Numerical Investigation of Flow Resistance and Bed Shear Stress in Vegetation Canopies

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Abstract

Aquatic vegetation considerably modifies the flow in rivers, floodplains and coastal areas. Vegetation exerts drag forces that reduce flow velocities and can greatly alter the mean and turbulent velocity structure. By modifying sediment transport processes, vegetation can enhance sediment deposition, reduce erosion, and improve channel and bank stability in rivers. An understanding of the effects of vegetation on both flow resistance and sediment transport is essential for designing sustainable and effective vegetation restoration schemes. This thesis presents new insight into how emergent canopies modify hydrodynamic processes and resistance forces under both unidirectional and oscillatory flow conditions, and develops new formulations for (i) canopy drag coefficients and (ii) the bed shear stress on vegetated beds.

In the first part of the thesis, Large Eddy Simulations (LES) are used and existing experimental data are re-examined to investigate the fine-scale hydrodynamics within emergent canopies in current dominated flows with solid area fractions ranging from 0.016 to 0.25 at Reynolds numbers between 200 and 1340. The influences of three mechanisms in modifying canopy drag (blockage, sheltering, and delayed separation) were investigated. While the effects of sheltering and delayed separation were found to slightly reduce the drag of very sparse canopies, the blockage effect significantly increased the drag of denser canopies. An analogy between canopy flow and wall-confined flow around bluff bodies is used to identify an alternative reference velocity in the definition of the canopy drag coefficient; namely, the constricted cross-section velocity ($U_c$). Typical formulations for the drag coefficient of a single cylinder are shown to accurately predict the drag coefficient of staggered emergent canopies when $U_c$ is used as the reference velocity.

In the second part and for wave dominated flows, numerical simulations were performed over a wide range of Keulegan–Carpenter number ($KC$) ($2 < KC < 100$) while the Reynolds number was kept constant at 100. The significance of the blockage effect and sheltering effect in altering the drag force exerted on cylinders inside an array (relative to that on a single cylinder) were evaluated. The numerical results revealed that, similarly to current-dominated flows, the blockage effect is responsible for increasing the canopy drag coefficient in inertia-drag and drag-dominated regimes for medium to high density
canopies. In addition, similar to tandem cylinders in unidirectional flow, it was observed that canopy drag is considerably augmented for $KC > 20$ when the cylinders spacing is in the range of a critical spacing. Sheltering serves to slightly reduce the drag coefficient in the sparsest canopies considered.

In the third part of the thesis and to investigate the bed shear stresses in the presence of vegetated canopies, numerical simulations of flow through arrays of emergent canopies were conducted. The numerical results revealed extreme spatial variability in the bed shear stress that increase with canopy density, emphasising the errors associated with relying on bed shear stress observations from only a limited number of experimental measurement points within a canopy. In contrast to the case of bare beds, turbulent kinetic energy was shown not to be directly linked to bed shear stress in vegetated channels. A Linear Stress Model (LSM), which relies on defining a viscous sublayer to estimate the bed shear stress, was assessed and was found to be a reliable tool to predict bed shear stresses in canopies. Based on a balance between turbulent kinetic energy production in the canopy element wakes and the viscous dissipation near the bed, an enhanced model was employed to predict the height of the viscous sublayer which improved the accuracy of the LSM in estimating temporally and spatially averaged bed shear stress and extended its range of validity. Employment of the LSM with the proposed viscous sublayer height model showed excellent agreement with numerical and experimental estimates of friction velocities in the presence of canopies.

The results of this study improve the current understanding of the impact of the aquatic vegetation on its environment and can have significant implications for a wide range of environmental and ecological processes. In particular, the improved predictive capabilities for vegetation-induced flow resistance and sediment transport provided by this study enhance the understanding of the interaction between flow and natural vegetation, which is of fundamental importance for the development of sustainable river and coastal management strategies.
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Authorship declaration: co-authored publications

This thesis contains work that has been published or prepared for publication:

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- Student contribution to work:
  The set-up and execution of the numerical simulations, together with the post-processing and analysis of the results and writing the manuscript was my own work although carried out under the supervision of Ryan Lowe and Marco Ghisalberti.

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The set-up and execution of the numerical simulations, together with the post-processing and analysis of the results was my own work although carried out under the supervision of Ryan Lowe and Marco Ghisalberti. In addition, Marco Ghisalberti provided significant advice on model development.

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Chapter 1
Introduction

1.1 Significance of the research
Aquatic canopies that are formed by organisms such as coral, seagrass, kelp, and other macrophytes provide a wide range of ecosystem services in coastal regions. Marshes and mangroves reduce coastal erosion by damping waves and storm surge [Marjoribanks et al., 2014; Ozeren et al., 2014], and riparian vegetation enhances bank stability [Pollen-Bankhead and Simon, 2010]. Suspended sediments which are rich in organic material and nutrients deposit within and downstream of vegetation canopies, promoting the expansion of the vegetated regions [Gurnell, 2014; Zong and Nepf, 2010]. The uptake of nutrients and production of oxygen improve water quality [Wilcock et al., 1999]. The potential removal of nitrogen and phosphorous is so high that some researchers advocate widespread planting of aquatic vegetation in waterways [Mars et al., 1999]. Seagrasses form the foundation of many food webs [Green and Short, 2003], and vegetation within channels promotes biodiversity by creating different habitats with spatial heterogeneity flow speeds [Kemp et al., 2000]. Through the processes described above, aquatic vegetation provides ecosystem services with an estimated annual value of over $10 trillion worldwide [Costanza et al., 1997].

One of the most direct impacts of aquatic canopies on their environment is increasing the flow resistance. This additional flow resistance has been traditionally viewed as a problem as it can lead to a decrease in mean velocity and thus the ability of a river channel to achieve a given discharge [Järvelä, 2002; Marjoribanks et al., 2014]. Historically, in some cases the mechanical removal of vegetation has been proposed to reduce flow resistance in waterways and accelerate flow [Kouwen, 1992; Wu et al., 1999a]. However, the restoration of vegetation is also increasingly being considered as a natural approach
to manage flood risk by allowing channels in flood-suitable areas to return to their natural vegetated state which results in increasing the potential for overbank flows and, therefore, flood risk in urban areas downstream may decrease [Evans et al., 2008]. In addition, vegetation induced flow resistance influences other ecological services provided by vegetation such as uptake of nutrients, production of oxygen, carbon sequestration, etc. through altering the flow field. This further underlines the importance of understanding the mechanisms governing vegetation flow resistance and the need for a reliable method to predict channel resistance in the presence of vegetation. Generally, the flow resistance in vegetated channels is by convention parameterised by a drag coefficient $C_d$ that depends on both flow conditions and vegetation configuration [Tanino and Nepf, 2008a]. In spite of decades of research on this topic [Marjoribanks et al., 2014] and due to the limited understanding of complex physics inherent in relevant flow phenomena [Liu et al., 2008; Stoesser et al., 2010], difficulties still exist in the prediction of vegetation resistance due to the reliance on highly empirical vegetation drag formulations that often vary on a case-by-case basis.

Coastal vegetation has also long been recognized for its ability to attenuate wave energy in wave-exposed coastal environments. These coastal areas are typically of low elevation and relief, making land and infrastructure highly susceptible to inundation by storm surge and waves [Anderson et al., 2011]. The severity of this threat is exacerbated by sea level rise and a possible increase in storm frequency and strength due to climate change. There is a general consensus that wetlands, which often serve as transition zones between open water and dry land, could act as buffers and reduce storm surge and propagating waves substantially before they encounter coastal development. For example, wave attenuation in a coastal mangrove system has been shown to be 5–7.5 times greater than that due to bottom friction alone [Quartel et al., 2007]. Utilizing such outstanding capacities of coastal vegetation to dissipate waves is crucial to ecosystem management. This accounting is accomplished by incorporating simplified vegetation models into larger scale coastal models [Zeller et al., 2014]. An effective vegetation model must factor in essential vegetation parameters to accurately translate fluid velocities from a large-scale model into estimated wave attenuation. The primary way that wave attenuation by vegetation is incorporated into large-scale models is also through an effective drag coefficient $C_d$ [Dalrymple et al., 1984; Kobayashi et al., 1993; Mendez and
Losada, 2004], that in this case parameterises the wave-induced drag forces. Numerous drag coefficient formulations proposed by various researchers [Henry et al., 2015] yield highly scattered results which is partly due to the different experimental conditions that each formulation is based on. In addition, most of these studies suffered from a lack of comprehensive and reliable knowledge of fine-scale flow structure within canopies. This fact highlights the need for a drag coefficient formulation that is based on analysing the hydrodynamics of flow inside aquatic canopies and quantifying the in-canopy flow dissipation.

By increasing the flow resistance and reducing the bed shear stress, vegetation canopies create regions of sediment retention [Cotton et al., 2006], enhance channel stability and reduce bank erosion [Afzalimehr and Dey, 2009; Pollen-Bankhead and Simon, 2010]. The generally stabilizing effect of vegetation on soils has been the subject of many field and experimental studies attempting to explain channel stabilization, morphology and patterns in fluvial systems over a wide range of temporal and spatial scales [Gran and Paola, 2001; Nanson et al., 1995; Pollen and Simon, 2005; Tal et al., 2004]. Empirical studies have shown that vegetated channels are eroded more slowly, and are deeper and narrower than similar non-vegetated banks [Hey and Thorne, 1986; Hickin, 1984]. However, tools for quantifying the interactions between vegetation and sedimentation processes are necessary if we are to move away from general qualitative description of vegetation effects to more accurate prediction of rates of sediment transport. In addition, unlike open-channel conditions, the sediment transport pattern varies spatially at the stem scale over vegetated beds and we need to understand how this spatial variability may impact bulk transport rates and how best to parameterize it [Nepf, 2012]. In bare beds, the bed shear stress has been shown to indicate the rate of sediment transport [Wilcock, 1996]. It is not clear yet if sediment transport within vegetation can be estimated from bed shear stress alone, but it is reasonable to expect that the bed stress play an important role [Nepf, 2012]. Therefore, investigating bed shear stress in vegetated flows and developing reliable predictive formulations is relevant to a number of practical coastal and hydraulic engineering applications within natural aquatic systems.
1.2 Research aims

The overall objectives of this research are to understand the mechanisms responsible for canopy drag modification and to develop frameworks for predictive quantifications of canopy drag and bed shear stress. To address these objectives, three main research aims have been identified as described below:

1.2.1 Canopy drag in current dominated flows

Most previous studies on canopy drag in current dominated flows have observed an increase in canopy drag as the canopy solid fraction or density $\lambda$ increases (e.g. Figure 1-1) [Cheng and Nguyen, 2011; Ishikawa et al., 2000; Kothyari et al., 2009; Stoesser et al., 2010; Tanino and Nepf, 2008a]. However, none of these studies have provided any physical mechanism responsible for this drag enhancement. Some studies have tried to quantify canopy drag by proposing empirical drag formulations that vary with flow conditions and canopy density [Cheng and Nguyen, 2011; Tanino and Nepf, 2008a]. While these formulations can be useful in practice, they do not provide insight into the hydrodynamic processes responsible for the observed trends. Specifically, one of the challenges in quantifying the canopy drag is choosing the proper reference velocity for normalizing the drag force and calculating $C_d$. A proper reference velocity should be based on a physically appropriate flow velocity that directly governs the generated drag forces. In Chapter 2, Large Eddy Simulations are employed to investigate the different mechanisms (namely sheltering effect, delayed separation and blockage effect) that could potentially be responsible for modifying the canopy drag coefficient relative to that of a single cylinder in unidirectional flow. The relative importance of these mechanisms in determining canopy drag and also the performance of alternative reference velocities in predicting canopy drag coefficient is then assessed using the numerical results.
1.2.2 Canopy drag in wave dominated flows

The capacity of coastal vegetation to act as a natural form of coastal protection and attenuate incident waves is usually parametrized using a drag coefficient, $C_d$. Accurate quantification of $C_d$ significantly relies on understanding the small-scale interactions between vegetation stems and fluid motion that govern the rate at which wave energy is attenuated (dissipated) by vegetation. In Chapter 3, oscillatory flow through emergent canopies which is closely related to wave dominated canopy flows is numerically studied. Canopy drag coefficients across a wide range of flow conditions are measured and hydrodynamic mechanisms that govern the drag forces exerted by the canopy are investigated. The numerical results are also used for developing new predictive formulations for specifying canopy drag coefficients in wave dominated flows.

1.2.3 Providing predictive formulations for bed shear stresses in the presence of canopies

Different methods can be used to estimate the sediment transport over bare beds [Biron et al., 2004]. However, none of these methods are applicable to vegetated channels, partly due to the impact of vegetation on the velocity profile and turbulence production. Recently, a Linear Stress Model (LSM) has been proposed to estimate the bed shear stress over vegetated beds which is believed to significantly affect the sediment transport [Yang
et al., 2015]. In Chapter 4, the present numerical model results are used to evaluate and improve the performance of the LSM in predicting vegetated bed shear stress. In addition, the spatial variability of bed shear stress as function of canopy density is investigated. The overall result is the development of a new model that can be used to predict bed shear stresses in the presence of canopies as a function of the flow conditions and canopy geometry parameters.

1.3 Outline of the thesis

The contents of this thesis are arranged as a compilation of journal papers with the main body of work presented in Chapters 2 to 4, which corresponds to three journal papers. Chapter 2 investigates the canopy drag modification mechanisms for unidirectional flow and proposes a predictive formulation for canopy drag based on an analogy between canopy flow and wall-confined flow. In Chapter 3, the canopy drag in oscillatory flow and relevant mechanisms are analysed and depending on flow regime, the appropriate formulations are proposed to estimate the canopy drag coefficient. Chapter 4 illustrates the spatial variability of bed shear stress over vegetated beds and propose a new formulation to improve the accuracy of Liner Stress Model to predict bed shear stress. Finally, Chapter 5 presents a brief summary of the thesis conclusions regarding the improved understanding of canopy flow structures and induced forces.
Chapter 2

A new model for predicting the drag exerted by vegetation canopies

2.1 Introduction

Aquatic vegetation substantially alters the hydrodynamics in streams, rivers, floodplains and the coastal ocean. This vegetation exerts drag forces that reduce flow velocities near the bed [Bennett et al., 2008; Tsujimoto, 1999] and can greatly modify the mean and turbulent velocity structure [Liu et al., 2008; Nezu and Rodi, 1986; Stoesser et al., 2010]. Moreover, through a reduction in bed shear stress in submerged canopies, aquatic vegetation is well-known to reduce sediment erosion and suspended sediment transport [López and García, 1998; Vargas-Luna et al., 2015]. The extent to which vegetation modifies the flow and, in turn, processes such as sediment transport, is largely determined by the cumulative drag forces exerted by the vegetation on the water column [Tanino and Nepf, 2008a].

A number of approaches have been adopted to quantify the drag exerted by stands of aquatic vegetation (herein referred to as ‘canopies’). Initial studies of aquatic canopy flows treated vegetation resistance using conventional bed stress formulae, e.g. the Darcy-Weisbach, Chezy and Manning equations, to model the flow resistance [Arcement et al., 1988; Kadlec, 1990; Petryk and Bosmajian, 1975; Thompson and Roberson, 1976]. While these conventional approaches are straightforward and readily applied, they typically require significant calibration with empirical friction coefficients. Moreover,

---

these treatments assume that energy losses occur via ‘bed stresses’, rather than the distributed drag forces that characterize a canopy [Marjoribanks et al., 2014]. A more physically-correct approach for quantifying vegetative flow resistance is based on the definition of a bulk canopy drag coefficient ($C_d$), which relates the time-averaged drag force on canopy elements ($F_d$) to the characteristic element width ($d$) and height ($h$), the fluid density ($\rho$) and a reference velocity ($U_{rel}$):

$$C_d = \frac{F_d}{\frac{1}{2} \rho d h U_{rel}^2}$$  \hspace{1cm} (2-1)

The application of equation (2-1) is complicated by the fact that $C_d$ is known to significantly vary with canopy density (indicated here by the solid fraction, $\lambda$), the element Reynolds number ($Re = U_{rel} d / \nu$) and element morphology [Nepf, 2011b]. Experimental and numerical studies of cylinder arrays (representing vegetation canopies) have shown that the trends in the variation of bulk drag coefficients with Reynolds number closely follow that of a single cylinder in isolation [Cheng and Nguyen, 2011; Ishikawa et al., 2000; Kothyari et al., 2009; Stoesser et al., 2010; Tanino and Nepf, 2008a]. However, the effect of canopy density is much more poorly understood, with recent studies demonstrating seemingly contradictory results, i.e. observations that $C_d$ can both increase [Stoesser et al., 2010; Tanino and Nepf, 2008a] and decrease [Lee et al., 2004; Nepf, 1999] with increasing density.

The development of robust formulations to predict canopy drag coefficients is hampered by the several potential choices of reference velocity in equation (2-1) that can be used to define both the drag coefficient and Reynolds number. Ultimately, the reference velocity should be based on a physically-appropriate flow velocity that directly governs the generated drag forces. The reference velocity has been taken as both the bulk channel velocity ($U_b = Q / Wh$ where $Q$ is the channel discharge, $W$ is the channel width and $h$ is the flow depth) [Ishikawa et al., 2000; Lee et al., 2004; Wu et al., 1999b] and the pore velocity ($U_p$) [Cheng and Nguyen, 2011; Kothyari et al., 2009; Tanino and Nepf, 2008a; Zhao et al., 2013], the latter of which represents the spatially-averaged flow velocity in the spaces between canopy elements. In emergent canopies, these two velocity scales are related by $U_p = U_b / (1 - \lambda)$. As the pore velocity is more indicative of the velocity that would interact with the canopy elements, one might expect that drag coefficients defined using the pore velocity (denoted $C_{dp}$) to closely follow the drag coefficient of a single
cylinder. However, at all values of $Re_p$ (the Reynolds number based on the pore velocity, $U_p d / v$), $C_{d,p}$ is not equivalent to the single cylinder drag coefficient and has typically been observed to increase with canopy density [Kothyari et al., 2009; Stoesser et al., 2010; Tanino and Nepf, 2008a]. This increase is even more pronounced when the bulk velocity is used to define the drag coefficient (denoted $C_{d,b}$). That is, neither the pore nor the bulk velocities accurately represent the velocity that determines drag forces on canopy elements.

Quantifying the mechanisms responsible for variation of canopy drag forces requires high-resolution flow field data throughout a canopy array. Experimental studies typically face the constraints of having a limited number of velocity measurements within the canopy and, in some cases, requiring the removal of canopy elements to allow velocity probe access [Luhar et al., 2010; Nepf, 1999; Pujol et al., 2013]. This adds significant uncertainty to estimates of spatially-averaged flow properties. Moreover, in the majority of experimental studies, the total drag force exerted by the canopy has been estimated from measured energy slopes [James et al., 2004; Kothyari et al., 2009; Liu et al., 2008; Tanino and Nepf, 2008a] (which may contain substantial uncertainty), rather than from direct measurement of hydrodynamic forces exerted on canopy elements. In contrast, high-resolution computational fluid dynamics (CFD) simulations can provide detailed turbulent flow field information and also provide direct measurements of canopy element drag forces. In recent decades, Large Eddy Simulation (LES) has proven to be a reliable tool for modelling complex flow around bluff bodies where large-scale periodicity is present due to vortex shedding from the solid bodies [Breuer, 1998; 2000; Sohankar et al., 2000]. LES has also been successfully used in modelling flow thorough aquatic canopies [Cui and Neary, 2008; Stoesser et al., 2010; Stoesser et al., 2009].

