functional relationship does not have a proper asymptotic boundary condition when t tends to infinity.	Hamill (1987); Hong <i>et al.</i> (2013)
Confined scour:		Effect of quay wall	
(i) Effect of quay wall (Sec. III B 1)	The presence of a perpendicular wall augments the equilibrium maximum scour depth compared to that of the unconfined scour when $X_w/X_{m,u} < 2.4$. With increasing wall clearance, the location of the maximum scour depth switches from the toe of wall to the upstream of wall, which results in two types of scour profiles with respect to varying wall clearances. Empirical equations are available for predicting the maximum scour depth.	The identified two types of scour profiles with varying wall clearances have not been quantitatively and physically demarcated in terms of wall clearance. The temporal development of the scour depth at a perpendicular quay wall is overlooked by past researchers.	Hamill <i>et al.</i> (1999b); Yuksel <i>et al.</i> (2019)
	The parallel quay and combined quay walls show that the confined scour depth at the quay wall is inversely proportional to the wall clearances while directly proportional to the densimetric Froude number. The corresponding empirical equations are available for predicting the maximum scour depth and its temporal development.	Most existing equations proposed for confined scour are subjected to limited datasets, which are not sufficiently extensive for rigorous multiple regression analyses. For this reason, they should be considered as a background for understanding the functional relationship governing the scouring process and used for the initial design guide only.	Hashmi (1993); Qurraïn (1994)
		Effect of rudder	
(ii) Effect of rudder (Sec. III B 2)	Compared to the unconfined scour, the presence of rudder augmented the scour depth by ~25% when the rudder angle is zero. The thalweg of the scour hole was found to be well in line with the rudder angle. Empirical equations are available for predicting the maximum scour depth and its temporal development.	The proposed empirical equations should be considered as a background for understanding the functional relationship governing the scouring process and used for the initial design guide only.	McGarvey (1996); Hamill <i>et al.</i> (2001)

TABLE II. (Continued).

Type of propeller scour	Summary of finding	Limitations/remarks	References
Combined effects of a rudder and quay wall			
(iii) Combined effects of rudder and quay wall (Sec. III B 3)	A rudder and a parallel wall: The scour depth at the wall increases with increasing rudder angle. Empirical equations are available for predicting the maximum scour depth and its temporal development.	The proposed empirical equations should be considered as a background for understanding the functional relationship governing the scouring process and used for the initial design guide only.	Ryan and Hamill (2011)
	A rudder and a perpendicular wall: The scour depth at the wall decreases with increasing rudder angle. Empirical equations are available for predicting the temporal development of the maximum scour depth.	For the case of combined effects of the rudder and perpendicular wall, the proposed equations are applicable for certain propeller models only and thus lack generalized applications.	Ryan and Hamill (2013)
	In both cases, the loci of the maximum scour depth of the scour hole are approximately aligned to the rudder angle.		Ryan and Hamill (2011, 2013)
Effect of open quay slope			
(iv) Effect of open quay slope (Sec. III B 4)	The open quay slope steeper than 1:1.5(V:H) is not recommended for the sake of scour protection.	The rudder effect has not been jointly investigated in the case of an open quay.	Cihan <i>et al.</i> (2012)
	With varying toe clearances, three types of scour profile are identified, namely, near (Type N), intermediate (Type I), and far (Type F) toe clearance fields. The demarcations between them are given as $X_t/X_{m,u} = 1$ and 1.9. Empirical equations are available for predicting the temporal development of the maximum scour depth.	The slope angle effect is not included in the current empirical model. The proposed equations should be considered as a background for understanding the functional relationship governing the scouring process and used for the initial design guide only.	Wei and Chiew (2017)
Scour mechanism (Sec. IV)	Both open and closed quays essentially exert longitudinal obstruction on the development of propeller jet when the propeller axis is perpendicular to the quay. In this sense, the associated scour mechanisms are deciphered as an interplay between the jet and junction flows under varying toe/wall clearances.	Recent advances in jet-induced scour and junction-flow-induced scour (e.g., pier scour) highlight remarkable progress in theoretical work, which may shed light on further research toward the confined propeller scour.	Wei <i>et al.</i> (2019); Wei and Chiew (2018)
	The junction flow formed in front of the obstruction structures is depended on the structure type (open or closed quays) and eventually governs the local scour hole at the quay.	The formation of the junction flow is closely related to the characteristics of the obstruction structure. Further research on this aspect is needed.	Wei <i>et al.</i> (2019); Wei and Chiew (2018)
	The measured flow field data within a developing scour hole highlights the important role of the turbulence effect on sediment transport during the scouring process. Both the mean and turbulent flow components should be taken into account in terms of their contributions to sediment entrainment.	Sediment transport within a developing scour hole is subjected to highly turbulent flow, which may be used as a heuristic scenario for investigating the turbulence effect on sediment transport.	Wei <i>et al.</i> (2019)

there. During the scouring process, the scour hole simply enlarges monotonically with the growing vortex. However, it is noted that the dimension of the vortex is physically curbed by the flow separation point at the slope toe, which in turn prevents the further enlargement of the scour hole.

On the other hand, in the case of the closed quay, Fig. 17 (lower row) shows that due to the wall effects, a complex vortex system comprising three vortices (V1, V2, and V3) is formed in front of the wall. At $t = 0$ h, Fig. 17(a2) shows that the initial flat bed facilitates the formation of a dominant V1 and two smaller vortices (V2 and V3) around it. As soon as an initial local scour hole is formed ($t = 0.5$ h), the original “confinement effect” affected by the flat bed diminishes, allowing the jet flow to be deflected downwards along the wall. As a result, a well-established V3 is formed inside the scour hole [see Fig. 17(b2)]. Thereafter, Figs. 17(b2)–17(e2) simply show that V3 increases in size and dictates the scouring action.