In this study, we employ LES and analyze previous experimental data sets to investigate the drag forces and flow structure within emergent canopies, modelled here as staggered arrays of rigid cylinders. The focus is on elucidating the hydrodynamic mechanisms responsible for drag modification within canopies and the development of new predictive formulations for specifying bulk canopy drag coefficients. This will allow the development of an improved understanding of the dynamics of large-scale flows through vegetation canopies.
2.2 Theoretical framework

As summarized above, previous studies have shown a contradictory dependence of the canopy drag coefficient on canopy density. While some studies indicate that the canopy drag coefficient decreases with higher density, and have attributed this trend to the reduction in flow velocities to which downstream elements are exposed (the so-called 'sheltering effect') [Nepf, 1999], many other studies conclude that the canopy drag coefficient increases with density; albeit without explaining the specific hydrodynamic mechanisms responsible for this [Cheng and Nguyen, 2011; Ishikawa et al., 2000; Kothyari et al., 2009; Stoesser et al., 2010; Tanino and Nepf, 2008a]. In this section, a brief overview is presented of some of the mechanisms that could potentially be responsible for modifying the canopy drag coefficient relative to that of a single cylinder. The relative importance of these mechanisms in determining canopy drag is then assessed in the results that follow.

2.2.1 Sheltering effect

The term ‘sheltering effect’ describes the condition where two bluff bodies are situated such that one body is located in the wake region of the upstream body [Raupach, 1992]. The downstream body experiences a lower incident velocity than the upstream body (i.e. through ‘sheltering’), which results in a lower drag force. This effect becomes more significant as the spacing between the bodies decreases [Sumner, 2010; Zdravkovich, 1987]. In the canopy context, sheltering occurs when the velocity approaching a canopy element is less than the spatially-averaged value, $U_p$, due to the influence of upstream elements. The sheltering effect can be of relevance to a canopy flow, but will be highly dependent upon the arrangement of canopy elements.

A model developed for calculating the drag coefficient of each cylinder within random and staggered arrays of cylinders based on the proximity of the nearest upstream cylinder [Nepf, 1999] shows how the canopy drag coefficient ($C_{d,p}$) can decrease by a factor of four as canopy density increases (from $\lambda = 0.001$ to 0.24) [Nepf, 1999]. This result is likely valid only for relatively sparse canopies and thus implies it should not necessarily be extended to denser canopies, given that recent observations indicate that canopy drag coefficients can significantly increase as canopy density increases; however, we assess the role of the sheltering effect across a wide range of canopy densities in this study.
2.2.2 Delayed separation
The separation angle ($\theta_s$) of the flow around a single cylinder can be a major factor in controlling drag coefficients at moderate to high Reynolds numbers ($Re > 100$), where form drag dominates [Zdravkovich, 1997]. In an array of cylinders, it is possible for the mean separation angle to exceed that of a single cylinder in isolation for two reasons: (1) turbulent fluctuations in the wakes of upstream elements introduce additional kinetic energy into the boundary layer of each element that may delay separation [Nepf, 1999; Zukauskas, 1972], and (2) the flow is accelerated through constrictions created by canopy elements, keeping the near-cylinder velocity positive for longer in the face of the adverse pressure gradient, which may also serve to delay separation. This delayed flow separation would tend to decrease the drag coefficient of a canopy, relative to a single cylinder. The variation of separation angle with canopy density and Reynolds number, and the subsequent impact on drag, will be investigated here.

2.2.3 Blockage effect
A flow past a bluff body that is confined by lateral walls is subject to what is commonly referred to as the ‘blockage effect’ [Maskell, 1963]. The blockage effect alters the flow around a bluff body in several ways [Zdravkovich, 2003]: (1) The presence of the body reduces the cross-sectional area locally, which results in a local increase in the velocity around the body, and (2) the side walls hinder the widening of the wake, while the increased velocity outside the wake reduces the pressure within it. Wall-confined bodies have thus been shown to have significantly different wake characteristics to unconfined bodies. In particular, the blockage effect tends to significantly increase the drag coefficient ($C_{d,b}$) of the bluff body at a given bulk velocity $U_b$, due to the dominant effect of the reduced wake pressure (see Zdravkovich [2003] for a detailed review). Likewise, the blockage effect also increases the Strouhal number ($St_b = f d / U_b$, where $f$ is the vortex shedding frequency) of vortex shedding in the wake. This suggests that the bulk velocity may not be the optimal reference velocity for describing drag and wake structures under confined flow conditions [Zdravkovich, 2003].

To describe this increase in cylinder drag coefficient $C_{d,b}$ with blockage ratio ($d/W$, where $W$ is the spacing between the walls), some authors tried to replace $U_b$ with alternative reference velocities such as separation velocity $U_s$, which represents the flow velocity at the boundary of the wake region [Roshko, 1954], and the constricted cross-section
velocity $U_c$, which is the spatially-averaged velocity over the constricted cross section between cylinders [Ng, 1972]. Maskell [1963] applied free streamline theory to suggest that the value of $C_{d,b}/(U_s/U_b)^2$ does not vary with blockage ratio. Here, the separation velocity $U_s$ is defined as

$$U_s = U_b \sqrt{1 - C_{pb}}$$  \hspace{1cm} (2-2)

where $C_{pb}$ is the base pressure coefficient and is calculated by averaging the pressure coefficient ($c_p = (p - p_\infty)/0.5\rho U_b^2$ where $p$ is the local time-averaged pressure and $p_\infty$ is the pressure of the undisturbed flow) over the cylinder flow separated region. Although $U_s$ is assumed to be the flow velocity at the edge of the wake region [Roshko, 1954], it is typically calculated using equation (2-2) rather than being measured directly. Since pressure (form) drag constitutes the major portion of the drag force at medium to high Reynolds numbers, a dependence of drag force on $C_{pb}$, and consequently on $U_s$, is logical. However, as a velocity scale that is simply an indirect measure of form drag, $U_s$ has little predictive utility. On the other hand, it has been shown that, at least for moderate blockage ratios, the ratio of separation velocity $U_s$ to constricted cross-section velocity $U_c$ is also approximately constant with blockage ratio [Ng, 1972] (refer to Figure 2-1 for definitions of the different velocities). This is explained by the fact that, as previously mentioned, the wake pressure decreases (and thus form drag increases) with increasing $U_c$. Unlike $U_s$, the value of $U_c$ can be readily calculated from conservation of mass if both $U_b$ and the blockage ratio are known. The parabolic increase in conventional $C_{d,b}$ with blockage ratio is thus replaced by $C_{d,c}$ and $C_{d,s}$ (drag coefficients based on $U_c$ and $U_s$, respectively), which tend to be invariant with blockage ratio [Ramamurthy and Lee, 1973]. That is, both the separation velocity $U_s$ and constricted cross-section velocity $U_c$ are physically-reasonable reference velocities to normalize the drag force of wall-confined cylinders.

While a wall-confined flow past a bluff body is not entirely identical to flow through an array of cylinders, there are clear analogies. It is reasonable to hypothesize that the blockage that occurs at the constricted cross-sections of canopies where flow is confined between laterally adjacent cylinders is similar to the blockage observed in flow past a cylinder between parallel walls (Figure 2-1). Schematically, Figure 2-1 shows the constricted cross-section velocity $U_c$ and the bulk velocity $U_b$ in both wall-confined and
canopy flows indicating how the reduction of flow cross-section increases the local velocity. Therefore, the constricted cross-section velocity and separation velocity can be evaluated as reference velocities for normalizing the canopy drag force. The constricted cross-section velocity for an array of circular cylinders can be readily obtained through conservation of mass:

$$U_c = \frac{1 - \lambda}{1 - \frac{2\lambda}{\sqrt{\pi}}} U_p = \frac{1}{1 - \frac{2\lambda}{\sqrt{\pi}}} U_b$$

(2-3)

In this study, we assess how the use of $U_c$ and $U_s$ as reference velocities can improve predictions of canopy drag coefficients.

### 2.3 Numerical modelling

#### 2.3.1 Governing equations and numerical methods

In LES, the spatially-filtered, three-dimensional, time-dependent Navier-Stokes equations are solved numerically for all motions with a scale larger than the mesh size of the numerical grid, while smaller-scale motions are simulated using a sub-grid scale (SGS) model. The filtered equations in tensor notation are:

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_i}{\partial x_j} \tilde{u}_j = \frac{1}{\rho} \frac{\partial \tilde{\rho}}{\partial x_i} + \frac{\partial (2\nu S_{ij})}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}$$

(2-5)

Figure 2-1 Analogy between (a) a wall-confined flow and (b) a canopy flow, with blockage by laterally-adjacent cylinders. The bulk velocity $U_b$ (the spatially-averaged velocity over the channel cross section) and constricted cross-section velocity $U_c$ (the spatially-averaged velocity over the constricted cross sections) are shown along with the spatial variation of velocity in the corresponding cross sections.
where \( i \) and \( j \) vary from 1 to 3. \( u_i \) are the velocity vector components (\( u_1 \) and \( u_2 \) are in the streamwise and spanwise directions, respectively), \( p \) is the pressure, \( \rho \) is the fluid density and \( \nu \) is the kinematic molecular viscosity. The overbar denotes spatially-filtered quantities. \( \bar{S}_{ij} \) is the rate of strain of the resolved flow field and has the form

\[
\bar{S}_{ij} = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right)
\]

The turbulence closure model then predicts \( \tau_{ij} \) based on the resolved-scale velocity \( \bar{u}_j \). In this study, a standard Smagorinsky model was adopted:

\[
\tau_{ij} = -2\nu_t \bar{S}_{ij} + \frac{2}{3} k \delta_{ij}
\]

[Smagorinsky, 1963] where \( \delta_{ij} \) is the Kronecker delta and \( \nu_t \) is the SGS eddy viscosity. \( k \) represents the SGS kinetic energy for the Smagorinsky model and is given by \( k = 2(c_k/c_e)^2 \Delta^2 (\bar{S}_{ij} - (1/3)\bar{S}_{kk})^2 \), where \( \Delta \) is the filter width and values of \( c_e = 1.048 \) and \( c_k = 0.05 \) are taken here (\( c_e \) and \( c_k \) relate to classical Smagorinsky constant as \( C_s = (c_k^2/c_e)^{1/4} \) which yields \( C_s = 0.104 \) [Lysenko et al., 2012]). All simulations were carried out in OpenFOAM version 2.3.0, which has been widely used for modelling flow around bluff bodies [Lloyd and James, 2015; Lysenko et al., 2012; 2014; Sidebottom et al., 2015].

The incompressible solver pimpleFoam was used, which has the merged PISO-SIMPLE algorithm implementation. In addition, a dynamic adjustable time-stepping technique was used to guarantee a local Courant number less than 0.5.

### 2.3.2 Model configuration

Due to the complexity of modelling the geometry of real natural canopies, it is common practice to approximate aquatic canopies as arrays of rigid circular cylinders [Dean, 1978; Ghisalberti and Schlosser, 2013; Hu et al., 2014; Lowe et al., 2005; Nepf, 1999; Tanino and Nepf, 2008a]. In this study, emergent aquatic canopies were modelled as a staggered array of cylinders. Four emergent cylinders were included within the computational domain and to mimic an infinite array of cylinders, cyclic boundary conditions were imposed in both the streamwise and spanwise directions. A mean pressure gradient was imposed in the streamwise direction to drive the flow at the specified velocity. At the bed and cylinder surfaces, a no-slip condition was applied. To avoid the complexity of modelling the free surface, the upper boundary of the domain was treated as a frictionless rigid lid. The array densities (\( \lambda \)) were determined by adjusting the cylinder spacing, \( S \).
In this study, six array densities were modelled: \( \lambda = 0.016, 0.04, 0.08, 0.12, 0.20 \) and 0.25 (Table 2-1). As \( S/d = 1/\sqrt{2\lambda/\pi} \), this corresponds to \( S/d = 10, 6.3, 4.4, 3.6, 2.8 \) and 2.5, respectively. These values of \( \lambda \) were chosen to cover the densities of a wide range of aquatic vegetation from typical marsh grasses [Nepf, 2011b] to mangroves [Mazda et al., 1997]. The water depth in all cases was \( 10d \), with the exception of the lowest density array (\( \lambda = 0.016 \)), where the depth was \( 10.8d \) to match the experimental conditions of Liu et al. [2008] (whose results are used to validate the model).

The grid topology consisted of four sets of cells (one for each cylinder), with each set consisting of an O-grid block around the cylinder and a Cartesian H-grid block in the far field (Figure 2-2b). The H-grid is uniform in the horizontal plane but the size of the O-grid cells was decreased as each cylinder is approached. In the vertical direction, the cell sizes were decreased towards the bed. The details of the grid for each array density are summarized in Table 2-1. In all simulations, the cell sizes adjacent to solid surfaces (i.e. around each cylinder and at the bed) were chosen such that the maximum dimensionless...
wall distance of the first cell \( n^+ = n u_* / \nu \), where \( u_* \) denotes the wall friction velocity and \( n \) the normal distance from the wall) was kept below 1.

The simulations were allowed to run for at least 15 flow-through periods to reach a fully-developed condition before any data was collected. Time-averaging of flow parameters was performed over a period of 45 flow-through cycles. Simulations were carried out at up to four Reynolds numbers \((Re_p = 200, 500, 1000 \) and 1340\)) for each canopy density (Table 2-1). These Reynolds numbers are typical of those in flows through aquatic vegetation \([Nepf, 2011b]\). In addition, simulations of flow around a single cylinder at the same Reynolds numbers were conducted for comparison with the canopy flow results.

\[
c_p = 1 - \frac{p_{\theta=0} - p}{0.5 \rho U_p^2}
\]  

in which the angle \( \theta \) is measured from the upstream stagnation point. The flow separation angle \((\theta_s)\) was determined as the point along the cylinder where the surface shear stress changed sign \([Kundu et al., 2012]\). Drag coefficients and Reynolds numbers were defined using four distinct reference velocities, namely the bulk velocity \( U_b \), the pore velocity \( U_p \), the constricted cross-section velocity \( U_c \) and the separation velocity \( U_s \) (refer to Figure 2-1). The corresponding drag coefficients and Reynolds numbers are summarized in Table 2-2. The form and viscous contributions to the drag force exerted on each cylinder were determined through integrating the pressure and shear stress distributions over the surface of the cylinders. The distribution of drag force along the vertical length of the cylinders was almost uniform with small deviations in a region near the bed. The drag coefficients presented here are determined from the total drag force on the cylinders. We also note that there is negligible variation between the drag forces exerted on the four cylinders in the staggered array; so, for any given Reynolds number and canopy density, the results for any one of the canopy elements will be presented.

<table>
<thead>
<tr>
<th>Reference velocity</th>
<th>Symbol</th>
<th>Reynolds number</th>
<th>Drag coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pore velocity</td>
<td>( U_p )</td>
<td>( Re_p )</td>
<td>( C_{d,p} )</td>
</tr>
<tr>
<td>Bulk velocity</td>
<td>( U_b )</td>
<td>( Re_b )</td>
<td>( C_{d,b} )</td>
</tr>
<tr>
<td>Separation velocity</td>
<td>( U_s )</td>
<td>( Re_s )</td>
<td>( C_{d,s} )</td>
</tr>
<tr>
<td>Constricted cross-section velocity</td>
<td>( U_c )</td>
<td>( Re_c )</td>
<td>( C_{d,c} )</td>
</tr>
</tbody>
</table>
2.3.3 Model validation

For validation of the model, numerical results were compared to the experimental results of mean and turbulent velocity in emergent cylinder arrays of Liu et al. [2008] ($\lambda = 0.016$ and $Re_p = 1340$). To evaluate the grid-size independence of the numerical solution, results for both the default computational grid described above and a finer grid (with resolution increased by approximately 40%) were also compared. There is excellent agreement between model and experimental profiles of time-averaged streamwise velocity and turbulence intensity (the ratio of the root-mean-square of the streamwise velocity fluctuations, $u'_1$, to $U_p$) at five different locations within the array (Figure 2-3).

The flow velocity between the cylinders (Vertical 4) is considerably higher than that immediately upstream (Verticals 1 and 3) or downstream (Verticals 2 and 5) of the cylinders. In addition, since the cylinder geometry is uniform over depth, the streamwise velocity and turbulence intensity are both almost constant in the vertical (consistent with

![Figure 2-3](image-url)

Figure 2-3 (a) Comparison of model results with experimental results from Liu et al. [2008]. Time-averaged streamwise velocity (black) and turbulence intensity (red) profiles are presented at five locations (shown in (b)) for $\lambda=0.016$ and $Re_p=1340$. The angular brackets <> denote time-averaged variables.
The main discrepancy between the model and experiment can be seen in mean velocity profiles at Vertical 2, which is located just behind a cylinder and therefore in a region with pronounced velocity gradients, making the co-location of the experimental data and model results difficult. The increase in experimental values of streamwise velocity just below the water surface at Vertical 2 is most likely due to a local free surface depression (as also described by Stoesser et al. [2010]) that is not captured by the LES simulations that employ a rigid, free-slip water surface. Finally, differences between numerical results generated with the two grid resolutions are negligible, indicating grid-size independent solutions.

To further validate the model configuration, the pore-velocity-based drag coefficients ($C_{d,p}$) of the model were compared to previously-reported drag coefficients (Table 2-3). There is very good agreement (less than 5% discrepancy) between the present study results and these previous studies.

### 2.4 Results

#### 2.4.1 Impact of canopy density on key parameters affecting the drag

##### 2.4.1.1 Spatial velocity structure

The spatial structure of the temporally- and vertically-averaged streamwise velocity, and its variation with canopy density, are shown in Figure 2-4. As the canopy density increases, the flow channeled between cylinders follows an increasingly tortuous path. Furthermore, the cylinder wakes become constrained by neighboring cylinders in both the streamwise and spanwise directions, such that the wake length and width vary inversely with canopy density. The difference between maximum and minimum local velocities can also be seen to increase significantly with canopy density. This increase in spatial velocity variance has also been observed in flow through random cylinder arrays [White and Nepf, 2003].
2.4.1.2 Strouhal Number

The frequency of vortex shedding around a cylinder depends on several parameters, including the width of the near-wake region; the narrower the wake, the greater the shedding frequency [Zdravkovich, 1997]. Figure 2-4 shows that the wake width decreases at higher canopy densities. Accordingly, the Strouhal number \( (St_p = f d / U_p) \) increases with canopy density (Figure 2-5b), in agreement with, e.g., Koch and Ladd [1997]. This trend is also consistent with observations of increasing Strouhal number with blockage ratio in wall-confined flow around bluff bodies [Mabuchi and Hiwada, 1987; Mitry, 1977; Toebes and Ramamurthy, 1970], as we discuss further below. At lower densities \( (\lambda \leq 0.12) \), the variation of Strouhal number with array density is not substantial, with \( St_p \) differing little from that of a single cylinder (Figure 2-5a). However, there is a large increase in \( St_p \) as \( \lambda \) increases from 0.12 to 0.20.

![Figure 2-4 Contours of the dimensionless temporally- and vertically-averaged stream-wise velocity \( \langle u_1 \rangle / U_p \) (upper row) and streamlines (lower row) at three canopy densities: (a) and (d) \( \lambda = 0.016 \); (b) and (e) \( \lambda = 0.12 \); (c) and (f) \( \lambda = 0.25 \) \( (Re_p=1340) \). Contours in (b) and (c) are presented by repeating the computational domain (of four cylinders) to keep the dimensions of each of the three panels in the upper row consistent.](image)
2.4.1.3 Pressure Coefficient

As the canopy density increases for a given bulk velocity, the normalized streamwise velocities \( \langle u_1 \rangle / U_p \) are greater in the constricted spaces between cylinders due to the reduction in local cross-sectional area (Figure 2-4). This enhanced flow velocity outside the cylinder wake reduces the pressure inside the wake (the blockage effect discussed in Section 2.2.3). This reduction is further illustrated in Figure 2-6a, where the pressure coefficient \( c_p \) generally decreases with increasing canopy density. However, there is a slight increase in the pressure coefficient towards the rear of the cylinder \( \theta \geq 130^\circ \) for the very dense canopies with \( \lambda = 0.20 \) and 0.25; this is due to the cylinders being so closely-spaced that the wake pressure is augmented by the high-pressure stagnation region of the cylinder immediately downstream. The other exception is the sparsest canopy \( (\lambda = 0.016) \), whose pressure coefficient is greater than that of a single cylinder. The wake of the upstream cylinder reduces the impact velocity so the magnitude of base pressure, and consequently the form drag, in this canopy is lower than a single cylinder for the same Reynolds number; this is the sheltering effect discussed in Section 2.2.12.2.1. This overcomes the blockage effects seen at higher densities, as the velocity increase between the cylinders is comparatively weak in such a sparse canopy (Figure 2-4). The pressure coefficients did not vary significantly with Reynolds number over the range studied here (Figure 2-6b).
Flow Separation

The separation angle $\theta_s$ (measured from the upstream stagnation point) of a single cylinder is known to decrease with increasing Reynolds number over the range considered here [Pruppacher et al., 1970], due to the widening of the wake region [Zdravkovich, 1997]. The model results for the single cylinder confirm this trend (Figure 2-7a). For the cylinder arrays, a similar trend with Reynolds number is also observed, as well as an increase in the separation angle with canopy density (Figure 2-7b). There can be two possible reasons for this delayed separation. Firstly, increased turbulence in dense canopies enhances the mixing of momentum through the cylinder boundary layer (Figure 2-7c). Secondly, as the canopy density increases, so too does the velocity between adjacent cylinders (i.e $U_c$ is enhanced, Figure 2-7d), which also serves to delay separation through increasing boundary layer momentum (see Section 2.2.2).
2.4.2 Assessing the influence of reference velocities used to define canopy drag coefficients

Both the bulk velocity \( U_b \) and pore velocity \( U_p \) are commonly used to normalize the canopy drag force (with resultant drag coefficients \( C_{d,b} \) and \( C_{d,p} \), respectively; Table 2-2). The values of \( C_{d,b} \) and \( C_{d,p} \) are plotted as a function of Reynolds number across the range of canopy densities (Figure 2-8). Noting that for a single cylinder \( U_b = U_p \), and consequently \( C_{d,b} = C_{d,p} \), the variation of drag coefficient of a single cylinder with Reynolds number, based on the well-established formula proposed by White [1991]:

\[
C_{d,b \ (or \ p)} = 1 + 10Re_b^{-2/3} ,
\]

(2-9)

Figure 2-7 Variation of the angle of separation (\( \theta_s \)) with (a) Reynolds number (\( Re \)), (b) canopy density (\( \lambda \)), (c) spatially-averaged turbulence intensity (\( u_1/U_p \)), and (d) \( U_c/U_p \). The angle of separation increases with canopy density, possibly due to both the increased turbulence intensity and the enhanced velocity in the vicinity of canopy elements.
is plotted for comparison. The weak trend of decreasing drag coefficient with Reynolds number for a single cylinder is also observed with the cylinder arrays. However, $C_{d,b}$ and $C_{d,p}$ vary much more strongly with canopy density (Figure 2-8). This enhancement of the drag coefficients is more pronounced for $C_{d,b}$ due to the increase in the ratio $U_b/U_p$ with canopy density. Most importantly, it is not possible to collapse the canopy drag coefficients on the single cylinder curve through the use of either of these common reference velocities. The mechanisms responsible for this lack of collapse are discussed in further detail in Section 2.5, guided by the three potential mechanisms of drag modification described in Section 2.2.

2.5 Discussion

2.5.1 Mechanisms of drag modification within a canopy

The drag forces exerted by vegetation canopies have been observed here to vary significantly with canopy density, consistent with previous experimental observations. However, the physical mechanisms responsible for this variation have yet to be fully explained. Here we assess how different mechanisms modify canopy drag forces, specifically examining the role of sheltering, delayed separation and the blockage effect.

The results presented in Section 2.4 indicate that delayed separation and sheltering are generally ineffective in modifying canopy drag, except at very low densities. This is based on the fact that canopy drag coefficients are clearly enhanced (relative to that of a single cylinder) at high densities, whereas the mechanisms of delayed separation and sheltering both act to reduce drag. It is evident that separation can be significantly delayed in a canopy (Figure 2-7) and that one might expect the overall drag to be reduced. However, the delayed separation that results from increasing canopy density is also associated with a considerable decrease in wake pressure due to the blockage effect (Figure 2-6a). The blockage effect is dominant such that the drag coefficient is clearly enhanced as the canopy density increases (Figure 2-8). The effects of sheltering and delayed separation, which serve to decrease the drag force, are noticeable only in the sparsest canopy ($\lambda = 0.016$) where the drag force is reduced (as indicated by the increased wake pressure in Figure 2-6a). In such a sparse canopy, the interactions between neighboring cylinders are weak, such that the blockage effect becomes comparatively less significant. Finally, it is important to note that the sheltering effect is highly arrangement-specific and its
significance in a non-staggered array depends strongly on the relative positions of cylinders (this is discussed further in Section 2.5.3).

The results of this study indicate that flows through canopy arrays have many features in common with a wall-confined flow past a single cylinder. In a wall-confined flow, an increase in the blockage ratio, $d/W$, can result in a significant decrease in the cylinder base pressure coefficient $C_{pb}$ [Mabuchi and Hiwada, 1987; Modi and El-Sherbiny, 1971; Singha and Sinhamahapatra, 2010]. This is similar to the trend observed for canopy flows, where the pressure coefficient decreased significantly for the denser canopies (Figure 2-6). Moreover, several studies have shown that the Strouhal number $St_b (= f d/U_b)$ increases with blockage ratio [Mabuchi and Hiwada, 1987; Mitry, 1977; Toebes and Ramamurthy, 1970]; a similar dependence of Strouhal number $St_p$ on canopy density was likewise observed (Figure 2-5). As shown in Figure 2-7, an increasing canopy density delays the flow separation, also consistent with wall-confined flow, where the separation point moves downstream as the blockage ratio increases [Chakraborty et al., 2004; Mitry, 1977; Singha and Sinhamahapatra, 2010]. Finally, it has been shown that the drag coefficient for a single cylinder is strongly enhanced due to the presence of the confining walls [Chakraborty et al., 2004; Modi and El-Sherbiny, 1971; Ramamurthy and Lee, 1973]. For example, in extreme cases where $d/W = 0.8$, the drag coefficient $C_{d,b}$ has been observed to increase to as much as 20 times the unconfined value [Hiwada and Mabuchi,
[100x795]Chapter 2

In a similar fashion, the canopy drag coefficients substantially increase with canopy density (Figure 2-8).

Thus, by analogy to a wall-confined flow, we can explain the drag enhancement observed within canopies. Guided by this analogy, in the following section we develop a new model for predicting canopy drag coefficients that accounts for blockage effects and compare these predictions to the model results.

### 2.5.2 A new model for canopy drag

To predict drag enhancement for a wall-confined flow, it is customary to employ alternative reference velocities, such as the separation velocity $U_s$ and constricted cross-section velocity $U_c$, rather than the bulk flow velocity $U_b$. By analogy, we assess whether these alternative reference velocities can also be employed to improve predictions of the canopy drag force. Here, the separation velocity is calculated using equation (2-2), where $C_{pb}$ is determined by averaging the pressure coefficient $c_p$ over the wake separated region (i.e. $\theta > \theta_s$) and the pore velocity $U_p$ is used in place of the bulk flow velocity $U_b$.

The collapse of $C_{d,s}$ onto a single curve (not shown here) is likely due to the fact that, at these Reynolds numbers, the cylinder drag is dominated by pressure drag and the separation velocity is, by definition, directly related to the base pressure. In spite of the superior performance of $C_{d,s}$ in collapsing the drag coefficient onto a single curve, predictive drag formulations based on $U_s$ are of little practical utility because $C_{pb}$ cannot be readily predicted. On the other hand, the calculation of $U_c$ as a function of the bulk velocity $U_b$ and canopy density $\lambda$ is reasonably straightforward (e.g. equation (2-3) for a cylinder array). The approximately constant ratio of $U_s/U_c$ across the range of canopy density and Reynolds number studied here (Figure 2-9a) reaffirms the validity of using $U_c$ as the reference velocity in the description of canopy drag, based on the analogy between canopy flow and wall-confined flow (see section 2.2.3). The collapse of $C_{d,c}$ across the range of canopy density studied here (Figure 2-9b) is far superior to the large scatter observed in $C_{d,p}$ or $C_{d,b}$ (Figure 2-8). Furthermore, $C_{d,c}$ values collapse onto the same curve as a single cylinder in isolation. That is, the canopy drag coefficient can be expressed as:

$$C_{d,c} = 1 + 10Re_c^{-2/3}$$  \hspace{1cm} (2-10)
This indicates that $U_c$ is in fact the velocity that determines the drag force on canopy elements across the density and Reynolds number range studied here.

It can be seen in Figure 2-9b that equation (2-10) slightly overestimates $C_{d,c}$ for the sparser canopies ($\lambda = 0.016$ and 0.04). This confirms that the blockage effect is not as significant in sparse canopies due to the smaller increase in local velocities that are created (Figure 2-4a). Values of $C_{d,p}$ in the sparser canopies ($\lambda = 0.016$ and 0.04) fall close to the single cylinder line (Figure 2-8a, as in Figure 6 of Nepf [2011b]), suggesting that at such low densities, the effects of drag modification mechanisms are so insignificant that the pore velocity $U_p$ (the spatially-averaged velocity within the canopy) is effectively the velocity governing the canopy drag forces. However, at such low canopy densities, the pore velocity $U_p$ and constricted cross section velocity $U_c$ are not significantly different and can be used interchangeably. Therefore, equation (2-10) can be used also to predict the drag coefficient of sparse canopies ($\lambda \lesssim 0.04$) within reasonable accuracy.

To further demonstrate the validity of using the constricted cross-section velocity $U_c$ as the reference velocity in describing canopy drag, the formulation in equation (2-10) is tested against existing numerical [Stoesser et al., 2010] and experimental [Cheng and Nguyen, 2011; Stone and Shen, 1997] observations of the canopy drag coefficient (Figure

![Figure 2-9](image-url)
Each of these studies employed staggered cylinder arrangements. It is evident that equation (2-10) predicts the measured canopy drag coefficients very well (Figure 2-10b), whereas the conventional use of $U_{ref} = U_p$ does not allow accurate prediction of canopy drag (Figure 2-10a). In addition, Figure 2-10b indicates that it is possible to extend the application of the proposed model to an even wider range of Reynolds number than that covered in this study. A description of drag based on the constricted cross-section velocity may also have utility in studying flows through channels with patchy vegetation distributions, where the blockage effect of adjacent patches is likely to be significant (see, e.g., Luhar and Nepf [2013]).

### 2.5.3 Implications for randomly-arranged canopies

While investigating the mechanisms responsible for drag modification in canopies is simplest with regular cylinder arrangements, here we briefly discuss the prospects of extending this work in the future to characterize randomly-distributed canopy arrays. Although a detailed investigation of drag in random arrays is beyond the scope of the present study, we focus here on one example to illustrate this extension and provide a foundation for dedicated future work.

To examine the applicability of the model presented here to random canopies, a case study of 16 randomly-distributed cylinders in discrete $x$ and $y$ positions is considered.
(Figure 2-11, $\lambda = 0.08$ and $Re_p = 500$). Similarly to the staggered arrays, cyclic boundary conditions are imposed in both the streamwise and spanwise directions. It is evident that the mean velocity approaching each cylinder is significantly affected by neighboring cylinders (Figure 2-11). For example, the elevated flow velocity (due to the blockage effect) around cylinder 14 can be clearly seen, whereas both cylinders 1 and 8 are sheltered by upstream cylinders and experience very low impact velocities. Moreover, the wake structure is also affected; the wake areas of cylinders 7 and 9 are distorted as a result of asymmetrically-positioned downstream cylinders. Generally, there is a greatly enhanced spatial variability of velocity in the random canopy relative to a staggered canopy of equivalent density.

The drag coefficients of the 16 cylinders were determined using both the constricted cross-section velocity $U_c$ and pore velocity $U_p$ as reference velocities. $U_c$ was evaluated for each individual cylinder as the spatially-averaged flow velocity over the spanwise constricted cross sections on both sides of the corresponding cylinder (see Figure 2-1b; Note that cyclic boundary conditions are imposed in spanwise direction which means that the model is periodically repeated in this direction). Individual values of $C_{d,c}$ and $C_{d,p}$ both vary over an order of magnitude (Figure 2-12a), due partly to the fact that local variations of velocity are not taken into account; the same value of $U_p$ is employed for all cylinders (as it is a spatially-averaged property) and, while individual values of $U_c$ are determined for each cylinder, the sheltering effect of the upstream cylinders is not taken into account. This sheltering effect is most prominent for cylinders 1 and 8; accordingly, these two cylinders have the lowest calculated drag coefficients.

While the drag forces on individual elements in a randomly-distributed canopy will vary greatly with their position relative to neighboring elements, of practical interest here is a model capable of predicting the overall canopy drag. The average drag coefficient using $U_{ref} = U_c$ over the entire canopy is within 8% of the predicted value by the proposed model in equation (2-10) (shown as a curve in Figure 2-12a). In contrast, the average drag coefficient calculated using $U_{ref} = U_p$ lies more than 23% above this curve.
The performance of the proposed model is further evaluated by investigating the variation of the ratio of the drag force on individual elements to that predicted by the model in equation (2-10) \( \left( \frac{F_d}{F_{d,\text{model}}} \right) \). This is presented as a function of \( \frac{U_c^2}{U_{c,\text{model}}^2} \) (Figure 2-12b), representing the ratio of the constricted cross-section velocity of each element to the average canopy value given by equation (2-3). Despite the scatter in the data due to local sheltering effects, the average value of \( \frac{U_c^2}{U_{c,\text{model}}^2} \) of all cylinders in this random array is 1.02. This suggests that equation (2-3) is an appropriate and robust formula for predicting the average constricted cross-section velocity \( U_c \) even in a random array. Importantly, the average value of \( F_d/F_{d,\text{model}} \) in the random array is approximately 0.9 (the red circle in Figure 2-12b), which implies that equation (2-10) predicts the average drag force in a random array to within 10%. Sheltering effects cause local deviations from the 1:1 relationship in Figure 2-12b. Cylinders 1 and 8, which are significantly affected by sheltering and thus experience greatly reduced drag forces, are clear outliers in Figure 2-12b. In addition, comparison of cylinders 13 and 15 reveals that in spite of experiencing the same blockage effect, the drag force exerted on cylinder 13 is lower because of the sheltering effect of cylinder 12. Finally, although cylinder 14 experiences the highest blockage effect, the drag force is somewhat lower than expected due to the sheltering effect of cylinder 12.

Figure 2-11 Contours of dimensionless temporally- and vertically-averaged stream-wise velocity \( \langle u_1 \rangle/U_p \) for the randomly-distributed canopy (\( \lambda=0.08 \) and \( Re_p=500 \)).
Collectively, these results indicate that, while sheltering can significantly impact drag coefficients for individual cylinders, equation (2-10) can still provide a significant improvement in the quantitative prediction of average drag coefficients in random arrays. This model therefore represents an advancement over traditional approaches that employ $U_p$ as the reference velocity in the description of canopy drag.

2.6 Conclusions

To investigate the mechanisms responsible for drag modification within emergent vegetation canopies, numerical simulations of flow through arrays of circular cylinders (with densities ranging from $\lambda = 0.016$ to 0.25) were conducted. The roles of the blockage effect, sheltering and delayed separation on modifying the canopy drag coefficient, relative to that of a single cylinder, were quantified. This analysis revealed that canopy flow shares several characteristics with wall-confined flow around a cylinder, where drag is enhanced through a reduction in wake pressure. This analogy provides a physical framework for explaining and predicting the enhancement of drag forces within a canopy array. In contrast to the conventional use of either the bulk or pore velocities, a new reference velocity, the constricted cross-section velocity ($U_c$) is shown to be the more appropriate reference velocity that dictates canopy drag. Use of $U_c$ collapses the
canopy drag coefficient data onto a single curve (equation (2-10)), both for the present data and prior experimental datasets. The sheltering effect and delayed separation serve to slightly reduce the drag coefficient in sparse canopies; however these effects are sufficiently weak that either the constricted cross-section velocity or the pore velocity can be used as a reference velocity in sparse canopies ($\lambda \lesssim 0.04$). Finally, the model proposed here is useful in predicting the bulk drag coefficient of randomly-arranged arrays, if not the values of individual canopy elements.
3.1 Introduction

Coastal vegetation provides a wide range of ecosystem services, such as the reduction of coastal erosion, provision of habitat and enhancement of local water quality. The capacity for coastal vegetation to act as a natural form of coastal protection by attenuating incident waves has been the subject of numerous studies [Anderson and Smith, 2014; Houser et al., 2015; Jadhav et al., 2013; Zeller et al., 2014]. Field studies have shown that wave attenuation over salt marshes [Cooper, 2005] and mangroves [Quartel et al., 2007] was at least 2 and 5 times greater than over mudflats, respectively. Despite many efforts to quantify how vegetation controls wave attenuation, there is still a lack of understanding of the small-scale mechanisms responsible for energy dissipation within canopies and, most significantly, how to best parameterise these processes in predictive models.

Wave attenuation by vegetation is a large-scale process (often developing over hundreds of meters) that relies on small-scale interactions between vegetation stems and the fluid motion [Zeller et al., 2014]. The rate at which wave heights $H$ are attenuated by coastal canopies, i.e. $dH/dx$ (where $x$ is the cross-shore distance), is often predicted in large-scale coastal hydrodynamic models by incorporating simplified vegetation models that parameterise wave dissipation. An effective model to predict wave dissipation must correctly incorporate both the vegetation characteristics (which are not accurately captured by existing models) as well as wave parameters. Early approaches simulated the effect of vegetation by assigning an increased bed friction coefficient [Camfield, 1983; Price et al., 1968]; however, more recent efforts attempt to predict wave dissipation using the conservation of wave energy equation and a dissipation term to account for the vegetation effects [Dalrymple et al., 1984; Mendez and Losada, 2004] or by adopting a
conservation of momentum approach [Kobayashi et al., 1993; Lima et al., 2007]. However, an important common feature of both of these approaches is the parameterisation of vegetative resistance using a drag coefficient, $C_d$, i.e. with analytical solutions predicting wave decay as $H/H_o = 1/(1 + ax)$ [Dalrymple et al., 1984] and $H/H_o = \exp(-kx)$ [Kobayashi et al., 1993] where $H_o$ is the incident wave height and both $a$ and $k$ are damping coefficients which are functions of $C_d$ and wave characteristics. While waves induce both drag and inertial forces on canopies, this dependence of wave dissipation on $C_d$ is justified given that the work done by drag forces controls the rate of wave dissipation [Lowe et al., 2007].