Overall, the comparison between the flow patterns of the open and closed quays shows that the difference in the geometry of the quay structures evidently determines the formation and evolution of the vortex system that governs the scouring process. In the closed quay, the continuous wall boundary of the vertical quay wall exerts no limit on the growth of the scour-driving vortex, thus resulting in a considerably larger V3 [see Fig. 17(e2)] compared to its counterpart [see Fig. 17(e1)] in the open quay. Consequently, one may deduce that in practice, the open type quay will have advantages over the closed type quay to lessen scour damages.

C. Implications of turbulence effect for “scour sediment transport”

Wei *et al.*⁶⁸ stated that the boundary layer of a wall-bounded swirling jet does not fit the logarithmic law of the wall. This perception may be reasonably applied to the flow within a scour hole. Conventional sediment transport theories, which were largely based on the presupposition of a uniform flow condition, may not be able to adequately describe the sediment transport in a local scouring process that is subjected to high turbulence. In addition, several studies have also highlighted the turbulence effect on sediment transport under complex flow environments.^{69–72} This perception, therefore, necessitates a detailed examination of the turbulence quantities within the developing scour hole, which is of great importance in understanding the interaction between the flow and scour bed.

Wei and Chiew⁶⁷ examined the near-bed Reynolds shear stress (RSS) within the developing scour hole around an open quay. Their results showed that when the near-bed shear stress (estimated by the near-bed RSS) progressively decreased to less than the critical shear stress needed for sediment initiation, scouring still persists. This implies that the critical shear stress, which customarily can be computed using the Shields diagram, may not be an effective indicator for defining the initiation and termination of scour. A most likely possibility of this inference is that the turbulence level is significantly higher in the scour hole. A similar finding was also reported for sediment transport in vegetated flows.⁷¹ As for the case of the closed quay, Wei *et al.*⁶⁸ showed that the turbulent kinetic energy (TKE) and near-bed average kinetic energy (AKE) exhibit significantly more changes during the scouring process than the near-bed RSS. Figures 18(a) and 18(b), respectively, present the temporal

developments of the near-bed TKE and AKE within a developing scour hole around the closed quay wall in which $\text{TKE} = 0.75(\overline{u'^2} + \overline{w'^2})/U_o^2$ and $\text{AKE} = 0.5(u^2 + w^2)/U_o^2$. Note that the near-bed quantities were extracted at a distance of 2.7 mm above the scoured bed boundary (along the centerline of the propeller rotation axis) at selected time intervals, i.e., $t = 0$ h, 0.5 h, 2 h, 12 h, and 24 h.

At the onset of the scouring action ($t = 0$ h), Fig. 18(a) reveals that the near-bed TKE profile has a hump shape with a local peak (around $x/D_p = 1$ –1.5), whose location corresponds to the core of the near-bed vortex [i.e., V3 refers to Fig. 17(a2)]. As the scour hole develops ($t = 0.5$ h–12 h), the overall TKE value undergoes a significant reduction. The overall decreasing trend manifests a reduction of TKE associated with the scour-driving vortex, denoting a weakening of the scouring capacity. The local increase in TKE around $x/D_p = 2$ (which is at the quay wall), on the other hand, is likely attributed to the presence of the corner vortex that formed at the junction between the scour bed and the quay wall. At the equilibrium state ($t = 24$ h), the near-bed TKE distribution drops to be insignificant except for the local region at the toe of wall, when the scour process almost ceases. It is interesting to note that TKE exhibits a consistent trend with that of the scouring rate. One may therefore infer that TKE plays an important role in sediment transport in the scour hole.

On the other hand, Fig. 18(b) shows that the development of the near-bed AKE profile follows an opposite trend to that of its turbulence counterpart. Initially, the flat bed acts as a blockage and restricts jet expansion; this constraint leads to an energy transfer from the mean flow to the turbulent flow field, thus resulting in a relatively small AKE value along the initial bed at $t = 0$ h. Thereafter, at $t = 0.5$ h–2 h, the data show that the AKE increases locally around $x/D_p = 1$ –1.5, which is likely caused by the growing near-bed vortex, V3 (see Fig. 17). Entering the stabilizing phase ($t = 12$ h–24 h), the larger scour hole seems to be able to stabilize the well-established near-bed vortex, which, in turn, conserves the mean flow energy as the AKE is found to exceed its TKE counterpart. Overall, both the mean and turbulent flow components should be taken into account when considering their contributions to sediment transport during the entire scouring process. This inference, to a large extent, is consistent with the finding of Cheng *et al.*,⁷⁰ who unified the prediction of the sediment pickup rate under various turbulent flow environments by incorporating the bulk mean and near-bed turbulent fluctuating velocities.

For easy reference, the main findings and remarks regarding the propeller scour related research (Secs. III and IV) are summarized in Table II.

V. FUTURE RESEARCH NEEDS

This section highlights future research needs with respect to the open problems identified based on all available research findings to date. In addition, other important aspects that have not been included in this review, while involved in practical situations, are briefly outlined.