The dynamics governing the forces exerted on single (isolated) cylinders in a vertically-uniform oscillatory flow (as under shallow-water waves) have been comprehensively studied [Bearman et al., 1985; Sarpkaya, 1986; Tatsuno and Bearman, 1990; Williamson, 1985]. These forces are comprised of both drag force $F_d$ and inertial force $F_i$ contributions, where the latter is induced due to flow acceleration. The in-line force on a cylinder in oscillatory flow can be represented by the well-known Morison equation [Morison et al., 1950]:

$$F_x = F_d + F_i = C_d u |u| + \frac{1}{2} C_m \frac{\pi}{KC} \frac{du}{dt}$$

In equation (3-1), $F_x = \bar{F}_x/0.5 \rho U_{ref}^2 L d$, $\bar{F}_x$ is the dimensional streamwise force exerted on cylinder, $\rho$ is fluid density, $U_{ref}$ is the reference velocity, $L$ is cylinder length, $d$ is cylinder diameter, $u$ is the dimensionless streamwise velocity component ($u = \bar{u}/U_{ref}$), $KC$ is the Keulegan–Carpenter number ($= U_{ref} T/d$ where $T$ is the oscillation or wave period), $t$ is the dimensionless time ($= \bar{t}/T$) and $C_m$ is the inertia coefficient. However, for linear waves where the flow velocity varies sinusoidally, the inertial force does not contribute to wave dissipation as it is 90 degrees out of phase with velocity implying that net work done by inertial force is zero [Lowe et al., 2007]. For this reason, the primary focus of this study is on understanding the processes that govern differences in the drag coefficient $C_d$ rather than the inertia coefficient $C_m$. The drag coefficient of cylinders in oscillatory flow is known to depend on two key dimensionless parameters; namely, $KC$ that is related to ratio of the oscillatory flow excursion length to the cylinder diameter and the Reynolds number ($Re = U_{ref} d/\nu$, where $\nu$ is fluid kinematic viscosity) or $Re/KC$ [Sarpkaya and Isaacson, 1981]. For a given $Re/KC$ and at low $KC$ where flow is inertia dominated ($KC <$
the drag coefficient initially decreases with $KC$ since there is no separation of the flow from the cylinder ($KC \lesssim 2$). However, as $KC$ increases towards the upper limit of the inertia dominated regime ($KC \approx 7$), flow separation occurs and vortices begin to shed and drag coefficient increases [Bearman et al., 1985]. At even higher $KC$ where flow is drag dominated ($KC \gtrsim 20$), the flow becomes dominated by vortex shedding and the drag coefficient approaches a constant value for $KC > 40$ independent of increasing $KC$ [Sarpkaya, 1975].

Predicting the drag coefficient for emergent canopies, which are commonly modelled as arrays of cylinders [Hu et al., 2014; Kothyari et al., 2009; Liu et al., 2008; Stoesser et al., 2010; Tanino and Nepf, 2008a], is much more complicated compared to that of a single cylinder due to the interactions between neighbouring stems/cylinders. Even for the case of unidirectional flow, $C_d$ can be highly variable depending on both the Reynolds number and canopy density (or solid fraction, $\lambda$) [Etminan et al., 2017; Tanino and Nepf, 2008a]. The unsteadiness of an oscillatory flow makes quantifying the $C_d$ of canopies in wave-dominated flows even more complex. Similarly, the drag forces exerted on two or more cylinders in oscillatory flow have been reported to be complex and substantially different from those on a single cylinder depending on their spacing, orientation and value of $KC$ [Tong et al., 2015; Williamson, 1985; Yang et al., 2013; Zhao and Cheng, 2014]. For example, the drag coefficient of two cylinders in a side-by-side arrangement with spacing equal to the cylinder diameter is approximately 50 percent higher than that of a single cylinder at a given $Re$ and $KC$ [Zhao and Cheng, 2014]. In such arrangement, the drag coefficient decreases with cylinder spacing. On the other hand, for a tandem arrangement (where the cylinders are separated in the flow direction), the drag coefficient of either cylinder is lower than that of a single cylinder, increasing with spacing and decreasing with $KC$. The mean drag coefficient of three cylinders in a side-by-side arrangement and four cylinders in a square arrangement has also been reported to be higher at small spacing and approaches that of a single cylinder as spacing increases [Bonakdar et al., 2015; Tong et al., 2015]. For example, the mean drag force exerted on a group of three side-by-side cylinders is 80 and 50 percent higher than that of a single cylinder when the spacing equals half and one cylinder diameter, respectively [Bonakdar et al., 2015]. The observed variations of drag coefficients of cylinders inside groups of a small number of cylinders can be helpful in investigating the drag coefficient of infinite array of cylinders.
Due to the flow complexity inherent in canopy flows, models to predict the canopy drag coefficients have relied on highly empirical relationships that may not adequately capture many key aspects of the physical processes. For example, a number of studies have attempted to formulate the drag coefficient of vegetative canopies as functions of either $Re$ or $KC$, usually in the forms of $C_d = \alpha + (\beta/Re)^\gamma$ or $C_d = a KC^b$, respectively, where $\alpha, \beta, \gamma, a$ and $b$ are fitting coefficients obtained by experimental data (for a list of these models see Table 1 in Henry et al. [2015]). Notably, none of these studies have directly incorporated the effects of varying canopy density in formulating predictions of canopy drag coefficients. Moreover, a majority of these studies have determined $C_d$ based on measurements of wave attenuation through canopies rather than direct measurement of drag forces, and there can be large discrepancies in predicted drag coefficients when comparing different formulations. The fact that $C_d$ is obtained by fitting datasets of wave attenuation can be contaminated by the simplifications in the model used to predict dissipation (e.g. assuming linear wave theory), the structure of the in-canopy flow, variation of the flow velocity both over the water depth and along the vegetation patch, etc. Ultimately, a successful drag coefficient model relies on insight into the flow structure that occurs inside the canopy [Lowe et al., 2007].

In this study, the two-dimensional dynamics of oscillatory flow through arrays of circular cylinders is numerically studied. The choice of two-dimensional simulations over three-dimensional ones is justified based on the following considerations. First, the in-line forces $F_x$ exerted on cylinders in oscillatory flow (at $Re \leq 1500$) [Yang and Rockwell [2002]], and more specifically the drag component of the force $F_d$ (at $Re \leq 170$) [Nehari et al., 2004a; Nehari et al., 2004b], are only weakly affected by three-dimensional effects. Second, the vortex shedding patterns around cylinders in oscillatory flow do not qualitatively change due to the three-dimensionality of the flow ($Re \leq 170$) [Nehari et al., 2004a]. There are many numerical studies that have successfully used two-dimensional models to reproduce vortex shedding regimes induced by oscillatory flow around circular cylinders [Dütsch et al., 1998; Iliadis and Anagnostopoulos, 1998; Lin et al., 1996; Scandura et al., 2009; Tong et al., 2015; Uzunoğlu et al., 2001; Zhao and Cheng, 2014]. Finally, using high-resolution two-dimensional simulations makes it possible to investigate the oscillatory flow through arrays of cylinders over a wide range of $KC$ and solid fractions at affordable computational costs without losing the ability to accurately estimate the
drag forces and resolving the key flow features. Nevertheless, in this study we initially compare the results of a few three-dimensional simulations with the corresponding two-dimensional simulations results to further confirm the consistency of the current approach (see section 3.3.4).

While the hydrodynamic forces exerted by vegetated canopies under unidirectional flow have been increasingly studied in recent years (e.g. Etminan et al. [2017], Stoesser et al. [2010], Tanino and Nepf [2008a]), studies of the detailed mechanisms responsible for forces induced by oscillatory flow are still very limited. In this study, the oscillatory flow through emergent canopies (modelled here as arrays of rigid cylinders) with densities of $\lambda = 0.02 - 0.22$ at $Re = 100$ and $KC = 2 - 100$ which are within the realistic field ranges [Henry et al., 2015; Nepf, 2011b] were investigated and the various potential mechanisms responsible for modifying canopy drag were evaluated. It should be noted that modelling the submerged canopies oscillatory flow was not possible due to prohibitive computational costs. The objective of this paper is thus to develop a fundamental understanding of the hydrodynamic mechanisms that control drag forces in oscillatory flow through emergent canopies, which can be used in future as a basis for developing new predictive formulations for assigning bulk canopy drag coefficients.

3.2 Theoretical framework

There are two potential mechanisms that can cause the forces exerted on an individual cylinder located within a canopy array to be different with that of a single isolated cylinder under the same flow conditions, as a consequence of the interaction with flow structures generated around neighbouring cylinders. In this section, a brief overview is presented of these mechanisms that have the potential to modify the canopy drag coefficient relative to that of a single cylinder (see also section 2.2). The relative importance of these mechanisms is then assessed in the results that follow.

3.2.1 Blockage effect

A flow past a bluff body that is confined by lateral walls is subject to what is commonly referred to as the ‘blockage effect’, which enhances drag forces [Maskell, 1963]. The blockage effect alters the flow around a bluff body in several ways [Zdravkovich, 2003]: (1) The presence of the body reduces the cross-sectional area locally, which results in a local increase in the velocity around the body, and (2) the side walls hinder the widening
of the wake, while the increased velocity outside the wake reduces the pressure within it. Wall-confined bodies have thus been shown to have significantly different wake characteristics to unconfined bodies. In particular, the blockage effect tends to significantly increase the drag coefficients of the bluff body at a given upstream velocity, due to the dominant effect of the reduced wake pressure (see Zdravkovich [2003] for a detailed review). Likewise, the blockage effect also increases the vortex shedding frequency in the wake. While a wall-confined flow past a bluff body is not identical to flow through an array of cylinders, there are clear analogies when a cylinder is located between laterally positioned neighbouring cylinders (Figure 3-2a). For unidirectional flow, it has been shown that an analogous blockage effect occurs in the confined flow in constricted cross-sections between laterally adjacent cylinders [Etminan et al., 2017]. In addition, an alternative reference velocity, namely the constricted cross-section $U_c$ which is calculated by averaging the velocity over constricted cross sections has been found to be an appropriate reference velocity to normalize the canopy drag force (Figure 3-2a). At large $KC$, an oscillatory flow effectively approaches a unidirectional flow, due to the insignificance of flow accelerations, and we hypothesise that the blockage effect should eventually become effective in modifying the flow and drag forces. In this study, we assess the role of blockage in dictating canopy drag and evaluate the use of $U_c$ as a reference velocity in drag formulations.

### 3.2.2 Sheltering effect

The term ‘sheltering effect’ describes the condition where two bluff bodies are situated such that one body is located in the wake region of the upstream body [Raupach, 1992]. The downstream body experiences a lower incident velocity than the upstream body (i.e. through ‘sheltering’, see Figure 3-2b), which results in a lower drag force. This effect becomes more significant as the spacing between the bodies decreases [Sumner, 2010; Zdravkovich, 1987]. In the context of a canopy, sheltering occurs when the velocity approaching a canopy element is less than the instantaneous pore velocity (equal to the velocity averaged over the pore spaces between cylinders at each time) due to the influence of upstream elements. The sheltering effect can be of relevance to a canopy flow in oscillatory flow specifically when $KC$ is large enough that the flow excursion amplitude is equal or larger than the cylinder spacing ($KC\sqrt{\lambda} \geq 1.25$ or $KC/s \geq 1$ where $s = S/d$ and $S$ is the inter-cylinder spacing; see Figure 3-2). However, sheltering can be highly
dependent upon the arrangement of canopy elements. It has been observed that for unidirectional flow the sheltering effect is noticeable only in sparse canopies ($\lambda < 0.04$) and becomes increasingly insignificant compared to blockage effect at higher canopy densities [Etminan et al., 2017]. Here, we assess the role of the sheltering effect in oscillatory flow across a wide range of canopy densities and $KC$.

3.3 Numerical Modelling

3.3.1 Governing Equations and Numerical Methods

The dimensionless forms of the governing equations for simulating incompressible two-dimensional oscillatory fluid flow are

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (3-2)
\]

\[
\frac{1}{KC} \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + \frac{\partial p}{\partial x} = \frac{1}{Re} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - B_x \quad (3-3)
\]

\[
\frac{1}{KC} \frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + \frac{\partial p}{\partial y} = \frac{1}{Re} \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) \quad (3-4)
\]

where $x$ and $y$ are dimensionless streamwise and transverse coordinates ($x = \bar{x}/d$ and $y = \bar{y}/d$ where $\sim$ denotes dimensional variables), $v$ is the dimensionless transverse velocity component ($= \bar{v}/U_{ref}$) and $p$ is the dimensionless pressure ($p = (\bar{p} - p_0)/\rho U_{ref}^2$ where $p_0$ is a reference pressure). In equation (3-3), $B_x$ is the dimensionless pressure gradient that drives the flow such that the oscillatory velocity as
which is imposed as a body force on the fluid within the computational domain [Cui and Neary, 2008; Ellero and Adams, 2011; Moin and Kim, 1982]. In section 3.4, results are presented at different phase angles $\phi$ which is defined such that, for example, $u = 0$ and 1 for $\phi = 0$ and $\pi/2$, respectively.

All simulations were carried out using the Open-source Field Operation and Manipulation (OpenFOAM®) C++ libraries, which is an open-source computational fluid dynamics (CFD) package. The incompressible solver pimpleFoam was used, which has the merged PISO-SIMPLE algorithm implementation. In addition, a dynamic adjustable time stepping technique was used to guarantee a local Courant number less than 0.2.

### 3.3.2 Model Data Analysis

Depending on the reference velocity $U_{ref}$ used in the definition of $F_x$, the drag and inertia coefficients of cylinders inside arrays (calculated using equation (3-1)) can acquire different values. In this study, drag coefficients are calculated based on the pore velocity $U_p$ and constricted cross-section velocity $U_c$ which are denoted $C_{d,p}$ and $C_{d,c}$, respectively. Similarly, Reynolds numbers based on $U_p$ and $U_c$ are denoted as $Re_p$ and $Re_c$, respectively. Note that $U_c$ for staggered arrays can be calculated as

$$U_c = \frac{1 - \lambda}{1 - \sqrt{2\lambda/\pi}} U_p$$

[Etminan et al., 2017] where $\lambda$ is the canopy density or solid fraction $\lambda (= \pi/2s^2)$. For a single cylinder, the drag coefficient is denoted as $C_d$ and the subscripts $p$ and $c$ are
dropped as $U_p = U_c$ for a single cylinder. A least-squares method [Wolfram and Naghipour, 1999] was adopted in this study to quantify the drag and inertia coefficients based on the Morison equation (i.e. equation (3-1)) using the time series of streamwise forces $F_x$ exerted on each cylinder. The least-squares method relies on minimization of the error between the calculated and approximated force time series and yields constant values of drag and inertia coefficients. Despite the insignificant variation between the forces exerted on the individual cylinders in the staggered arrays (<5%), the force results presented here for each array refer to the results of the cylinder located at the origin of the coordinating system near the centre of the domain (shown as a grey cylinder in Figure 3-2a) for the sake of consistency among the presented results.

### 3.3.3 Model Configuration

The computational domain includes 12 cylinders (Figure 3-2); however, to mimic an infinite array of cylinders, cyclic boundary conditions were imposed in the streamwise and transverse directions. At the cylinder surfaces a no-slip condition was applied. The array densities ($\lambda$) were determined by adjusting the cylinder spacing, $S$ (Figure 3-2a). In this study, six array densities $\lambda$ were modelled: $\lambda = 0.02, 0.06, 0.1, 0.14, 0.18$ and 0.22. As $s = 1/\sqrt{2\lambda/\pi}$, this corresponds to $s = 8.86, 5.12, 3.96, 3.35, 2.95$ and 2.67. The selected values of $\lambda$ cover the densities of a wide range of aquatic vegetation from typical marsh grasses [Nepf, 2011b] to mangroves [Mazda et al., 1997].

The grid topology consisted of twelve sets of cells (one for each cylinder), with each set consisting of a block around the cylinder (block A) and a H-grid block in the interstitial spaces (block B, Figure 3-2b). The H-grid block was uniformly spaced but the size of the

<table>
<thead>
<tr>
<th>Density, $\lambda$</th>
<th>Spacing, $S$</th>
<th>Grid points in each set</th>
<th>Total Number of Grid Points</th>
<th>$K_C$ $(Re_p = 100)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>8.86</td>
<td>280x99 + 4x8x97</td>
<td>88x88</td>
<td>459,696</td>
</tr>
<tr>
<td>0.06</td>
<td>5.12</td>
<td>280x90 + 4x9x79</td>
<td>88x88</td>
<td>429,456</td>
</tr>
<tr>
<td>0.10</td>
<td>3.96</td>
<td>280x82 + 4x8x78</td>
<td>86x86</td>
<td>394,224</td>
</tr>
<tr>
<td>0.14</td>
<td>3.35</td>
<td>280x81 + 4x8x78</td>
<td>86x86</td>
<td>390,864</td>
</tr>
<tr>
<td>0.18</td>
<td>2.95</td>
<td>280x80 + 4x8x78</td>
<td>86x86</td>
<td>387,504</td>
</tr>
<tr>
<td>0.22</td>
<td>2.67</td>
<td>280x78 + 4x8x78</td>
<td>86x86</td>
<td>380,784</td>
</tr>
</tbody>
</table>

2, 5, 10, 15, 20, 30, 40, 50 and 100
grids in the block around cylinders was decreased as each cylinder is approached. The details of the grid for each array density are summarized in Table 3-1. In all simulations, the cell sizes adjacent to the cylinders were chosen such that the maximum dimensionless wall distance of the first cell $n^+$ ($= nu_*/v$, where $u_*$ denotes the wall friction velocity and $n$ the normal distance from the wall) was kept below 1.

The simulations were allowed to run for 10 oscillation periods before any data was collected and then the flow parameters were measured over at least 50 oscillation cycles. Simulations were carried out at Reynolds number of 100 and at 9 different KC numbers (i.e. 2, 5, 10, 15, 20, 30, 40, 50 and 100) for each canopy density to cover the expected inertia ($KC < 7$), drag-inertia ($7 \leq KC < 20$) and drag dominated ($KC \geq 20$) regimes. In addition, simulations of flow around a single cylinder at the same Reynolds number and KC numbers were conducted to provide a reference for how the flow structure and force coefficients are modified for cylinders in a canopy array.

### 3.3.4 Model Validation

To validate the model, the numerically computed force coefficients (drag and inertia) and velocity profiles of flow around a single cylinder were compared with experimental data. Four additional two-dimensional and two three-dimensional simulations were conducted to compare the current model results of $C_d$ and $C_m$ with the experimental results of Kuhtz [1996] that investigated the forces exerted on a single circular cylinder in oscillatory flow at $Re/KC = 53$. There was very good agreement between the two-dimensional numerical and experimental results (with an average error of 8.6% for $C_d$ and 7.1% for $C_m$ across all simulations; Figure 3-3). Three-dimensional results are very

![Figure 3-3 Comparison of (a) $C_d$ and (b) $C_m$ of two- and three-dimensional single cylinders in oscillatory flow calculated by present model and measured in experiments of Kuhtz [1996] for $Re_p/KC=53$.](image-url)
close (within ~4% on average) to the two-dimensional results, confirming the insignificance of any three-dimensionality effects for the flow conditions considered. Further validation of the present numerical model was achieved by comparing the calculated velocity profiles with the experimental results of Dütsch et al. [1998]. In their experiments, Dütsch et al. [1998] used Laser Doppler Anemometry (LDA) measurements to study the flow induced by the harmonic in-line oscillation of a circular cylinder in water otherwise at rest. Figure 3-4 compares the present model results of streamwise and transverse velocity components profiles with experimental data at four cross sections and two phase angles. Note that in the present numerical model, the cylinder was fixed in position and exposed to oscillating fluid, while in the Dütsch et al. [1998] experiments the cylinder was forced to oscillate in otherwise still water. Therefore, the coordinates and velocity were transformed as [Tong et al., 2015]: \[ \xi = x + (A/d) \sin \psi, \psi = \phi - \frac{\pi}{2}, u_a(t) = u(t) - \sin(2\pi t) \text{ and } v_a(t) = v(t). \] Here \( A \) is the amplitude of the movement in the experimental study of Dütsch et al. [1998], \( \xi, \psi, u_a \) and \( v_a \), respectively, describe the horizontal coordinate, the phase angle, the horizontal velocity component and the vertical velocity component in the experimental study, and \( x, \phi, u \) and \( v \) are, respectively, the corresponding variables in the present study. The numerical results agree well with the measured data (averaged RMS error of 0.06).

The mesh used to simulate oscillatory flow around a single cylinder has a total number of grid points of 83,100 with 280 grid points on cylinder surface. Note that in initial sensitivity tests, we observed that using a finer mesh had a negligible influence on the results and therefore the same mesh scheme was applied to generate the mesh around cylinders in arrays.
3.4 Results

3.4.1 Streamwise Velocity Contours and Streamlines

Investigating the velocity contours and streamlines in an oscillatory flow structure interacting with bluff bodies can provide insight into the flow structures and flow regimes that are established, highlighting the significance of mechanisms that potentially affect the hydrodynamic forces. Of particular interest are velocity contours and streamlines at
\( \phi = \pi/2 \) when the flow velocity and, consequently, the drag force are the maximum during each flow oscillation cycle (Figure 3-5). For oscillatory flow around a single

![Figure 3-5 Instantaneous streamwise velocity component contours superimposed by streamlines at KC=15 and \( \phi=\pi/2 \) for (a) Single cylinder and arrays with densities of (b) \( \lambda=0.02 \), (c) \( \lambda=0.1 \) and (d) \( \lambda=0.22 \). Distorted streamlines at higher array densities combined with enhanced local velocity indicates higher blockage effect. Regions with velocity deficiency shown as blue regions may imply sheltering effect.](image)
cylinder at $KC = 15$ and $Re = 100$, it has been shown that diagonal double-pair vortices are formed and flow is convected diagonally away from cylinder as shown in Figure 3-5a [Tatsuno and Bearman, 1990]. However, for arrays of cylinders this flow structure is broken due to the interactions between the vortices shed from neighbouring cylinders and flow structure can become irregular depending on the array density (Figure 3-5b-c). Furthermore, streamlines at sparse arrays are roughly straight lines in most of the flow domain, specifically in areas away from cylinders (Figure 3-5b). As the array density increases, the streamlines become increasingly curved, which combined with enhanced local velocities indicate acceleration of flow within the constricted cross-sections between cylinders (i.e. the presence of a blockage effect, section 2.2.3) (Figure 3-5c and d). On the other hand, areas of deficit velocity upstream of cylinders inside arrays, indicated by blue shades in Figure 3-5b-d, might be regarded as an indication of the lower impact velocity received by the corresponding cylinder (sheltering effect). Finally, the cylinder wake region shown as dark blue areas are constrained as the array density increases (Figure 3-5b-d).

### 3.4.2 Velocity time series

Assessment of the velocity variations over a full oscillatory flow cycle can further help reveal the relative importance of sheltering and blockage effects (Figure 3-6). Specifically, an enhancement of velocity variations at $(x, y) = (0, -0.67)$ (point 1) can be regarded as an indication of the importance of the blockage effect. This is mainly because point 1 is located at the constricted cross section, is not located directly in the area sheltered by the upstream cylinder, and is also far enough from its adjacent cylinder not to be affected by its boundary layer [Etminan et al., 2017]. The velocity variations at point 1 suggest that the blockage effect is negligible at the lowest $KC$, since for all canopy densities the velocity variations at point 1 are nearly identical for that of single cylinder (Figure 3-6a). However, as $KC$ increases the velocity signature of a blockage effect increases, with the velocity at point 1 reaching much greater values than for a single cylinder, especially for the higher canopy densities (e.g. for $\lambda = 0.22$ in Figure 3-6e).

The frequency and onset of vortex shedding may also indicate the significance of the blockage effect [Etminan et al., 2017]. The observed high-frequency velocity fluctuations (indicated in Figure 3-6c for $\lambda = 0.22$) in each half cycle of free stream oscillation at $KC = 15$ and 100 (Figure 3-6c to f) imply the occurrence of vortex shedding. Figure 3-6f clearly
shows that vortex shedding frequency increases with canopy density. In addition, the results indicate that the onset of vortex shedding for $\lambda = 0.22$ at $KC = 100$ becomes significantly delayed compared to other canopy densities (Figure 3-6e and f). These results further confirm that the blockage effect is enhanced at higher $KC$ and canopy densities.

Conversely, velocity variations at $(x, y) = (1.34, 0)$ (point 2) can reveal the significance of the sheltering effect given that this point is positioned within an expected sheltered area by an immediate upstream cylinder. The sheltering effect also appears negligible at $KC =$
However, as $KC$ increases the velocity at point 2 is observed to be significantly lower than the free stream velocity indicating some significant sheltering (Figure 3-6d and f). The sheltering effect is stronger for the canopy with density of $\lambda = 0.02$ than denser canopies. Note that except for $\lambda = 0.22$, in which the point 2 is located at the midpoint of a streamwise line connecting two neighbour cylinders (and therefore equally sheltered by the upstream cylinder in each half cycle of flow oscillation), for lower canopy densities the point 2 is closer to its upstream cylinder in the first half cycle of oscillation ($0 < \phi < \pi$) than the second half cycle ($\pi < \phi < 2\pi$). This results in weaker sheltering and higher velocity, particularly within the second half cycle (Figure 3-6d and f). However, the observed equal sheltering effect for the canopy with the density of $\lambda = 0.22$ is only true for the perfectly staggered canopy used in this study and is not necessarily the case for a random canopy with the same density.

### 3.4.3 Transverse Force Fluctuations

The transverse forces exerted by cylinders inside an array vary with both $KC$ and canopy density (Figure 3-7). At very low $KC$ (i.e. $KC \leq 7$), the oscillation period is too short for vortex shedding to occur and the vortices remain attached to the cylinders, which results in negligible transverse forces (Figure 3-7a). However, as the $KC$ increases, the transverse forces become noticeable due to the vortex shedding. In addition, at high $KC$ for which the flow excursion amplitude is much larger than cylinder spacing (i.e. $KC/s > 6$ or $KC\sqrt{\lambda} > 7.5$) and for a cylinder spacing equal to or larger than a critical spacing $s_c$, the root-mean-square of transverse forces drastically increases for both cylinders in array exposed to oscillatory flow and downstream cylinder of a pair of tandem cylinders subjected to unidirectional flow. The value of $s_c$ for $Re_p=100$ for both unidirectional and oscillatory flow is between 3.3 and 4.

![Figure 3-7](image.png)
the vortices that are shed from each cylinder impinge on a downstream cylinder, enhancing the transverse force magnitude (Figure 3-7a). Such a sudden rise in transverse force at $s = s_c$ has previously been observed to occur with tandem cylinders in unidirectional flow [Sumner, 2010; Zdravkovich, 1977]. For example, at $Re = 100$, the critical spacing of two tandem cylinders has been found to be between 3.3 and 4 [Carmo et al., 2010; Sharman et al., 2005]. Plotting the root-mean-square of transverse forces of cylinders in arrays against their corresponding spacing (summarised in Table 3-1) reveals that at $KC = 100$ the critical spacing is within the same range as the critical spacing $s_c$ observed for tandem cylinders in unidirectional flow, i.e. corresponding to $\lambda \approx 0.1$ in the present study (Figure 3-7b). Note that since the flow acceleration is inversely related to $KC$, at high $KC$ the flow acceleration becomes insignificant and the oscillatory flow in each half cycle approaches the results corresponding to a unidirectional flow. The observed variations of transverse forces with $KC$ and canopy density are used to justify the variations of drag forces in section 3.4.5.

### 3.4.4 Streamwise and transverse force time series

Both the streamwise and transverse force time histories of cylinders in arrays are greatly affected by $KC$ and array density (Figure 3-8). At low $KC$, there is a large phase-shift between the streamwise force and free stream velocity (i.e. given that this coincides with an inertia dominated regime, Figure 3-8a); however, at high $KC$ the streamwise force and free stream velocity are nearly in-phase (i.e. within a drag dominated regime, Figure 3-8e). The amplitude of the streamwise force varies inversely with array density at low $KC$ (Figure 3-8a) when the streamwise force is dominated by the inertia force. This reduction in the streamwise force amplitude is due to the dependency of inertia force on the bulk of fluid in the pore spaces between cylinders, which decreases with array density [Anagnostopoulos and Minear, 2004]. In the intermediate drag-inertia regime there is no appreciable change in the streamwise forces with varying array density (Figure 3-8c); however, at high $KC$ the streamwise forces become substantially larger at higher array densities (Figure 3-8e). The transverse forces are negligible at small $KC$ (Figure 3-8b) due to the lack of vortex shedding, but increase notably with $KC$ such that for $\lambda = 0.1$ at some instances the transverse force is larger than the streamwise force (Figure 3-8d and f). This was also observed in Figure 3-7. In addition, the transverse force fluctuations that indicate shedding of vortices show that the vortex shedding frequency increases and also
delays with increasing density for a given $KC$ in the drag-dominated regime (Figure 3-8f). The variations in the streamwise force amplitude and transverse force fluctuations with $KC$ and $\lambda$ can provide indications of the significance of the different potential mechanisms governing canopy drag forces introduced in section 2, which are assessed further in section 3.5 (Discussion) below.

Figure 3-8 Variations in the streamwise force $F_x$ and of the transverse force $F_y$ within one oscillatory flow cycle for $KC=2$, 15 and 100. The free stream velocity is included as a phase reference. The streamwise force amplitude decreases with array density at low $KC$ while the opposite is correct for large $KC$. The frequency of transverse force fluctuations increases with canopy density.
3.4.5 Drag Coefficient

The drag coefficients for cylinders in array vary with both $KC$ and the array density (Figure 3-9). At low $KC$, where the flow is inertia-dominated, the drag coefficients $C_d,p$ (based on the pore velocity) of the sparse arrays ($\lambda < 0.14$) are very close to that of a single cylinder and even for denser arrays ($\lambda \geq 0.14$) the drag coefficients are comparable (within 10%). However, in intermediate drag-inertia regime ($7 < KC \leq 20$), when $KC$ increases the drag coefficient curves for different canopy densities markedly diverge, such that $C_d,p$ varies from $\sim 1.5$ to $\sim 2.5$ in the drag-dominated regime ($KC \geq 20$). Drag coefficients generally increase with canopy density in the drag-dominated regime, similar to the trend observed for unidirectional flow [Etminan et al., 2017]. The drag coefficients of $\lambda = 0.02$ and 0.06 are lower than denser arrays for the full range of $KC$ studied here (except for $KC = 2$) and roughly follow the single cylinder $C_d$ curve. The cylinders in arrays with densities of $\lambda = 0.18$ and 0.22 are observed to have the highest drag coefficient except for the largest $KC$. We also note that the drag coefficient enhancement of cylinders in arrays with densities of $\lambda = 0.10$ and 0.14 for $KC > 30$ is consistent with the increase in their $F_{y,\text{rms}}$ (Figure 3-7a).

3.5 Discussion

Two mechanisms responsible for modifying canopy drag coefficients relative to that of a single cylinder were introduced in section 3.2: the blockage effect and the sheltering effect. A discussion on the relative importance of these mechanisms now follows.

The results indicate that an oscillatory flow through canopy arrays have many features in common with a wall-confined flow past a single cylinder, particularly in the drag-
dominated regime \((KC \geq 20)\) for medium to high density canopies \( (\lambda \geq 0.06; \text{see Figure 3-9})\). The flow velocity around each cylinder inside an array increases significantly with density (Figure 3-5c-d and Figure 3-6c and e). This enhancement in local velocity within the constricted cross-section acts to decrease the cylinder wake pressure, similar to what was observed for unidirectional flow by Etminan et al. [2017]. Moreover, the cylinder wake area contracts as the canopy density increases (Figure 3-5c-d). Similarly, studies on wall-confined flow around cylinders have shown that the cylinder base pressure and cylinder wake area both increase considerably at increasing blockage ratio, defined as the ratio of cylinder diameter to the width of constricted cross section [Mabuchi and Hiwada, 1987; Modi and El-Sherbiny, 1971; Singha and Sinhamahapatra, 2010]. In addition, the vortex shedding frequency, as reflected in the transverse force oscillations, were found to increase with array density (Figure 3-8d and f). This is also a signature of an enhancement of the blockage effect with array density, as it is well-accepted that for wall-confined flows the vortex shedding frequency increases substantially with blockage ratio [Mabuchi and Hiwada, 1987; Mitry, 1977; Toebes and Ramamurthy, 1970]. Finally, the onset of vortex shedding has been shown to be delayed at higher blockage ratios which is also consistent with present results, e.g. as evident by the postponed vortex shedding for an array with density of 0.22 at \(KC = 100\) (Figure 3-8f).

The analogy between canopy flow and wall-confined flow in the drag-dominated regime indicates the significance of the blockage effect in canopy flows and can be used to predict the canopy drag coefficient. For unidirectional flow, it has been shown that using the constricted cross-section velocity \(U_c\) as the reference velocity makes it possible to estimate the canopy drag coefficient with the existing formulations for predicting single cylinder drag coefficient as [Etminan et al., 2017]:

\[
C_{d,c} = 1 + 10Re_c^{-2/3}
\]

(3-7)

where \(Re_c\) is the Reynolds number based on \(U_c\) as the reference velocity \((U_c d / \nu)\). Similarly, in oscillatory flow the blockage effect governs the enhancement of the canopy drag coefficient in the drag-dominated regime \((KC \geq 20)\). In addition, the second term on the right-hand side of equation (3-1) is inversely related to \(KC\) which indicates that the inertial forces in the drag-dominated regime (i.e. large \(KC\)) are insignificant and oscillatory flow is expected to behave equivalent to a corresponding unidirectional flow.
Therefore, we suggest using equation (3-7) to estimate the canopy drag coefficient in the drag-dominated regime \((KC \geq 20)\). To verify this approach for high \(KC\) oscillatory flow, the \(C_{d,p}\) of the present study and experimental results of Ozeren et al. [2014] \((Re < 4500)\) were also compiled for those conditions in the drag-dominated regime \((KC \geq 20)\) and then converted to \(C_{d,c}\) as \(C_{d,p} \frac{U_p^2}{U_c^2}\). While the conventional approach of predicting the canopy drag coefficient \((C_{d,p})\) based on the pore velocity \((U_p)\) in the drag dominated regime deviates substantially from the \(C_d\) of a single cylinder in unidirectional flow (Figure 3-10a), a comparison of the measured \(C_{d,c}\) of canopies with those calculated using equation (3-7) shows good agreement (Figure 3-10b), thus confirming the validity of using this approach in the drag-dominated regime.

The results also indicate that the drag and transverse forces exerted on cylinders inside an array are enhanced when the spacing \(s\) between tandem cylinders is smaller than the flow excursion amplitude \((i.e. KC/s > 6 \text{ or } KC\sqrt{\lambda} > 7.5)\) and is in the range of a critical spacing \(s_c\) (Figure 3-7 and Figure 3-9). This is due to the fact that when the cylinder spacing increases toward \(s_c\), each cylinder inside the array departs from the low pressure wake region of its upstream cylinder, receives vortices shed from it and consequently experiences augmented drag and transverse forces. This alteration of flow and forces with spacing has been observed for pairs of tandem cylinders in unidirectional flow [Sumner, 2010; Zdravkovich, 1977]. For \(Re_p = 100\), the critical spacing of two cylinders with a tandem arrangement in unidirectional flow has been shown to be \(s_c = 3.3 - 4\) [Carmo et al., 2010; Sharman et al., 2005], which is equivalent to \(\lambda = 0.10 - 0.14\) for the

![Figure 3-10 Good agreement between the measured values of \(C_{d,c}\) in the present study and experimental study of Ozeren et al. [2014] averaged over the drag-dominated regime \((KC>20)\) with calculated values of \(C_{d,c}\) using equation (3-7) plotted in terms of canopy density \(\lambda\).]
present staggered configuration (to maintain the same spacing between any two tandem cylinders within the array). Consequently, we find that the drag coefficients of arrays with specific densities of 0.10 and 0.14 are enhanced for $KC \geq 30$ (Figure 3-9) and even exceed the $C_{d,p}$ of the array with a density of 0.22 that is most enhanced by the blockage effect. It should be noted that for $KC/s < 6$ (or $KC\sqrt{\lambda} < 7.5$), either there is no vortex shedding or the flow excursion amplitude is not large enough for the vortices shed from each cylinder to effectively impinge on a downstream cylinder and enhance its drag and transverse forces.

Although the sheltering effect was present, it was generally ineffective in substantially modifying canopy drag, except at very low densities. This is based on the fact that canopy drag coefficients were clearly enhanced (relative to that of a single cylinder) at medium to high densities, whereas the sheltering mechanism acts to reduce the drag. The blockage effect and also the critical spacing (for $\lambda = 0.10 - 0.14$) ultimately becomes dominant over the sheltering effect causing the drag coefficients to significantly increase as the canopy density increases (Figure 3-9). Therefore, while it was expected that sheltering decreases the canopy drag for $KC\sqrt{\lambda} \geq 1.25$ or $KC/s \geq 1$, the present results reveal that sheltering is noticeable only at $KC > 15$ and in the sparsest canopy ($\lambda = 0.02$), where the drag force is reduced compared to that of single cylinder. In such a sparse canopy, the cylinder spacing is greater than the critical spacing (i.e. $s > s_c$) and also the interactions between neighbouring cylinders are weak, such that both the critical cylinder spacing effect and the blockage effect are not significant. Finally, it is important to note that the sheltering effect can be highly arrangement-specific and its significance in a non-staggered / random array depends strongly on the relative positions of cylinders, as was illustrated by Etminan et al. [2017] for the case of unidirectional flow.