A. Analytical solution

Based on the efforts from Hamill¹⁸ to Hong *et al.*,⁴³ it is now plausible to semi-analytically describe the velocity distribution in a

free propeller jet flow by following the seminal work of Albertson *et al.*⁴⁰ on the diffusion of a submerged jet. In contrast, due to the complexity of propeller scour, most of the existing prediction equations were empirically fitted to laboratory data. As a consequence, when extrapolated to the prototype condition, laboratory-based empirical equations often are susceptible to scale effects, resulting in inconsistent predictions. By comparing with the field data, Mujal-Colilles *et al.*⁷³ commented that among the numerous available equations, only Eq. (13) of Hong *et al.*³² and Eq. (14) of Hamill *et al.*⁸ are recommended to be used for unconfined and confined (closed quay) propeller scour cases.

More importantly, empirical equations generally lack solid physical reasoning and sometimes may even be physically flawed. Recent advances in the local scour community highlight the theoretical endeavor in predicting the jet scour^{74,75} and pier scour,^{76–78} which provide new insights into the scaling issue of the scour depth. Neglecting swirling effects on the scour depth, Hong *et al.*³² and Hoffmans⁹ suggested that propeller jets and conventional circular jets could be considered indistinctively as the same kind of three-dimensional offset jets. Given that the confined propeller scour is essentially subjected to a combined effect of jet flow and junction flow, the theoretical methodologies developed in the conventional jet scour and pier scour could shed more light on the understanding of propeller scour, which may eventually facilitate an analytical solution for propeller scour.

B. Twin and multiple propellers

Throughout this review, the primary focus has been placed on the research of a single propeller. For better maneuverability, twin or multiple propellers are not uncommon.⁸⁰ Thus far, the twin or multiple propeller induced jet and the associated scour issue have not received the same kind of research attention as that of a single propeller. Currently, the state-of-the-art approach for estimating velocities behind twin or multiple propellers is simply extrapolated from the understanding of a single propeller. For instance, Verhey⁵⁷ and BAW³⁴ indicated that the velocity field induced by twin or multiple propellers could be considered as a linear superposition of the flow fields induced by each propeller individually. However, PIANC¹ suggested that such a simplification is physically incorrect since it results in an artificial increase of the total impulse in the axial direction of the superimposed jet. Moreover, the development of multiple propeller jets is accompanied by the complex vortex-induced entrainment, mixing, and merging processes associated with two or multiple counter-rotating swirling jets, which are inherently overlooked in the superposition method. Only very recently, some researchers^{81–84} have dabbled into scour research studies with twin propellers. Studies of the flow field generated by twin or multiple propellers and the associated scour issue are still in their embryonic stage, and the physical interactions between individual jets and the associated scour mechanisms hitherto remain elusive. Clearly, further research is needed.

C. Other aspects

Currently, the majority of the published literature is confined to propeller jets at the simplified bollard pull condition with zero advance velocity. As such, some important aspects under real

situations, such as the effects associated with ship berthing and de-berthing operation and co-flow associated with ship maneuvers, have been overlooked. Consequently, one may find difficulties when applying the present methodologies, either for predicting jet velocity or scour depth, to the complex reality of a maneuvering ship, as highlighted by Llull *et al.*⁸⁵ Mujal-Colilles *et al.*'s⁷³ case study also revealed the discrepancy between the estimated scour depth given by empirical methods and field data. To this end, further laboratory and field studies on propeller jet accompanied by the co-flow, which simulates the maneuvering ship, are required to bridge this gap.

Moreover, alongside the quay structural instability caused by the propeller scour, several studies^{43,86–88} have underlined potential environmental impacts such as contaminants deposited on the seabed being re-suspended into the water column by moving ships. While of significant importance, such a topic has rarely been investigated. For estimating the sediment suspension induced by a propeller jet, Hong *et al.*⁸⁸ modified the Rouse equation by taking into account the effects of jet velocity distribution and scour hole configuration. As the propeller jet is highly turbulent and three-dimensional, its turbulence effect on sediment suspension is of particular interest and needs further detailed research.

VI. CONCLUDING COMMENTS

A thorough review of propeller jet flow and its associated scour is presented in this paper. The scope of the review is limited to the studies regarding non-ducted ship propellers operating at the bollard pull condition. First, similar to the approach adopted in the research of conventional jets without swirl, the efflux velocity and jet diffusion of a propeller jet also are delineated because they are, respectively, the primary parameter and behavior of turbulent jets. The former serves as the velocity scale used in predicting the decay of the maximum velocity and thereby the velocity distribution within the jet. Moreover, it also acts as a measure of the jet flow intensity in estimating the maximum scour depth. However, despite the significant efforts of past studies, a unified solution for predicting the efflux velocity still remains unavailable, which clearly requires additional research. As for the jet diffusion behavior, the velocity distribution within a free propeller jet has been mathematically described by both semi-empirical and theoretical equations. For bounded propeller jets, however, the available research findings had mainly focused on the boundary effects on the development of the jet with the aim to provide implications for potential scour actions when the jet is placed near an erodible bed. More efforts are needed to further examine the possible self-similarity within the confined flow patterns, which would improve a quantitative understanding of confinement effects on the development of the turbulent jet and related issues such as the sediment re-suspension and concentration field in the confined marine environment.