In the alternative low $KC$ limit (i.e. $KC < 7$) where the flow is in the inertia dominated regime, the canopy drag coefficients are not significantly affected either by the blockage effect, the sheltering effect nor the critical cylinder spacing. This is due to the fact that at such low $KC$ the flow excursion amplitude is small and the interactions between neighbouring cylinders are limited. Therefore, the canopy drag coefficient in inertia dominated regime can be estimated based on single cylinder values alone, independent of canopy density.
Finally, we consider the likely applicability of the present study results to a wider range of flow conditions than in the present study. While only Reynolds number of 100 is considered in this study, which is at the lower end of practical flow conditions [Ghisalberti and Nepf, 2002], we postulate that the same general mechanisms and drag coefficient trends would also hold at higher Reynolds numbers. Several studies have suggested that in the inertia dominated regime ($KC < 7$), the mean drag coefficient of group of cylinders is very close to that of a single cylinder for any given $KC$ [Anagnostopoulos and Dikarou, 2011; Bonakdar et al., 2015; Chern et al., 2013; Tong et al., 2015]. For unidirectional flow, which is considered to be equivalent to drag dominated oscillatory flow ($KC \geq 20$), it has been already shown that the blockage effect is the dominant mechanism that governs the canopy drag coefficient over a wide range of Reynolds number ($Re_c < 6000$) and equation (3-7) can be used to accurately estimate $C_{d,c}$. Although the results would strictly be most applicable to emergent canopies, we also suggest that the results of this study would likely be relevant to dense submerged canopies ($ah > 0.1$ where $a$ is canopy frontal area) where flow velocity is independent of depth over most of the height of the canopy [Nepf, 2011a]. The results in this present study specifically focused on canopies in a uniform-spaced array, so further work is needed to assess the extension of the results to random arrays. However, the results from Etminan et al. [2017] for unidirectional flow found that equation (3-7) can predict the bulk drag coefficient of randomly arranged canopies within 10%, thus showing some promise in extending the present results to random arrays. Lastly and in spite of focusing on vegetation canopies, investigations on wave loads on cylindrical marine structures, which are usually arranged as groups of cylinders, may also benefit from the present study results.

### 3.6 Conclusions

Numerical simulations of flow through arrays of circular cylinders (with solid fractions ranging from 0.02 to 0.22) were conducted to investigate the mechanisms responsible for drag modification within emergent vegetation in oscillatory flow. The simulations covered a wide range of $KC$ that spanned the inertia-dominated ($KC < 7$), intermediate drag-inertia ($7 \leq KC < 20$) and drag dominated regimes ($KC \geq 20$), while the Reynolds number was kept constant at 100. The significance of the blockage and sheltering effects in altering the drag force exerted on cylinders inside an array relative to that of a single cylinder were evaluated. This analysis revealed that blockage effect is the dominant
mechanism responsible for increasing the canopy drag coefficient in the drag dominated regime for medium to high density canopies ($\lambda \geq 0.06$). A recently proposed drag formulation for canopies in unidirectional flow was found appropriate to estimate the drag coefficient of canopies in drag-dominated oscillatory flow. Similar to tandem cylinders in unidirectional flow, it was observed that canopy drag is augmented for $KC \geq 20$ when the cylinders spacing was in the range of critical spacing $s_c$ ($\lambda = 0.14 - 0.10$). Sheltering was found to play only a minimal role, only slightly reducing the drag coefficient in sparsest canopies ($\lambda \leq 0.02$). In conclusion, the results of this study indicate that

- In inertia dominated regime ($KC < 7$), the drag force is not affected by the interactions between cylinders and canopy drag coefficient and can be estimated based on single cylinder values alone, independent of canopy density.

- In the drag dominated regime ($KC \geq 20$), the blockage effect dominates the drag and equation (3-7) can be used to estimate the canopy drag coefficient.

While in the present study the Reynolds number was set at 100, we expect similar mechanisms govern the canopy drag coefficient at higher Reynolds number but actual drag coefficient values could be modified. The results of this study can be used as a basis for developing new predictive formulations for specifying bulk canopy drag coefficients and quantifying wave attenuation by coastal vegetation.
Chapter 4
Predicting bed shear stress in vegetated channels

4.1 Introduction

Aquatic vegetation often has a significant influence on the flow in rivers, floodplains and coastal areas. The vegetation creates velocity and turbulence intensity profiles near the bed that deviate from those in flows over bare beds [Liu et al., 2008; Nepf, 1999; Yager and Schmeckle, 2013]. As a consequence, sediment transport characteristics can be significantly altered when flow moves through vegetation canopies [Nepf, 2012]. Vegetated beds often contain finer sediment (with higher organic and nutrient content) than unvegetated regions [Clarke and Wharton, 2001; Larsen et al., 2009] and display higher rates of sediment deposition [Corenblit et al., 2007; James et al., 2004]. The increased sediment deposition can promote vegetation propagation and can enhance channel stability [Afzalimehr and Dey, 2009; Pollen-Bankhead and Simon, 2010]. In addition, sediment transport significantly affects the function and morphology of channels [Bennett et al., 2008; Robbins and Simon, 1983] and the turbidity of fish habitats [Lenhart, 2008; Montakhab et al., 2012]. These and other applications emphasize the importance of understanding the mechanisms that drive sediment transport in aquatic vegetation, and the need to develop robust predictive formulations.

Conventional models that are used to predict sediment transport over bare beds are not applicable to vegetated channels [Nepf, 2012]. In bare-bed channels, the onset and rates of sediment transport are typically related to the bed shear stress $\tau_b$. The bare bed shear stress can be estimated using several methods such as fitting the mean velocity profile based on a logarithmic Law of the Wall, by the water surface slope method which relies

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on a momentum balance, by extrapolating near-bed turbulent stress and using the empirical relation between turbulent kinetic energy (TKE) and bed shear stress (for detailed descriptions of these methods see Biron et al. [2004]). None of these methods are strictly applicable to vegetated channels, due partly to the impact of vegetation on the velocity profile and turbulence production [Yang et al., 2015]. For example, while the shear stress on bare beds can be estimated by extrapolating the linear vertical distribution of turbulent shear stresses to the bed, for vegetated regions the turbulent stress profile is not known *a priori*.

In practice it is important to be able to estimate the bed shear stress in vegetated regions based on parameters that can be easily measured, such as the vegetation density or solid fraction \( \lambda = (\pi/2)(d/s)^2 \), where \( d \) is the stem diameter and \( s \) is stem spacing) and pore velocity \( U_p = Q/Wh(1-\lambda) \), where \( Q \) is the channel discharge, \( W \) is the channel width and \( h \) is the flow depth. While it is not yet clear if sediment transport within vegetation canopies can be predicted based on the bed shear stress alone, it is reasonable to expect that bed shear stresses play a contributing role [Nepf, 2012]. In search of a predictive tool for vegetated bed shear stress, Yang et al. [2015] proposed a Linear Stress Model (LSM) that defines a viscous layer with a thickness of \( H_v \) immediately above the bed, within which the turbulent stress is negligible and the viscous stress decreases linearly with distance from the bed, resulting in a parabolic velocity profile. This assumption which indicates that the bed shear stress is governed by the thickness of the viscous layer \( H_v \), holds over most of the viscous layer except very close to the bed \( z^+ = z u_* / \nu < 5 \) with \( u_* \) as friction velocity and \( \nu \) as the kinematic viscosity) where the viscous stress is constant [Kundu et al., 2012], as represented in Figure 4-1. In the upper water column

![Figure 4-1](image.png)

*Figure 4-1 The velocity profile \( u(z) \) in emergent canopies (with green lines representing vegetation stems) can be approximated by (b) the velocity profile defined by the Linear Stress Model. The thickness of the viscous layer \( H_v \), within which the viscous stress is non-negligible and varies approximately linearly with distance from the bed, is indicated in (b) by the dashed line.*
(\(z \geq H_v\)), the streamwise velocity is assumed to be vertically-uniform such that viscous stress is negligible. It was found that this two-part velocity profile agreed well with velocity profiles measured along spanwise transects between rows of emergent dowels using both the friction velocity \(u_* = \sqrt{\tau_b/\rho}\) (with \(\rho\) indicating fluid density) and \(H_v\) as fitting parameters [Yang et al., 2015]. For sufficiently dense vegetation “canopies” (i.e. with a frontal area per volume, \(a\), that exceeds 4.3 m\(^{-1}\) [Yang et al., 2015]) and below a transition Reynolds number (i.e. \(Re_h = U_p h/\nu < 6000\)), the thickness of the viscous layer \(H_v\) was proposed to equal \(d/2\) associated with the coherent structures formed near the base of each stem. Above this transition Reynolds number, \(H_v\) is assumed to be the same in both bare and vegetated channels. Therefore, Yang et al. [2015] proposed that the spatially averaged thickness of the viscous layer could be estimated as \(H_v = \min(d/2, 22\nu/u_*)\), where the latter term in the parentheses denotes the value for a bare bed. However, the physical mechanisms governing \(H_v\) need to be further investigated over a wider range of Reynolds number and canopy density to ensure this relationship is broadly applicable. Specifically, the relationship between \(H_v\) and \(d/2\) has been attributed to strong vertical velocity induced by the coherent structures that are formed near the base of each stem. However, such strong vertical velocity is only observed in the vicinity of stems (see Figure 5 in Stoesser et al. [2010]), where the LSM does not actually hold and the local stress deviates significantly from the spatially-averaged value.

In contrast to bare beds, bed shear stress distributions in the presence of vegetation are highly spatially-variable [Nepf, 2012]. The onset of sediment resuspension and higher rates of sediment transport are both more likely to occur locally in the regions with higher bed shear stress. Experimental studies of bed shear stresses in the presence of vegetation have usually adopted one of two approaches: (1) measuring the velocity profiles at a limited number of points within the canopy [Yang et al., 2015] or (2) estimating values by measuring the energy slope (total flow resistance) and subtracting the predicted vegetative drag [Jordanova and James, 2003; Kothyari et al., 2009]. Neither of these approaches is capable of effectively capturing the spatial variability of bed shear stress. In contrast, high-resolution computational fluid dynamics (CFD) simulations can provide direct and detailed measurements of shear stress over an entire bed. In recent years, Large Eddy Simulation (LES) has proven to be a reliable tool for modeling complex flow around finite length bluff bodies and estimating the bed shear stress in open-channel
flows [Khosronejad et al., 2013; Kim et al., 2014; Sotiropoulos and Khosronejad, 2016]. LES has also been successfully used in modeling flow through both emergent and submerged rigid aquatic canopies [Chang and Constantinescu, 2015; Chang et al., 2017; Cui and Neary, 2008; Salvador et al., 2007; Stoesser et al., 2010; Stoesser et al., 2009]. Therefore, LES is an appropriate tool to address the aims of this study.

In this study, we employ LES and analyze previous experimental data sets to investigate the bed shear stress within emergent canopies, modeled here as staggered arrays of cylinders. First, we determine the effects of canopies on bed shear stress through highly-resolved 3D model simulations that allow determination of the average stress far more accurately than previous methods. We then adapt the Linear Stress Model by providing a new accurate, experimentally-validated formulation for the viscous layer thickness $H_v$. This will make it possible to develop full predictive capacity for bed shear stress over a much wider and realistic range of flow and canopy characteristics.

4.2 Numerical Modelling

4.2.1 Numerical Methods and Model Configuration

The results presented in this study are based on the numerical approach detailed in Etminan et al. [2017], with only a summary of that approach included here. Three-dimensional Large Eddy Simulations (LES) were used to model the flow through emergent canopies. In LES, the spatially-filtered, three-dimensional, time-dependent Navier-Stokes equations are solved numerically for all motions with a scale larger than the mesh size of the numerical grid, while smaller-scale motions are simulated using a subgrid scale (SGS) model (i.e. standard Smagorinsky model). The filtered equations in tensor notation are

$$\frac{\partial \hat{u}_i}{\partial x_i} = 0$$  \hspace{1cm} (4-1)

$$\frac{\partial \hat{u}_i}{\partial t} + \frac{\partial}{\partial x_i}(\hat{u}_j \hat{u}_i) = -\frac{1}{\rho} \frac{\partial \hat{p}}{\partial x_i} + \frac{\partial (2\nu S_{ij})}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j}$$ \hspace{1cm} (4-2)

where $i$ and $j$ vary from 1 to 3. $u_i$ are the velocity vector components ($u_1$ and $u_2$ are in the stream-wise and span-wise directions and are denoted as $u$ and $v$ hereafter, respectively), $p$ is the pressure and $S_{ij}$ is the rate of strain of the resolved flow field. The hat $\hat{}$ denotes spatially-filtered variables. All simulations were conducted using
OpenFOAM version 2.3.0, which has been widely used for modeling flow around bluff bodies [Lloyd and James, 2015; Lysenko et al., 2012; 2014; Sidebottom et al., 2015].

Due to the complexity of modeling the geometry of real natural canopies, it is common practice to approximate aquatic canopies as arrays of rigid circular cylinders [Dean, 1978; Ghisalberti and Schlosser, 2013; Hu et al., 2014; Lowe et al., 2005; Nepf, 1999; Tanino and Nepf, 2008a; Yang et al., 2015]. This study investigates the bed shear stress in the presence of emergent aquatic canopies, which tend to have stiff, rounded stems [Nepf, 2011b]. The rigid cylinder mimics are thus a reasonable proxy for a range of natural canopies (e.g. reeds, marsh grasses, etc.). Rigid cylinders do not, however, capture the pronation and flow-induced motion of flexible vegetation, such that extension to the full range of aquatic canopies requires additional consideration. In this study, four rigid emergent cylinders in a staggered arrangement were included within the computational domain and, to mimic an infinite array of cylinders, cyclic boundary conditions were imposed in both the streamwise and spanwise directions (Figure 4-2). A mean pressure gradient was imposed in the streamwise direction to drive the flow at the specified velocity. At the bed and cylinder surfaces, a no-slip condition was applied. To avoid the complexity of modeling the free surface, the upper boundary of the domain was treated as a frictionless rigid lid. The array solid fraction or density $\lambda$ was varied by adjusting the cylinder spacing, $s$ (Figure 4-2a). In this study, six array densities were modeled: $\lambda = 0.016, 0.04, 0.08, 0.12, 0.20, \text{ and } 0.25$ (Table 4-1). Given that $s/d = 1/\sqrt{2\lambda/\pi}$, this corresponds to $s/d = 10, 6.3, 4.4, 3.6, 2.8, \text{ and } 2.5$, respectively. These values of $\lambda$ were chosen to cover the densities of a wide range of aquatic vegetation, from marsh grasses [Nepf, 2011b] to mangroves [Mazda et al., 1997]. The flow depth, $h$, was equal to $10d$ in all cases.

**Figure 4-2** (a) The model domain and arrangement of cylinders (shown for $\lambda=0.08$). Dashed lines denote mesh block boundaries and dotted line indicates the transect along which the constricted cross-section velocity $U_c$ (equation (4-9)) was calculated. (b) One set of the computational grid, consisting of O-grid and H-grid mesh blocks.
The grid topology consisted of four sets of cells (one for each cylinder), with each set consisting of an O-grid block around the cylinder and a Cartesian H-grid block in the far field (Figure 4-2b). The H-grid was uniform in the horizontal plane but the size of the O-grid cells was decreased as each cylinder is approached. In the vertical direction, the cell sizes decreased toward the bed. In all simulations, the cell sizes adjacent to solid surfaces (i.e., around each cylinder and at the bed) were chosen such that the maximum dimensionless wall distance of the first cell $n^+ (= n u_*/v$ where $n$ is the normal distance from the wall) was kept below 1, ensuring that the first grid point was well within the viscous sublayer.

The simulations were allowed to run for at least 15 flow-through periods to reach a fully developed condition before any data was collected. Time-averaging of flow parameters was performed over a period of 45 flow-through cycles. Simulations were carried out at four Reynolds numbers ($Re_p = U_p d / v = 200, 500, 1000$ and $1340$) for each canopy density (Table 4-1). These Reynolds numbers are typical of those in flows through aquatic vegetation [Nepf, 2011b].

### 4.2.2 Model Data Analysis

The spatially-averaged friction velocity was calculated as
where $\bar{\tau}_b$ is derived from the temporally-averaged stream-wise velocity profile:

$$\bar{\tau}_b = \mu \left( \frac{\partial \bar{u}}{\partial z} \right)_{z=0}$$

with $\mu$ as the dynamic viscosity. The angular brackets $\langle \rangle$ indicate spatial averaging over the horizontal plane. There are alternative measures of the friction velocity that take into account the spanwise component of mean velocity, which can be non-negligible in the tortuous flow through arrays. However, the effect of the spanwise velocity is second-order and has been neglected for simplicity (see Section 4.4.5 for more detail). In addition, the spatially-averaged LSM friction velocity $\langle u_+ \rangle_{\text{LSM}}$ and the thickness of the viscous layer $H_v$ were determined by a least-squares fitting of the temporally- and spatially-averaged streamwise velocity vertical profile $\langle \bar{u} \rangle$ to the analytical profiles obtained through assumption of a linear stress profile:

$$\langle \bar{u} \rangle = \begin{cases} \frac{(\langle u_+ \rangle_{\text{LSM}})^2}{\nu} \left( z - \frac{z^2}{2H_v} \right), & z \leq H_v \\ \frac{(\langle u_+ \rangle_{\text{LSM}}H_v}{2\nu}, & z \geq H_v \end{cases}$$

[Yang et al. [2015]. Consequently, $\langle u_+ \rangle_{\text{LSM}}$ can be expressed as

$$\langle u_+ \rangle_{\text{LSM}} = \sqrt{\frac{2\nu U_o}{H_v}}$$

where $U_o$ is the uniform streamwise velocity in the upper layer ($z \geq H_v$).

In Section 4.4.3, we propose an alternative approach to that of Yang et al. [2015] for estimating the thickness of the viscous layer $H_v$. This approach centres around development of a scaling relationship for the balance between TKE production and viscous dissipation at the bed. For the purpose of validating this balance and also to investigate the relationship between bed shear stress and TKE in vegetated flows, the temporally- and spatially-averaged TKE was determined as

$$\langle \bar{k} \rangle = 0.5 \left( \langle u'^2 \rangle + \langle v'^2 \rangle + \langle w'^2 \rangle \right)$$
where \( u', v', \) and \( w' \) denote the three components of the turbulent velocity fluctuations. For comparison, TKE was also estimated using the model proposed by Tanino and Nepf [2008b]:

\[
\langle k \rangle = \begin{cases} 
1.21 U_p^2 c_{d,p}^{\text{form}} \frac{\lambda}{(1 - \lambda) \pi/2}^{2/3}, & d/s_n < 0.56 \\
0.77 U_p^2 c_{d,p}^{\text{form}} \frac{s_n}{d} \frac{\lambda}{(1 - \lambda) \pi/2}^{2/3}, & d/s_n \geq 0.56
\end{cases}
\] (4-8)

where \( s_n \) is the average surface-to-surface distance between a cylinder and its nearest neighbor (Table 4-1) and \( c_{d,p}^{\text{form}} \) is the form drag coefficient using \( U_p \) as the reference velocity (\( c_{d,p}^{\text{form}} = F_d^{\text{form}} / 0.5 \rho hdU_p^2 \)). Although the total drag force exerted on each cylinder consists of both form and viscous drag forces, only the form drag is considered in equation (4-8) as it transforms large-scale, shear-generated TKE into small-scale TKE in cylinder wakes, whereas the viscous drag provides a direct sink to heat for TKE [Raupach and Shaw, 1982]. It has been shown that the drag coefficient of arrays of cylinders can be estimated using the typical formulations for the drag coefficient of a single isolated cylinder when the average velocity over the constricted cross-sections of an array, namely \( U_c \), is used as the reference velocity [Etminan et al., 2017]. For staggered arrays of cylinders used in this study, this constricted cross section velocity \( U_c \) can be calculated as

\[
U_c = \frac{1 - \lambda}{1 - \sqrt{2\lambda/\pi}} U_p.
\] (4-9)

In addition, the present numerical results show that in the range of Reynolds number used in this study the form drag constitutes 90% of the total drag which yields

\[
c_{d,c}^{\text{form}} = 0.9 \left(1 + 10Re_c^{-2/3}\right)
\] (4-10)

where \( Re_c = U_c d/\nu \) is the Reynolds number based on \( U_c \) [Etminan et al., 2017]. Based on the definition of drag coefficient, the value of \( c_{d,p}^{\text{form}} \) can be then predicted as

\[
c_{d,p}^{\text{form}} = \frac{U_c^2}{U_p^2} c_{d,c}^{\text{form}}.
\] (4-11)
4.2.3 Model Validation

The numerical model has been previously validated against experimental data of mean and turbulent velocity in emergent canopy arrays [Etminan et al., 2017]. However, to further confirm the accuracy of the model in capturing the near-bed flow and bed shear stress, numerical results were compared to the experimental data of Yang et al. [2015]. In that study, streamwise velocity profiles in emergent cylinder arrays were measured at eleven locations between \( y/s = 0 \) and \( y/s = 0.5 \) along a transect at \( x/s = 0.5 \) (Figure 4-3a). A grid was generated to incorporate the specific canopy array geometry used in Yang et al. [2015], while maintaining the same grid scheme described in section 4.2.1. The flow was adjusted so that \( Re_p = 328 \), matching the experimental flow condition. There was very good agreement between observed and model velocity profiles \((R^2 = 0.88)\), both near the bed and in the upper water column (Figure 4-3a). Here velocities are normalized by \( \langle u_* \rangle_{LSM} \), obtained from equation (6) by spatially averaging the velocity profile along the transect only and not over the whole domain, consistent with the experimental measurement locations. Generally, the flow velocity increases along the transect from \( y/s = 0 \) towards \( y/s = 0.5 \), due to diminished sheltering from the upstream cylinder. The slight velocity overshoot and the near-zero values very close to the bed observed in the profiles at \( y/s \leq 0.2 \) and \( y/s \leq 0.065 \), respectively, are due to the formation of secondary flow pattern at the base of the upstream cylinder. Importantly, the value of

![Figure 4-3](image-url)

**Figure 4-3** Comparison of model results (lines) with the experimental results (symbols) of Yang et al. [2015]. (a) Dimensionless temporally-averaged streamwise velocity \((\bar{u}/\langle u_* \rangle_{LSM})\) profiles in the near-bed region at 11 locations along a transect \((y/s=0.5)\) at \( x/s=0.5 \) (as shown in the inset). Each velocity profile is offset horizontally by 3 units relative to the preceding profile. (b) Normalized viscous and Reynolds stress profiles averaged over the same transect.
\langle u_+ \rangle_{LSM} \text{ calculated in the model is } 0.0057 \text{ m s}^{-1}, \text{ within 5\% of the experimental result of 0.0055 m s}^{-1}. \text{ In addition, the viscous } (\mu \cdot \partial \bar{u} / \partial z) \text{ and Reynolds stress } (-\rho \bar{u}' \bar{w}') \text{ profiles averaged over the same transect are in excellent agreement with experimental data } (R^2 = 0.95 \text{ and } 0.81, \text{ respectively}; \text{ Figure 4-3b}). \text{ As in the profile of mean velocity, the overshoot in the Reynolds stress profile is associated with the secondary flow formed at the base of the upstream cylinder.}

4.3 Results

4.3.1 Influence of Canopy Density on Bed Shear Stresses and Stem Wakes

4.3.1.1 Spatial variability of Bed Shear Stresses

The temporally-averaged bed shear stress (\bar{\tau}_b) distributions display high spatial-variability (Figure 4-4). Although for sparse canopies the \bar{\tau}_b distributions eventually become approximately uniform far from the cylinders, \bar{\tau}_b is highly variable throughout denser arrays. Locally there is a small area with negative shear stress immediately upstream of each cylinder (indicated in blue in Figure 4-4), as a result of the horseshoe vortex formation at the base of cylinders. There is another area with negative shear stress downstream of each cylinder due to the recirculation in the wake region. Such regions of negative bed shear stress have been observed around single cylinders (e.g. Sumer [2002]). However, we note that both areas with negative shear stress become constrained by neighboring cylinders in the streamwise and spanwise directions as the

![Figure 4-4](image)

Figure 4-4 Contours of dimensionless temporally-averaged bed shear stress (\bar{\tau}_b/\rho U_p^2) at \text{Re}_p=1000 \text{ and three canopy densities of (a) } \lambda=0.016, \text{ (b) } \lambda=0.08 \text{ and (c) } \lambda=0.25. \text{ Contours in panels (b) and (c) are presented by repeating the computational domain (of four cylinders) to keep the dimensions of the three panels consistent. The flow direction is denoted by the arrow in (a).}
canopy density increases. Small areas with elevated stress on each side of the cylinder (indicated in dark red in Figure 4-4) are due to the local contraction of streamlines. The normalized magnitude of $\tau_b$ in these areas increases with canopy density.

The substantial spatial variability of bed shear stresses has important implications for understanding sediment transport patterns and also for conducting experimental measurements of bed shear stresses in the presence of vegetation. Contours of dimensionless temporally-averaged bed shear stress (Figure 4-4) reveal that canopy stems strongly modify the shear stress distribution, similar to what has been observed around isolated cylindrical piers [Sumer et al., 2001]. Similarly, a magnified view of the friction velocity distributions (Figure 4-6) indicates that for sparse canopies and in areas away from the canopy stems, the local friction velocity is close to the spatially-averaged value (indicated in white); whereas directly adjacent to each cylinder the friction velocity can locally be either highly elevated or reduced. As canopy density increases, the stem spacing decreases and regions around stems that experience highly variable shear stress cover a larger fraction of the total bed area; for example at $\lambda = 0.25$ (Figure 4-6c) there is only a very small portion of the bed that has a local shear stress approximately equal to the spatially-averaged value. Therefore, there can be large errors associated with measuring the bed shear stress at only a limited number of accessible locations, especially in denser canopies.
The spatial variability of dimensionless friction velocity $u' / \langle u' \rangle$ increases with canopy density: (a) $\lambda = 0.016$, (b) $\lambda = 0.08$ and (c) $\lambda = 0.25$. All panels display an area of dimensions $s \times s/2$; as the ratio of $s/d$ decreases with canopy density, the cylinders (of diameter $d$) appear larger at higher canopy densities. The dashed lines indicate the circular near-cylinder regions of diameter $d_c$ where data are excluded from calculating spatially-averaged values (see Table 4-1 and section 4.3.1.2).
4.3.1.2 The Near-Cylinder Region

To be able to determine the validity of the LSM, we first exclude the near-cylinder data from spatial averaging; in particular, within circular regions of diameter $d_e$ from the cylinder center (denoted by the dashed-line circles in Figure 4-5). The LSM is not valid in these regions (which encompass the near wakes of the cylinders) because of secondary flow structures and the resultant deviation of the local near bed viscous stress profile from a linear distribution [Yang et al., 2015]. In addition, for a mobile sediment bed, the regions of augmented bed stress areas close to canopy elements (indicated by dark red and blue colors in Figure 4-5) are prone to formation of scour holes. This bed response serves to diminish the near-cylinder stresses, such that these regions are not responsible for large fractions of bulk sediment fluxes at the canopy scale [Yang et al., 2015].

The value of $d_e$ for each canopy density was determined based on the size of the wake in the lee of each cylinder ($d_e = 2 \times \text{size of the wake} + d$; see Figure 4-5), with values summarized in Table 4-1. Figure 4-6 shows that the wake region of a cylinder contracts with increasing canopy density. Streamlines plotted on a vertical plane cutting through the center of a cylinder reveal that the streamwise extent of the wake region behind a cylinder reduces from ~0.75$d$ to 0.2$d$ as the canopy density increases from 0.016 to 0.25 (Figure 4-5). This reduction in the wake region is due to the constraining effects of neighboring cylinders on the pressure field [Etminan et al., 2017].

![Figure 4-6 Contours of dimensionless temporally-averaged streamwise velocity ($\bar{u}/U_p$) with temporally-averaged streamlines in a vertical plane (shown by the dotted line at top right) for densities of (a) $\lambda=0.016$, (b) $\lambda=0.08$ and (c) $\lambda=0.25$ ($Re_p=1000$). The wake areas with negative streamwise velocities (indicated in blue) become constrained by neighboring cylinders as the canopy density increases.](image)
almost vertically-uniform, except in the region very close to the bed where it is affected
by the horseshoe vortex.

4.3.1.3 Friction Velocities

In turbulent boundary layer flow over a smooth plate, the friction velocity is a function of
just the Reynolds number [Kundu et al., 2012]. However, for flow over a vegetated bed,
the spatially-averaged friction velocity \( \langle u_\ast \rangle \) depends on both the Reynolds number \( R_{ep} \)
and canopy density \( \lambda \) (Figure 4-7a). The friction velocity (normalized by \( U_p \)) increases
with canopy density, with this enhancement being more significant at lower Reynolds
numbers. In addition, the dimensionless friction velocity decreases slightly with Reynolds
number (\( R_{ep} \)). The ratio \( u_{\ast,\text{max}}/\langle u_\ast \rangle \) ranges from 1.9-2.8 and is higher in sparser canopies
(Figure 4-7b). The observed increase in \( \langle u_\ast \rangle/U_p \) and decrease in \( u_{\ast,\text{max}}/\langle u_\ast \rangle \) with canopy
density are both likely due to the greater areal fraction in denser canopies that is
comprised of the high stress regions near cylinders (Figure 4-5), which serves to increase
the estimated value of \( \langle u_\ast \rangle \). The same trends as \( \langle u_\ast \rangle/U_p \) are observed in the local
maximum values \( (u_{\ast,\text{max}}) \) of the friction velocity (Figure 4-7c) which occur in areas with
elevated shear stress located laterally on each side of cylinders. The observed increase in
\( u_{\ast,\text{max}}/U_p \) with canopy density for given \( R_{ep} \) is likely due to the increasing enhancement
of flow velocity in the constricted-cross sections of canopies at higher densities (i.e.
\( U_C/U_p \) increases with \( \lambda \); for more details see Etminan et al. [2017]), which in turn
significantly enhances \( u_{\ast,\text{max}} \).

Figure 4-7 Variation with \( R_{ep} \) of (a) the dimensionless spatially-averaged friction velocity \( \langle u_\ast \rangle/U_p \), (b) the
ratio of \( u_{\ast,\text{max}}/\langle u_\ast \rangle \) and (c) the dimensionless local maximum friction velocity \( u_{\ast,\text{max}}/U_p \). Both normalized
friction velocities increase significantly with canopy density, while the ratio \( u_{\ast,\text{max}}/\langle u_\ast \rangle \) decreases with
canopy density.
4.3.2 The Applicability of the Linear Stress Model in Vegetated Flows

4.3.2.1 Velocity Profile

To assess the ability of the Linear Stress Model (LSM) to reproduce the near-bed flow characteristics, the modeled velocity profiles were compared to those predicted by the LSM (Figure 4-8). The LSM velocity formulation (described in equations (4-5) and (4-6)) was fitted to the temporally- and spatially-averaged streamwise velocity \( \langle u \rangle \) for three canopy densities \( \lambda = 0.016, 0.08 \) and \( 0.25 \). At a constant Reynolds number, the thickness of the viscous region \( d_v \) (indicated by the dashed line in Figure 4-8) decreases with canopy density. This generates an increase in the spatially-averaged friction velocity (normalized by \( U_p \)), as seen in Figure 4-7. Note that the overshoot in the velocity profile just above \( d_v \) is due to the formation of the secondary flow pattern near the base of the cylinders, and is more pronounced at higher canopy densities.

4.3.2.2 Viscous Layer Heights

The LSM suggests that the thickness of the viscous layer \( H_v \) is required for calculating the friction velocity for any given flow velocity (equation (4-5)). \( H_v \) decreases with Reynolds number \( Re_p \) and canopy density \( \lambda \), consistent with the trends in the friction velocities...
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For sparser canopies ($\lambda \leq 0.08$), $d_v$ appears to strongly depend on canopy density, decreasing by approximately 50% as the canopy density increases from 0.016 to 0.08. However, for denser canopies ($\lambda > 0.08$) this dependence is greatly diminished.

4.3.2.3 Friction Velocities

As shown in Figure 4-10, the friction velocity estimates from the LSM ($\langle u_* \rangle_{LSM}$, equation (4-6)) agree very well with those calculated directly from the velocity gradient at the bed ($\langle u_* \rangle$, equation (4-3)). This agreement is excellent across all canopy densities. At the highest Reynolds number ($Re_p = 1340$), $\langle u_* \rangle_{LSM}$ is slightly less than $\langle u_* \rangle$.

4.3.3 Turbulent Kinetic Energy

In cylinder arrays, the turbulence intensity is often dominated by the production of turbulence in the wake of cylinders, except very near the bed [Nepf, 1999]. Based on turbulent and mean kinetic energy budgets, Tanino and Nepf [2008b] proposed a model to estimate the temporally- and spatially-averaged TKE in arrays of emergent cylinders (equation (4-8)). This model agrees very well with the numerical results of the present study (Figure 4-11). The increasing TKE at higher canopy densities is a result of a greater injection of wake turbulence by a greater number of cylinders per unit area. Note that the formulation used by Tanino and Nepf [2008b] to determine $C_{d,p}^{form}$ is a function of canopy density only (i.e. equations (2.10) and (2.11) in their paper) while the formulation used

Figure 4-9 Variation of the dimensionless viscous layer height $H_v/d$ with $Re_p$ for different canopy densities. $H_v$ is substantially higher in sparser canopies and becomes less sensitive to changes in canopy density in denser canopies. (Figure 4-9)
here is a function of both canopy density and Reynolds number (equations (4-10) and (4-11)). This alternative model for the drag coefficient yields four curves in Figure 4-11 (one for each Reynolds number) and a discontinuity at $\lambda \approx 0.1 \left( \frac{d}{s_n} = 0.56 \right)$ where there is a transition in the piecewise model. The agreement between the numerical values

![Graph](image1)

Figure 4-10 Agreement between the two estimates of spatially-averaged friction velocity obtained through (i) the Linear Stress Model $\langle u_* \rangle_{LSM}$ (i.e. calculated from equation (4-6)) and (ii) using the velocity gradient at the bed $\langle u_* \rangle$ (equation (4-3)).

![Graph](image2)

Figure 4-11 The numerical values of dimensionless temporally- and spatially-averaged turbulent kinetic energy $\left( \frac{\langle u^2 \rangle}{U_p} \right)^{1/2}$ (symbols) compare well to the proposed model of Tanino and Nepf [2008b] (lines). The discontinuity in model curves at $\lambda = 0.1 \left( \frac{d}{s_n} = 0.56 \right)$ corresponds to the transition point of the piecewise model (equation (4-8)).
of TKE and the predictions from Tanino and Nepf [2008b] makes it possible to use equation (4-8) in our proposed model for predicting the viscous layer thickness based on a TKE balance (section 4.4.3).

4.4 Discussion

4.4.1 Turbulent Kinetic Energy

For flow over a bare bed, the bed shear stress is directly related to the near-bed TKE:

\[
\langle \tau_b \rangle = C \left[ \frac{1}{2} \rho \left( \langle u'^2 \rangle + \langle v'^2 \rangle \right) \right]
\]

(4-12)

where \( C \) is a proportionality constant approximately equal to 0.19 [Biron et al., 2004; Kim et al., 2000]. On the other hand, turbulence in vegetated channels is dominated by the turbulence generated in the cylinder wakes [Nepf, 1999; Nepf and Vivoni, 2000] and, therefore, may not directly be related to bed shear stress. This may explain why bed shear stress models based on open channel studies that relate bed shear stress to TKE do not work in vegetated channels [Tinoco and Coco, 2014; Yager and Schmeeckle, 2013].

Figure 4-12 The proportionality constant \( C \) relating bed shear stress \( \langle \tau_b \rangle \) to TKE (equation (4-12)) is close to that of bare beds \( C=0.19 \) (dashed line) where wake-generated turbulence is small compared to bed-shear-generated turbulence. This occurs for the lowest Reynolds number \( (Re_p=200) \) and for \( Re_p=500 \) in sparse canopies \( (\lambda =0.016 \) and \( 0.04 \) (see inset). As the canopy density and Reynolds number increase, wake-generated turbulence becomes dominant and the proportionality constant approaches 0.05 (solid line).
The ratio of stress to TKE in vegetated channels is generally lower than that of bare beds, with some dependency on canopy density and Reynolds number (Figure 4-12). At the lowest Reynolds number considered ($Re_p = 200$), in which the wakes would be expected to be in early stages of transition from the laminar to turbulent regimes [Posdziech and Grundmann, 2001], the turbulence generated in the cylinder wakes is not significant and the proportionality constant $C$ in equation (4-12) is close to that of bare beds, $C = 0.19$ (see inset in Figure 4-12). In sparse canopies ($\lambda = 0.016$ and 0.04) at moderate Reynolds number ($Re_p = 500$), the wake-generated turbulence is not yet dominant, with the corresponding data points close to the bare-bed line. However, as canopy density and Reynolds number increase, the wake-generated turbulence becomes more significant and the proportionality constant reduces below 0.19 and approaches a limit of 0.05. These results confirm that a constant relationship between bed shear stress and TKE is not valid in vegetated channels.

4.4.2 Evaluating the Linear Stress Model
The LSM provides a means of estimating the bed shear stress in vegetated channels by identifying a viscous layer at the bed, where the viscous stress decreases linearly with distance from the bed, thereby resulting in a parabolic velocity profile [Yang et al., 2015]. Above the viscous layer, the viscous stress is negligible and the mean streamwise velocity is assumed vertically uniform, consistent with observations from a number of studies of flow through emergent vegetation [Liu et al., 2008; Nepf, 1999; Stoesser et al., 2010]. Figure 4-10 demonstrated the excellent performance of the LSM in estimating the friction velocity of vegetated beds across the Reynolds numbers and canopy densities covered in this study. Even for the sparsest canopy ($\lambda = 0.016$), with a density below the stated validity range of the LSM ($a \geq 4.3 \, m^{-1}$, Yang et al. [2015], equivalent to $\lambda \geq 0.034$), $\langle u_* \rangle_{LSM}$ is in good agreement with $\langle u_* \rangle$, implying the possibility of extending the LSM to very sparse canopies.

The mean streamwise velocity in the upper layer $U_o$ is not known a priori, and replacing it with a reference velocity that can be readily specified or measured improves the applicability of equation (4-6). The numerical results conducted over a wide range of flow conditions and canopy densities demonstrate that $U_p$ is a good measure of $U_o$, with the highest discrepancy of $\sim 10\%$ for $\lambda = 0.25$ (see Figure 4-8) which is mostly due to excluding velocities from the near-cylinder regions in the spatial averaging. Note that
even without removing near-cylinder regions data, \( U_p \) is not exactly equal to \( U_o \) due to the presence of the viscous layer in which the velocity magnitude approaches zero towards the bed. Replacing \( U_o \) with \( U_p \) in equation Figure 4-6 yields

\[
\frac{\langle u_\ast \rangle}{U_p} = \left( \frac{2}{Re_{p,H_v}} \right)^{1/2}
\]

(4-13)

where \( Re_{p,H_v} = U_p H_v / \nu \). In equation (4-13), \( \langle u_\ast \rangle_{LSM} \) has been replaced by \( \langle u_\ast \rangle \) (the actual bed shear stress) as these two friction velocities match very well (Figure 4-10). The friction velocities determined numerically \( \langle u_\ast \rangle \) and existing experimental data (from Yang et al. [2015]) strongly collapse on the curve represented by equation (4-13) (Figure 4-13), confirming that the friction velocity can be conveniently expressed in terms of the newly defined Reynolds number \( Re_{p,H_v} \).