In propeller scour related studies, the unconfined scour has been most extensively investigated to date. Due to the efforts of many researchers over the past decades, a number of prediction equations for estimating the scour depth, albeit based primarily on laboratory studies, are now available. Empirical equations notably are limited to the experimental data used, often producing widely varying and inconsistent predictions. There is no consensus to date

regarding which equation is preferable in practical designs, especially for the confined propeller scour, and designed engineers are left with their own conjecture. Moreover, the issue of scale effects is also not carefully discussed. Consequently, the existing equations should be used as an initial guide only. Because of the difficulty associated with a purely analytical/theoretical approach to scour and the uncertainty involved in empiricism, this review places particular emphasis on their underlying functional relationships that consider the influential factors governing the jet diffusion and scouring process. For confined conditions with multiple variables, such as quay clearance, slope angle, rudder angle, and so on, a generalized prediction equation is either hardly available or overly complicated, which limits general applications. A routine practice in the local scour community often entails a hybrid approach of a case-by-case model study accompanied by numerical simulations when estimating the local scour depth under complex conditions.

Recent research features the advances in measuring the flow fields in a developing scour hole, which provides new insights into the vortex evolutions associated with the bounded propeller jet and the underlying scouring mechanisms. By comparing the similarities and differences in the scouring mechanisms governing the scour around open and closed quays, this review outlines the state-of-the-art understanding of how the quay type affects the scouring process. Besides, the measured near-bed flow properties, for the first time, quantitatively reveal that the AKE and TKE within a scour hole, respectively, exhibit increasing and decreasing trends during the scouring process, confirming the important role that turbulence plays in an evolving scour hole.

Hitherto, the published literature on the topic of propeller jets and scour is primarily limited to laboratory studies that are largely based on simplified configurations and semi-empirical methodology. The inherent limitations of laboratory-scale experiments in turn highlight urgent research need in the theoretical work and field study, which are of keen interest for both scientific researchers and practicing engineers. Due to the complexity of turbulent flows associated with the scouring process, it remains a challenge for scientists to provide a purely theoretical solution for predicting local scour. With the aid of the measured flow field in and around the scour hole, one may presume that the unconfined propeller scour in nature differs little from the conventional jet scour, while the confined propeller scour is essentially subject to a combination of jet and junction flows. In light of this current knowledge, recent advances in theoretical works associated with pier-scour and jet-scour may provide impetus for future propeller scour research. Meanwhile, the prototype field data of both the propeller jet velocity and scour are imperative for calibrating and validating the current empirical methods as well as the potential theoretical and numerical models.

ACKNOWLEDGMENTS

The authors would gratefully like to acknowledge the financial support from the National Natural Science Foundation of China (Grant No. 51979242) and the China Postdoctoral Science Foundation (Grant No. 2020M671722). The authors would also like to thank the anonymous reviewers for their insightful comments, which helped improve the quality of the manuscript.

NOMENCLATURE

b	=	experimental coefficient = cx
C	=	clearance between the propeller lower tip and undisturbed bed
C_t	=	thrust coefficient
c	=	dimensionless coefficient = $0.1822C_t + 0.0797$
c_0	=	dimensionless coefficient
c_{1-4}	=	constant coefficients
D_h	=	propeller hub diameter
D_p	=	propeller diameter
d_{50}	=	median sediment size
F_o	=	densimetric Froude number
$F_{o,c}$	=	critical densimetric Froude number
g	=	gravitational acceleration
k_{1-3}	=	experimental coefficients
n	=	propeller rotational speed
p	=	blade pitch
Re	=	Reynolds number of propeller jet flow
R_{mo}	=	location of maximum velocity at the efflux plane
R_p	=	radius of propeller
r	=	radial distance within the jet
r_p	=	radial distance from the propeller rotational axis to an arbitrary point p
t	=	time
U_o	=	efflux velocity
u	=	mean horizontal velocity
$u_{m,x}$	=	local maximum velocity
$u_{x,r}$	=	mean velocity at any position in the jet defined by the axial direction x , from the propeller plane and the radial distance r , from the rotation axis
u'	=	horizontal velocity fluctuations
$\frac{\sqrt{u'^2}}{U_o}$	=	horizontal turbulence intensity
v	=	mean lateral velocity
w	=	mean vertical velocity
w'	=	vertical velocity fluctuations
$\frac{\sqrt{w'^2}}{U_o}$	=	vertical turbulence intensity
$X_{m,u}$	=	longitudinal location of the maximum scour depth of unconfined scour
X_t	=	toe clearance, i.e., distance from the propeller plane to the slope toe
X_w	=	wall clearance, i.e., distance from the propeller plane to the perpendicular wall
x	=	longitudinal distance measured from the propeller plane
Y_w	=	distance between the propeller axis and the parallel quay wall
y	=	lateral distance measured from the propeller axis
Z_b	=	clearance height measured from the propeller axis to bed
z	=	vertical distance measured from the bed
α	=	rudder angle relative to the propeller axis
β	=	blade area ratio
Γ	=	experimental coefficient
$\Delta\rho$	=	difference between the sediment-grain density and water density
$\varepsilon_{m,c}$	=	maximum confined scour depth at the closed (perpendicular) quay wall

$\varepsilon_{m,p}$	=	maximum confined scour depth at the parallel quay wall	ρ_s	=	density of sediment
ε_{mfw}	=	maximum scour depth at the perpendicular quay wall (in the combined quay wall case)	σ	=	standard deviation of velocity at the lateral section
ε_{msw}	=	maximum scour depth at the parallel quay wall (in the combined quay wall case)	Ω	=	experimental coefficient
$\varepsilon_{m,r}$	=	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			
$\varepsilon_{m,t}$	=	maximum scour depth at time t			
$\varepsilon_{m,u}$	=	maximum unconfined scour depth			
$\varepsilon_{m,o}$	=	maximum confined scour depth in the open quay case			
θ	=	circular integration viable			
μ	=	viscosity of the fluid			
ρ	=	density of water			

APPENDIX: SUMMARY OF PREDICTION EQUATIONS

List of equations for the efflux velocity. List of equations for the decay of maximum axial velocity. List of equations for predicting velocity distribution within a free propeller jet. Equations for predicting the maximum scour depth of unconfined scour. Equations for predicting the temporal development of the maximum scour depth of unconfined scour. Equations for predicting the maximum scour depth of confined scour. Equations for predicting the temporal development of the maximum scour depth of confined scour.

TABLE III. List of equations for the efflux velocity.

Authors	Efflux velocity coefficients or equations
Blaauw and Kaa (1978)	$c_o = 1.59$
Hamill (1987)	$c_o = 1.33$
Stewart (1992)	$c_o = D_p^{-0.0686} \left(\frac{P}{D_p} \right)^{1.519} \beta^{-0.323}$
Hashmi (1993)	$c_o = \left(\frac{D_p}{D_h} \right)^{-0.403} C_t^{-1.79} \beta^{0.744}$
Lam <i>et al.</i> (2012)	$c_o = 0.89-1.71$
Hamill <i>et al.</i> (2015)	$U_o = 1.22n^{1.01} D_p^{0.84} C_t^{0.62}$
Tan and Yüksel (2018)	$c_o = 1.42$

TABLE IV. List of equations for the decay of maximum axial velocity.

Authors	Equations	Remark
Fuehrer and Romisch (1977)	$\frac{u_{m,x}}{U_o} = 2.6 \left(\frac{x}{D_p} \right)^{-1.0}$	$x/D_p \geq 2.6$
Blaauw and Kaa (1978)	$\frac{u_{m,x}}{U_o} = 2.8 \left(\frac{x}{D_p} \right)^{-1.0}$	$x/D_p \geq 2.8$
Berger <i>et al.</i> (1981)	$\frac{u_{m,x}}{U_o} = 1.025 \left(\frac{x}{D_p} \right)^{-0.6}$	...
Verhey (1983)	$\frac{u_{m,x}}{U_o} = 1.97 \left(\frac{x}{D_p} \right)^{-1}$	$x/D_p \geq 2.77$
Hamill (1987)	$\frac{u_{m,x}}{U_o} = 0.87 \left(\frac{x}{D_p} \right)^{-\frac{\beta}{4}}$	ZFE
Hamill (1987)	$\frac{u_{m,x}}{U_o} = A' \left(\frac{x}{D_p} \right)^{B'}$ $A' = -11.4C_t + 6.65\beta + 2.16 \left(\frac{P}{D_p} \right)$ $B' = -C_t^{0.216} \beta^{1.024} \left(\frac{P}{D_p} \right)^{-1.87}$	ZEF

TABLE IV. (Continued).

Authors	Equations	Remark
Stewart (1992)	$\frac{u_{m,x}}{U_o} = 1.0172 - 0.1835 \left(\frac{x}{D_p} \right)$	$x/D_p < 3.25$
	$\frac{u_{m,x}}{U_o} = 0.543 - 0.0281 \left(\frac{x}{D_p} \right)$	$x/D_p \geq 3.25$
Hashmi (1993)	$\frac{u_{m,x}}{U_o} = 0.638e^{-0.097 \left(\frac{x}{D_p} \right)}$	ZEF
Hamill and Kee (2016)	$\frac{u_{m,x}}{U_o} = 1$	$x/D_p < 0.35$
	$\frac{u_{m,x}}{U_o} = 1.51 - 0.175 \left(\frac{x}{D_p} \right) - 0.460 \left(\frac{P}{D_p} \right)$	$0.35 \leq x/D_p < 3.25$
	$\frac{u_{m,x}}{U_o} = 0.964 - 0.039 \left(\frac{x}{D_p} \right) - 0.344 \left(\frac{P}{D_p} \right)$	$x/D_p \geq 3.25$

TABLE V. List of equations for predicting velocity distribution within a free propeller jet.

Authors	Equations	Remark
Hamill (1987)	$\frac{u_{x,r}}{u_{m,x}} = e^{-\frac{(r-R_{mo})^2}{2\sigma^2}}$ with $\sigma = \frac{R_{mo}}{2}$	ZFE for $x < 0.5D_p$
	$\frac{u_{x,r}}{u_{m,x}} = e^{-\frac{(r-R_{mo})^2}{2\sigma^2}}$ with $\sigma = \frac{R_{mo}}{2} + 0.075(x - R_p)$	ZFE for $x > 0.5D_p$
Fuehrer and Romisch (1977)	$\frac{u_{x,r}}{u_{m,x}} = e^{\left[-22.2 \left(\frac{r}{x} \right)^2 \right]}$	ZEF
Hong <i>et al.</i> (2020)	$\frac{u_{x,r}}{u_{m,x}} = \left[\frac{1}{2\pi b^2} \int_0^{2\pi} \int_{r_1}^{r_2} e^{-(r^2+r_p^2-2rr_p\cos\theta)/2b^2} r dr d\theta \right]^{1/2}$	Applicable for both ZFE and ZEF

TABLE VI. Equations for predicting the maximum scour depth of unconfined scour.