Equation (4-13) allows the prediction of friction velocity \( \langle u_\ast \rangle \) provided that the thickness of the viscous layer \( H_v \) is known, which according to the model proposed by Yang et al. [2015] can be specified as the minimum of the cylinder radius \( (d/2) \) and the value for bare beds \( (22 \nu / \langle u_\ast \rangle ) \). Yang et al. [2015] suggested that below a transition Reynolds number, a canopy with sufficient density \( (a \geq 4.3 \text{ m}^{-1} \), equivalent to \( \lambda \geq 0.034 \)) can reduce \( H_v \) to \( d/2 \). They argued that this is due to the coherent structures formed near the base of each stem that create strong vertical velocities that may lower \( H_v \) to a scale

![Figure 4-13 Numerical and experimental data (from Yang et al. [2015]) demonstrate that the dimensionless friction velocity \( \langle u_\ast / U_p \rangle \) is given by \( (2/Re_{p,H_v})^{1/2} \), as per equation (4-13).](image-url)
comparable to $d/2$. However, the physical mechanisms that govern the thickness of the viscous layer are not well understood. In addition, it is not clear if these coherent structures are effective in modifying the temporally- and spatially-averaged velocity profiles (and as a consequence $d\nu$). This is due to the fact that the cylinder wake regions (where strongest coherent structures are formed) are within the near-cylinder region and excluded from the domain before performing the averaging procedure, i.e. as recommended by Yang et al. [2015] and consistent with the observations shown in Figure 4-6. The results of this study show that, except for $\lambda = 0.04$, the actual values of $d\nu$ are considerably lower than the predictions of Yang et al. [2015], with a significant dependence on canopy density (Figure 4-14). This further suggests the limited validity of that model for prediction of $d\nu$. In the following section, a new model based on a balance between TKE production and viscous dissipation is introduced for predicting $d\nu$ in vegetated beds across a wide range of canopy densities and Reynolds numbers.

### 4.4.3 A New Model for Predicting $H_v$

To obtain a more robust predictive formulation for estimating the viscous layer height $H_v$, we consider the TKE budget near the bed:
0 \approx -\left( u_i' u_j'' \frac{\partial \bar{u}_i}{\partial x_j} \right) - \nu \left( \frac{\partial u_i'}{\partial x_j} \frac{\partial u_i'}{\partial x_j} \right) \quad \text{(4-14)}

[Raupach and Shaw, 1982; Tanino and Nepf, 2008b] where the \(\bar{\cdot}''\) denotes the spatial variations of the temporally-averaged quantities. We hypothesize that the viscous layer thickness \(H_v\) is governed by a balance between TKE production in the cylinder wakes and the viscous dissipation of TKE near the bed represented by the first and second terms on the right hand side of equation (4-14), respectively. In addition, it can be shown that the mean kinetic energy budget for flow within cylinder arrays reduces to

\[ 0 \approx \langle u_i \rangle F_i^{\text{form}} + \left( u_i' u_j'' \frac{\partial \bar{u}_i}{\partial x_j} \right) \quad \text{(4-15)} \]

[Raupach and Shaw, 1982; Tanino and Nepf, 2008b], which implies that the TKE production in the cylinder wakes balances the rate of work done by form drag (the first term on the right hand side of equation (4-15)). Note that \(i = 1\) is the only non-zero component of \(\langle u_i \rangle F_i^{\text{form}}\). Therefore, given that the form drag forces imposed by cylinders can be described as \(F_i^{\text{form}} = 0.5C_{d,c}^{\text{form}} a U_c^2\), then the rate of work done by form drag scales on \(C_{d,c}^{\text{form}} a U_c^3\) where \(U_c\) is the constricted cross section velocity and \(C_{d,c}^{\text{form}}\) is the form drag coefficient with \(U_c\) as the reference velocity, and is determined from equation (4-10). While previous studies have used a similar scaling with \(U_p\) as the reference velocity (\(C_{d,p}^{\text{form}} a U_p^3\); e.g. Nepf [1999] and Nepf and Vivoni [2000]), it has been recently shown that \(U_c\) provides a more accurate means for predicting the drag forces on circular cylinders inside arrays [Etminan et al., 2017]. Furthermore, viscous dissipation of TKE (the second term on the right hand side of equation (4-14)) near the bed is expected to scale on \(\nu \langle \bar{k} \rangle / H_v^2\). Combining equations (4-14) and (4-15), the thickness of the viscous layer can be estimated as

\[ H_v = \frac{\nu \langle \bar{k} \rangle}{C_{d,c}^{\text{form}} a U_c^3} \quad \text{(4-16)} \]

where \(c\) is a coefficient of proportionality.
Numerical results demonstrate that a strong correlation ($R^2 = 0.81$) exists between $H_v$ and $\sqrt{\nu \langle \tilde{k} \rangle / C_{d,c}^{form} a U_c^3}$, supporting the proposed scaling in equation (4-16) (Figure 4-15). The largest errors are observed for the lowest Reynolds number ($Re_p = 200$), where wake-generated turbulence is not as dominant and the scaling of TKE production that leads to equation (4-16) may break down. A linear regression of the numerical results indicates that $c = 5.15$.

### 4.4.4 Evaluating the Performance of the Revised LSM

Based on the scaling above and the linear fit to the numerical data (equation (4-16)), a revised Linear Stress Model is proposed to estimate the bed shear stress in vegetated channels. In this new model, $\langle \tilde{k} \rangle$, $U_c$ and $C_{d,c}^{form}$ are determined using equations (4-8), (4-9) and (4-10), respectively, and substituted into equation (4-16) to determine the viscous layer thickness $H_v$. Finally, equation (4-13) is used to estimate the spatially-averaged friction velocity $\langle u_* \rangle_{new}$ (note that the subscript 'new' denotes the friction velocity calculated using the revised LSM). Notably, this new LSM only requires a measure of the pore velocity (i.e. $U_p$) and canopy density ($\lambda$ or $a$) in order to predict the friction velocity, emphasizing its practical utility.

![Figure 4-15](image)

**Figure 4-15** The strong correlation between $H_v$ and $(\nu \langle \tilde{k} \rangle / C_{d,c}^{form} a U_c^3)^{\frac{1}{2}}$ indicates that the height of the viscous layer is governed by a balance between the TKE production in cylinder wakes ($\sim C_{d,c}^{form} a U_c^3$) and viscous dissipation of TKE at the bed ($\sim \nu \langle \tilde{k} \rangle / H_v^2$). The solid line is a least-squares linear fit and corresponds to equation (4-16) with $c=5.15$. 
To examine the performance of the proposed model, the friction velocity \( \langle u_* \rangle_{new} \) was predicted for the numerical flow scenarios and the experimental flows of Yang et al. [2015] using the procedure described above. The excellent agreement \( R^2 = 0.93 \) between the predicted values of \( \langle u_* \rangle_{new} \) and the measured numerical and experimental values (Figure 4-16) demonstrates the accuracy of the proposed model. It is interesting that the performance of the proposed model in very sparse canopies \( (\lambda = 0.002 \text{ and } 0.016) \) is also excellent, despite these canopies falling outside the stated range of validity of the LSM [Yang et al., 2015]. This outcome can be attributed to the physically-based model developed to predict \( H_e \) in this study. Figure 4-16 shows that the proposed model slightly overestimates (~9% on average) the experimentally-measured friction velocities. The likely reason for this overestimation is that part of the experimental transect was located in areas with locally diminished friction velocities, relative to the spatial average (compare the location of the experimental transect in Figure 4-3a and the friction velocity contours in Figure 4-5).

4.4.5 Model Application to Real Channels

While the LSM has been proposed to predict the bed shear stress in emergent canopies, we posit that the LSM can also be used to estimate the bed shear stress in dense
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Submerged canopies \((ah \gg 0.1)\) provided that the in-canopy pore velocity (which is different with the overall pore velocity) is taken as \(U_p\). In such dense submerged canopies, viscous layer dynamics should be largely unaffected by the canopy shear layer which is formed due to the difference between the above-canopy and in-canopy velocities. Therefore, the mean velocity profile deep within the canopy and above the viscous layer is near-uniform similar to that of emergent canopies.

It is instructive to consider the discrepancies between the spatially-averaged friction velocities \(\langle u_* \rangle\) calculated using equation (4-3) and those that result from the alternative method mentioned in section 4.2.2. For sparse canopies, the values of \(\langle u_* \rangle\) from equation (4-3) are very similar to those calculated using \(\langle u_* \rangle = \sqrt{\left(\frac{\tau_b^2 + \tau_{by}^2}{\rho}\right)^{0.5}}\), where \(\tau_{by}\) is the spanwise component of bed shear stress, but diverge as canopy density and Reynolds number increase. The difference reaches 20% for \(\lambda = 0.25\) and \(Re_p = 1340\). Such a noticeable discrepancy is due to the fact that at denser canopies, the flow that is channeled between cylinders follows an increasingly tortuous path, which results in an increasing spanwise component of mean velocity and, thus, local bed shear stress. Therefore, if one is interested in taking into account the spanwise bed shear stress in calculating the spatially-averaged friction velocity, then the proposed model in this study should be used with caution, especially at higher canopy densities.

Finally, it should be noted that if the results of this study (e.g. Figure 4-10) are not interpreted correctly, one may conclude that increasing vegetation density in channels increases the bed shear stress. However, for a channel with fixed flow rate, this is not the case. This is because higher vegetation density results in increased flow resistance, a greater flow depth, lower \(U_p\) and consequently lower friction velocity. As an example, we consider a channel with given flow rate \(Q\) (0.0095 m\(^3\)/s), bed friction factor \(f\) (0.055) and channel bed slope \(s_b\) (0.0005). Using the revised LSM combined with a momentum balance, the variation of flow depth \(h\) and spatially-averaged friction velocity \(\langle u_* \rangle\) with canopy density \(\lambda\) are demonstrated in Figure 4-17 (details of the approach are given in Appendix A). For the densest canopy, the flow depth increases by a factor of \(\sim 12\) across the range of canopy densities considered here. This results in a corresponding decrease in the pore velocity \(U_p\). The resultant increase in \(\langle u_* \rangle / U_p\) (Figure 4-7a) is not sufficient to counteract the reduction in channel velocity, such that the friction velocity in a \(\lambda = 0.25\)
canopy is less than half of that in a $\lambda = 0.01$ canopy. Indeed, the shear stress in this dense canopy is almost 80 times less than that over a bare bed in the same channel.

### 4.5 Conclusion

Numerical simulations of flow through emergent arrays of rigid cylinders (with solid fractions ranging from $\lambda = 0.016$ to 0.25) were conducted to investigate bed shear stresses in the presence of vegetation over a range of flow conditions. The spatial variability of the bed shear stress increases with array density, increasing the error associated with using point measurements within the canopy to define the average. The Linear Stress Model (LSM) recently proposed by Yang *et al.* [2015] to estimate the bed shear stress in vegetated flows was found to be a reliable tool across the wide and relevant range of flow and canopy characteristics. Based on a balance between TKE production in the canopy element wakes and the viscous dissipation of TKE near the bed, a physically-based model for the thickness of the viscous layer at the bed was proposed and validated. This has significantly improved the accuracy and extended the range of validity of the LSM in estimating temporally and spatially-averaged bed shear stresses in vegetated flows. The improved understanding and ability to predict bed shear stresses in the presence of canopies should support the development of more robust sediment transport models in vegetated coastal ecosystems. However, the performance of the proposed model in predicting the bed shear stress in real canopies with (for example) a
random stem arrangement, flexibility and/or complex plant morphologies requires further investigation.
Chapter 5
Conclusions

The drag forces and bed shear stresses in the presence of emergent aquatic canopies were investigated using high-resolution numerical simulations and analysing existing experimental data sets. Below is a summary of conclusions based on the results of this study addressing the research aims outlined in Chapter 1.

5.1 Concluding remarks

5.1.1 Canopy drag in current dominated flows
The individual contributions of the blockage effect, sheltering and delayed separation on modifying the canopy drag coefficient in current dominated flows, relative to that of a single cylinder, were quantified over a range of flow conditions and canopy densities. The canopy was modelled as a staggered array of rigid cylinders. The sheltering effect and delayed separation were found to slightly reduce the drag coefficient in sparse canopies. On the other hand, the blockage effect significantly increases the drag of denser canopies ($\lambda \gtrsim 0.04$) by imposing a local increase in velocity around canopy stems and, consequently, reducing their wake pressure (Chapter 2). Due to the dominance of the blockage effect over a wide range of canopy densities, and drawing on the analogy between canopy and wall confined flow, an alternative reference velocity was proposed to normalize the drag force. In contrast to the conventional use of either the bulk or pore velocities, the constricted cross-section velocity ($U_c$) was shown to be the more appropriate reference velocity that dictates canopy drag. Use of $U_c$ resulted in collapsing the canopy drag coefficient data onto a single curve (equation (2-10)), both for the present data and prior experimental datasets. Therefore, it was shown that the staggered canopy drag coefficient in unidirectional flow can be predicted using the single cylinder formulation with $U_c$ as the reference velocity.
In addition, the performance of the proposed model was examined in estimating the drag coefficient of a randomly distributed canopy. The numerical results indicated that while sheltering can significantly impact drag coefficients for individual cylinders, the proposed model for staggered canopies can still provide a significant improvement in the quantitative prediction of bulk drag coefficients in random arrays.

5.1.2 Canopy drag in wave dominated flows
The mechanisms responsible for drag modification within emergent vegetation in oscillatory flows, which is closely related to understanding how wave energy is dissipated by canopies, were investigated (Chapter 2). The significances of blockage effect, sheltering effect and tandem cylinders spacing effect in altering the drag force exerted on cylinders inside an array relative to that of a single cylinder were evaluated. The results indicated that blockage effect is the dominant mechanism responsible for increasing the canopies drag coefficient in drag dominated regimes for medium to high density canopies. Sheltering was found to play only a minimal role, only slightly reducing the drag coefficient in sparse canopies. In addition, the numerical results show that for $KC \geq 20$ and when the cylinders spacing was in the range of a critical spacing ($Sc = 3.3 - 4$), the canopy drag was enhanced similar to tandem cylinders in unidirectional flow.

Based on the numerical results presented in Chapter 3, it was concluded that in inertia-dominated regime ($KC < 7$), the canopy drag coefficient is close to that of a single isolated cylinder at the same $KC$. In addition, for drag dominated regime the canopy drag formulation proposed in Chapter 2 for unidirectional flow can be used to estimate the canopy drag coefficient.

5.1.3 Providing predictive formulations for canopy bed stress
The spatial variability of the bed shear stress was found to increase with canopy density revealing the significant errors associated with using the shear stress observations at a limited number of experimental measurement points within a canopy when assessing bed shear stresses (Chapter 4). The Linear Stress Model (LSM), which has been recently proposed to define a viscous layer to estimate the bed shear stress was found to be a reliable tool. However, the accuracy of this model was improved by proposing a new formulation to predict the height of the viscous layer. This formulation is based on a balance between TKE production in the canopy element wakes and the viscous
dissipation of TKE near the bed. Examining the results of LSM combined with the proposed viscous layer height model showed very good agreement with the numerical and experimental results of friction velocity.

5.2 Recommendations for future work

The present study provides a physical framework for explaining and predicting the drag forces in current and wave dominated flows in the presence of emergent canopies. In addition, it provided a more detailed understanding of bed shear stress variations in vegetated beds and has improved our ability to predict spatially-averaged bed shear stresses. However, despite these advances there is still much more potential to improve the present understanding of canopy flow. Some recommended interesting topics for future research include:

- While rigid elements are ideal to represent stem-like aquatic vegetation, they may not successfully recreate situations where flexibility, buoyancy and configuration of flexible plants are important. Therefore, incorporating the stems flexibility in the canopy drag coefficient model can improve the accuracy and extend the applicability of the proposed canopy drag coefficient in this study.

- Depending on the relative depth of submergence and canopy density, the flow velocity within and above submerged canopies can be different from that of emergent canopies that was the focus of this study. Studying the canopy stems drag variations over the canopy depth, and also the effect of the submergence ratio on the bed shear stress is an important area of future research.

- In shallow waters waves, the variation of flow velocity over the water depth is not significant. Therefore, in this study two-dimensional models were used to study the flow through emergent canopies in shallow waves. Considering the flow velocity variations over the water depth and also comparing the canopy flow in regular and random waves should be further investigated in future works.
Appendix A:
Calculating variations of friction velocity with canopy density for given flow rate and channel slope

For flow in a wide channel with a bare bed, the balance between the gravitational force and bed-induced flow resistance yields [Huthoff et al., 2007]

\[
\rho g h_{Bare\,Bed} = \rho f U^2 \tag{A-1}
\]

where \( f \) is the bed friction factor and \( U \) is the mean flow velocity. The depth of the flow over the bare bed can be then calculated as

\[
h_{Bare\,Bed} = \frac{3fQ^2}{\sqrt{g s_b}} \tag{A-2}
\]

For a wide channel with emergent vegetation (represented by arrays of cylinders), an additional flow resistance is introduced on the right hand side of equation (A-1) due to the vegetation drag. Thus, the force balance is written as

\[
(1 - \lambda) \rho g h s_b = (1 - \lambda) \rho f U_p^2 + 0.5 \rho C_{d,c} N d h U_c^2 \tag{A-3}
\]

where \( N \) is the number of stems per square meter. Noting that \( U_p = Q/h(1 - \lambda) \), \( U_c = Q/h \left(1 - \sqrt{2\lambda/\pi}\right) \) and \( N = 4\lambda/\pi d^2 \), equation (A-3) can be rewritten as

\[
(1 - \lambda) \rho g h s_b = \rho f \frac{Q^2}{(1 - \lambda)h^2} + \rho C_{d,c} \frac{2\lambda}{\pi d} \left(1 - \sqrt{2\lambda/\pi}\right)^2 h \tag{A-4}
\]

Multiplying both sides by \( h^2 \) and rearranging gives

\[
(1 - \lambda) g s_b h^3 - C_{d,c} \frac{2\lambda}{\pi d} \left(1 - \sqrt{2\lambda/\pi}\right)^2 h - \frac{f Q^2}{(1 - \lambda)} = 0 \tag{A-5}
\]
which is a cubic equation in terms of $h$ and can be solved for given $s_b, \lambda, Q$ and $f$. Note that $C_{d,c}$ can be calculated as $C_{d,c} = 1 + 10Re_c^{-2/3}$ [Etminan et al., 2017]. Having calculated $h$, one can determine $U_p$ from the flowrate and then $U_c$, $\langle \tilde{k} \rangle$ and $H_p$ using equations (4-9), (4-8) and (4-16), respectively. Finally, equation (4-13) can be used to calculate the spatially-averaged friction velocity $\langle u_* \rangle$. Following this procedure, the variations of flow depth and spatially-averaged friction velocity with canopy density $\lambda$ have been presented in Figure 4-17 for $Q = 0.0095 \text{ m}^3/\text{s}$, $f = 0.055$ and $s_b = 0.0005$. 
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