Authors	Equations	Remark
Hamill (1987)	$\frac{\varepsilon_{m,u}}{Z_b} = 0.0467 \left[\frac{F_o}{(Z_b/D_p)} \right]^{1.39}$	$0.81 \leq Z_b/D_p \leq 2.87$
		$5.55 \leq F_o \leq 18.72$
Stewart (1992)	$\frac{\varepsilon_{m,u}}{Z_b} = 0.0198 \left[\frac{F_o}{(Z_b/D_p)} \right]^{2.024}$	...
Hong <i>et al.</i> (2013)	$\frac{\varepsilon_{m,u}}{D_p} = 0.265 \left[F_o - \left(4.114 \frac{Z_b}{D_p} \right) \right]^{0.955} \left(\frac{Z_b}{D_p} \right)^{-0.022}$	$0.5 \leq Z_b/D_p \leq 1.5$
		$6.08 \leq F_o \leq 10.69$
Tan and Yüksel (2018)	$\frac{\varepsilon_{m,u}}{D_p} = 0.57 \left[F_o - \left(2.1 \frac{Z_b}{D_p} \right) \right]^{0.33} \left(\frac{Z_b}{D_p} \right)^{-1.1}$	$0.77 \leq Z_b/D_p \leq 3.08$
		$1.89 \leq F_o \leq 15.01$
Penna <i>et al.</i> (2019)	$\frac{\varepsilon_{m,u}}{D_p} = 0.06 F_o^{1.34}$	$0.83 \leq Z_b/D_p \leq 1.17$
		$3.65 \leq F_o \leq 9.54$

TABLE VII. Equations for predicting the temporal development of the maximum scour depth of unconfined scour.

Authors	Equations	Remark
Hamill (1987)	$\varepsilon_{m,t} = \Omega [\ln(t)]^\Gamma$	
	$\Omega = 6.9 \times 10^{-4} \left[\frac{C}{d_{50}} \right]^{-4.632} \left[\frac{D_p}{d_{50}} \right]^{3.575} [F_o]^{-4.535}$	$0.81 \leq Z_b/D_p \leq 2.87$ $5.55 < F_o < 18.72$
	$\Gamma = 4.1135 \left[\frac{C}{d_{50}} \right]^{0.742} \left[\frac{D_p}{d_{50}} \right]^{-0.522} [F_o]^{-0.682}$	
Qurraïn (1994)	$\varepsilon_{m,t} = \Omega [\ln(t)]^\Gamma$	
	$\Omega = \left[\frac{C}{d_{50}} \right]^{-4.758} \left[\frac{D_p}{d_{50}} \right]^{2.657} [F_o]^{3.517}$	$0.5 \text{ mm} < d_{50} < 4 \text{ mm}$
	$\Gamma = \left[\frac{C}{d_{50}} \right]^{0.768} \left[\frac{D_p}{d_{50}} \right]^{-0.339} [F_o]^{-0.479}$	
Hamill <i>et al.</i> (1999)	$\varepsilon_{m,t} = \Omega [\ln(t)]^\Gamma$	
	$\Omega = 38.97 \Gamma^{-6.38}$	$0.5 D_p < C < 2.5 D_p$
	$\Gamma = [F_o]^{-0.53} \left[\frac{D_p}{d_{50}} \right]^{-0.48} \left[\frac{C}{d_{50}} \right]^{0.94}$	
Hong <i>et al.</i> (2013)	$\frac{\varepsilon_{m,t}}{D_p} = k_1 \left[\log_{10} \left(\frac{U_o t}{D_p} \right) - k_2 \right]^{k_3}$	
	$k_1 = 0.014 F_o^{1.120} \left(\frac{Z_b}{D_p} \right)^{-1.740} \left(\frac{Z_b}{d_{50}} \right)^{-0.170}$	$0.5 < Z_b/D_p < 2.87$
	$k_2 = 1.882 F_o^{-0.009} \left(\frac{Z_b}{D_p} \right)^{2.302} \left(\frac{Z_b}{d_{50}} \right)^{-0.441}$	$5.55 < F_o < 11.1$
	$k_3 = 2.477 F_o^{-0.073} \left(\frac{Z_b}{D_p} \right)^{0.53} \left(\frac{Z_b}{d_{50}} \right)^{-0.045}$	
Tan and Yüksel (2018)	$\frac{\varepsilon_{m,t}}{D_p} = k_1 \left[\log_{10} \left(\frac{U_o t}{D_p} \right) - k_2 \right]^{k_3}$	
	$k_1 = 0.042 F_o^{1.120} \left(\frac{Z_b}{D_p} \right)^{-0.40} \left(\frac{Z_b}{d_{50}} \right)^{-0.170}$	$0.77 < Z_b/D_p < 3.08$
	$k_2 = 1.882 F_o^{-0.009} \left(\frac{Z_b}{D_p} \right)^{2.302} \left(\frac{Z_b}{d_{50}} \right)^{-0.441}$	$1.89 \leq F_o \leq 15.01$
	$k_3 = 2.477 F_o^{-0.073} \left(\frac{Z_b}{D_p} \right)^{0.53} \left(\frac{Z_b}{d_{50}} \right)^{-0.045}$	
Tan and Yüksel (2018)	$\varepsilon_{m,t} = \Omega [\ln(t)]^\Gamma$	
	$\Omega = 6.9 \times 10^{-4} \left[\frac{Z_b}{d_{50}} \right]^{-4.63} \left[\frac{D_p}{d_{50}} \right]^{3.58} [F_o]^{4.535}$	$0.77 < Z_b/D_p < 3.08$ $1.89 \leq F_o \leq 15.01$
	$\Gamma = 3.8 \left[\frac{Z_b}{d_{50}} \right]^{0.742} \left[\frac{D_p}{d_{50}} \right]^{-0.52} [F_o]^{-0.682}$	

TABLE VIII. Equations for predicting the maximum scour depth of confined scour. Note: The rudder angle should be converted to radians when using the equation.

Confined case	Authors	Equations	Remark
Perpendicular quay wall	Hamill <i>et al.</i> (1999)	$\left(\frac{\varepsilon_{m,c} - \varepsilon_{m,u}}{Z_b + \varepsilon_{m,u}}\right) + 1 = 1.18 \left(\frac{X_w}{X_{m,u}}\right)^{-0.2}$	$0.6 \leq X_w/X_{m,u} \leq 3.27$
	Yüksel <i>et al.</i> (2019)	$\frac{\varepsilon_{m,c}}{D_p} = 0.512 F_o^{2.27} \left(\frac{C}{d_{50}}\right)^{-0.65} \left(\frac{X_w}{D_p}\right)^{-0.543}$	$2.7 \leq X_w/D_p \leq 10.8$
Parallel quay wall	Hashmi (1993)	$\frac{\varepsilon_{m,p}}{\varepsilon_{m,u}} = 1.608 - 0.595 \left(\frac{Y_w}{D_p}\right) + 0.068(F_o)$	$1.52 < Y_w/D_p < 3.05$
Combined quay walls	Qurrain (1994)	$\frac{\varepsilon_{msw}}{\varepsilon_{m,u}} = 2.535 - 0.723 \left(\frac{Y_w}{D_p}\right) - 0.203 \left(\frac{X_w}{D_p}\right) + 1.095(F_o)$	Maximum depth of scour at the parallel wall
		$\frac{\varepsilon_{mfw}}{\varepsilon_{m,u}} = 2.463 - 0.208 \left(\frac{Y_w}{D_p}\right) - 0.118 \left(\frac{X_w}{D_p}\right) - 0.022(F_o)$	Maximum depth of scour at the perpendicular wall
Rudder	McGarvey (1996)	$\frac{\varepsilon_{m,r}}{\varepsilon_{m,u}} = 0.75 - 0.07 F_o + 0.02 \left(\frac{D_p}{d_{50}}\right) - 0.15(1 + \alpha)$	$4.13 \leq F_o \leq 12.46$
			$25.33 \leq D_p/d_{50} \leq 89.73$ $-35^\circ \leq \alpha \leq 35^\circ$
Rudder and parallel wall	Ryan and Hamill (2011)	$\frac{\varepsilon_{m,r,p}}{d_{50}} = 6.47 \times 10^{-5} \left(\frac{C}{d_{50}}\right)^{-5.42} \left(\frac{D_p}{d_{50}}\right)^{6.63} \left(\frac{Y_w}{D_p}\right)^{-0.437} F_o^{2.498} (1 + \alpha)^{-0.80}$	$4.87 \leq F_o \leq 11.2$
			$19.4 \leq C/d_{50} \leq 85.53$
			$39.1 \leq D_p/d_{50} \leq 172.37$
			$1.52 \leq Y_w/D_p \leq 3.05$ $-35^\circ \leq \alpha \leq 0^\circ$
Open quay slope	Wei <i>et al.</i> (2018)	$\frac{\varepsilon_{m,o}}{\varepsilon_{m,u}} = 0.86 \left(\frac{X_t}{X_{m,u}}\right)^{0.8}$	$0 < X_t/X_{m,u} \leq 1$
		$\frac{\varepsilon_{m,o}}{\varepsilon_{m,u}} = 1.85 \left(\frac{X_t}{X_{m,u}} - 0.91\right) \left(\frac{X_t}{X_{m,u}} - 1.91\right) + 1$	$1 < X_t/X_{m,u} < 1.9$
		$\frac{\varepsilon_{m,o}}{\varepsilon_{m,u}} = 1$	$X_t/X_{m,u} \geq 1.9$

TABLE IX. Equations for predicting the temporal development of the maximum scour depth of confined scour.

Confined case	Authors	Equations	Remark
Parallel quay wall	Hashmi (1993)	$\varepsilon_{m,t} = 540.14 e^{-3.13\Gamma} [\ln(t)]^\Gamma$ $\Gamma = 13.419 \left(\frac{Y_w}{D_p}\right)^{0.325} (F_o)^{-0.872} \left(\frac{C}{d_{50}}\right)^{0.63} \left(\frac{D_p}{d_{50}}\right)^{-0.662}$	Near-wall relationship $1 < Y_w/D_p < 3.05$
		$\varepsilon_{m,t} = 383.32 e^{-3.02\Gamma} [\ln(t)]^\Gamma$ $\Gamma = 36.582 \left(\frac{Y_w}{D_p}\right)^{-0.352} (F_o)^{-0.866} \left(\frac{C}{d_{50}}\right)^{0.818} \left(\frac{D_p}{d_{50}}\right)^{-0.892}$	Far wall relationship $3.05 < Y_w/D_p < 6.1$

TABLE IX. (Continued).

Confined case	Authors	Equations	Remark
Combined quay walls	Qurraïn (1994)	$\varepsilon_{m,t} = \Omega[\ln(t)]^{\Gamma}$	Scour depth at the toe of the parallel wall at any time $C/D_p = 0.8$ $X_w/D_p \leq 6$ $Y_w/D_p \leq 4.5$
		$\Omega = 1992 \left(\frac{Y_w}{D_p}\right)^{-8.271} \left(\frac{X_w}{D_p}\right)^{-5.678} (F_o)^{3.049}$	
		$\Gamma = 0.016 \left(\frac{Y_w}{D_p}\right)^{2.196} \left(\frac{X_w}{D_p}\right)^{1.82} (F_o)^{-0.854}$	
		$\varepsilon_{m,t} = \Omega[\ln(t)]^{\Gamma}$	Scour depth at the toe of the perpendicular wall at any time $C/D_p = 0.8$ $X_w/D_p \leq 6$ $Y_w/D_p \leq 4.5$
		$\Omega = 41.89 \left(\frac{Y_w}{D_p}\right)^{-0.202} \left(\frac{X_w}{D_p}\right)^{-2.839} (F_o)^{1.602}$	
		$\Gamma = 0.506 \left(\frac{Y_w}{D_p}\right)^{-0.327} \left(\frac{X_w}{D_p}\right)^{1.003} (F_o)^{-0.399}$	
Rudder	McGarvey (1996)	$\varepsilon_{m,t} = \Omega[\ln(t)]^{\Gamma}$	$4.13 \leq F_o \leq 12.46$ $25.33 \leq D_p/d_{50} \leq 89.73$ $-35^\circ \leq \alpha \leq 35^\circ$
		$\Omega = 0.268 \left(\frac{C}{d_{50}}\right)^{-3.294} \left(\frac{D_p}{d_{50}}\right)^{1.494} (F_o)^{4.437} (1 + \alpha)^{-1.038}$	
		$\Gamma = 0.705 \left(\frac{C}{d_{50}}\right)^{0.848} \left(\frac{D_p}{d_{50}}\right)^{-0.178} (F_o)^{-0.885} (1 + \alpha)^{-0.299}$	
	Hamill <i>et al.</i> (2001)	$\varepsilon_{m,t} = \Omega[\ln(t)]^{\Gamma}$	Applicable for positive rudder angles $0^\circ \leq \alpha \leq -35^\circ$
		$\Omega = 0.778 \left(\frac{C}{d_{50}}\right)^{-3.366} \left(\frac{D_p}{d_{50}}\right)^{1.166} F_o^{4.494} (1 + \alpha)^{-2.804}$	
		$\Gamma = 0.624 \left(\frac{C}{d_{50}}\right)^{0.818} \left(\frac{D_p}{d_{50}}\right)^{-0.087} F_o^{-0.998} (1 + \alpha)^{-0.668}$	
Rudder and parallel wall		$\varepsilon_{m,t} = \Omega[\ln(t)]^{\Gamma}$	Applicable for negative rudder angles $-35^\circ \leq \alpha \leq 0^\circ$
		$\Omega = 38.121 \left(\frac{C}{d_{50}}\right)^{-3.033} \left(\frac{D_p}{d_{50}}\right)^{1.70} F_o^{1.845} (1 + \alpha)^{0.175}$	
		$\Gamma = 0.197 \left(\frac{C}{d_{50}}\right)^{0.9} \left(\frac{D_p}{d_{50}}\right)^{-0.232} F_o^{-0.303} (1 + \alpha)^{0.05}$	
	Ryan and Hamill (2011)	$\varepsilon_{m,t} = \Omega[\ln(t)]^{\Gamma}$	$4.87 \leq F_o \leq 11.2$ $19.4 \leq C/d_{50} \leq 85.53$ $39.1 \leq D_p/d_{50} \leq 172.37$ $1.52 \leq Y_w/D_p \leq 3.05$ $-35^\circ \leq \alpha \leq 0^\circ$
		$\Omega = 87.045 \left(\frac{C}{d_{50}}\right)^{-3.44} \left(\frac{Y_w}{D_p}\right)^{0.225} \left(\frac{D_p}{d_{50}}\right)^{2.035} F_o^{0.498} (1 + \alpha)^{-0.276}$	
		$\Gamma = 0.339 \left(\frac{C}{d_{50}}\right)^{1.249} \left(\frac{Y_w}{D_p}\right)^{-0.181} \left(\frac{D_p}{d_{50}}\right)^{-0.734} F_o^{-0.002} (1 + \alpha)^{-0.172}$	
Rudder and perpendicular wall	Ryan and Hamill (2013)	$\varepsilon_{m,t} = \Omega[\ln(t)]^{\Gamma}$	131-mm propeller with a sediment of $d_{50} = 3$ mm
		$\Omega = \left(\frac{X_w}{D_p}\right)^{1.829} F_o^{-0.954} (1 + \alpha)^{-2.22}$	
		$\Gamma = \left(\frac{X_w}{D_p}\right)^{-0.519} F_o^{0.632} (1 + \alpha)^{0.706}$	
		$\varepsilon_{m,t} = \Omega[\ln(t)]^{\Gamma}$	

TABLE IX. (Continued).

Confined case	Authors	Equations	Remark
		$\Omega = \left(\frac{X_w}{D_p}\right)^{-0.71} F_o^{1.77} (1 + \alpha)^{0.145}$	76-mm propeller with a
		$\Gamma = \left(\frac{X_w}{D_p}\right)^{0.473} F_o^{-0.36} (1 + \alpha)^{-0.002}$	sediment with $d_{50} = 1.15$ mm
Open quay slope	Wei <i>et al.</i> (2018)	$\frac{\varepsilon_{m,t}}{\varepsilon_{m,o}} = 1 - \exp[-0.023(\frac{U_o t}{X_t})^{0.37}]$	$0.5 < Z_b/D_p < 2.87$ $5.55 < F_o < 11.1$

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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