WAVE AND CURRENT INDUCED FLOWS IN AQUATIC VEGETATION CANOPIES

Arie Arnold van Rooijen
Bachelor of Science (Civil Engineering), TU Delft
Master of Science (Civil Engineering) with distinction, TU Delft

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UWA Oceans Institute

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THESIS DECLARATION

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This thesis has been substantially accomplished during enrolment in the degree.

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The following approvals were obtained prior to commencing the relevant work described in this thesis: Laboratory experiment approval.

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This thesis contains published work and work prepared for publication, some of which has been co-authored.

Signature:      Date: 19-05-2019
ABSTRACT

Canopies formed by aquatic vegetation, such as seagrass meadows and mangroves, substantially modify a variety of nearshore hydrodynamic processes, which are traditionally neglected or highly simplified in coastal scale applications. With the increasing global focus on nature-based coastal protection, there is a need to increase our in-depth understanding of nearshore hydrodynamics in and around marine ecosystems. Recent studies have shown how the presence of aquatic canopies affects nearshore physical (e.g., currents, waves and sediment transport) and biological processes (e.g., nutrient transport and dispersal) through canopy-induced drag. In recent years, numerous parameterizations have been proposed that aim to improve predictions of drag, usually as function of the drag coefficient. This has resulted in a broad range of empirical formulations for a range of aquatic vegetation canopies that were derived from laboratory and field measurements. However, these models often present contradictory relationships with key variables related to the plant geometry as well as the drag coefficient. This is partly related to the complexity in applying a suitable parameterization that is valid across a wide range of different types of canopies, and partly to the difficulty in measuring and identifying the processes that govern the complex flow dynamics in marine ecosystems.

At present, even the most state-of-the-art coastal engineering models tend to incorporate the effect of vegetation on wave evolution based on isolated rigid cylinder theory. The drag coefficient is typically used as tuning parameter to provide a realistic estimation of canopy-induced drag and its effect on wave attenuation on wave-driven velocities. In that case, the drag coefficient partly accounts for complexity associated with flexible and spatially heterogeneous aquatic vegetation, and partly for flow dynamics that are not explicitly resolved. For instance, for commonly used phase-averaged wave models this includes wave-interaction effects associated with nonlinear waves. Phase-resolving wave models that are based on the Reynolds Averaged Navier-Stokes equations (e.g., non-hydrostatic wave models), do account for nonlinear wave dynamics but are computationally expensive, even on state-of-the-art multi-core computing systems. For field scale applications, these models are usually only used in depth-averaged mode thereby neglecting the vertical variation in flow dynamics observed in submerged
vegetation canopies. Moreover, since these models are based on spatial averaging of flow properties they do not account for the considerable flow variability inside a canopy.

This thesis aims to advance understanding of canopy flow dynamics in the nearshore ocean region. Although there is increasing research focusing on complex (e.g., flexible) vegetation canopies, idealized vegetation canopies are currently still predominantly used in applications, including state-of-the-art numerical models. As such, the focus here is on improving the underlying knowledge foundation for describing and predicting canopy flows using idealised representations of canopies (e.g., formed by uniformly spaced rigid cylindrical elements with a uniform height). Although results obtained with complex vegetation canopies may be closer to nature, the value of idealized representations is the ability to isolate key physical processes, and reach in-depth understanding of the driving mechanisms. In this thesis, theory is developed to derive a canopy flow parameterization that is valid across the range of (idealized) canopies (i.e., irrespective of canopy geometry) in both current and wave dominated environments. In Chapter 2, a recent formulation for current induced canopy drag due to emergent vegetation is extended for submerged vegetation, and evaluated using experimental data obtained in a current flume and from available data in the literature. In Chapter 3, a high-resolution (non-hydrostatic) numerical model for nearshore wave propagation is validated using data obtained in a large-scale wave flume, and is used to study the canopy-induced wave hydrodynamics inside and around the aquatic vegetation. Lastly, in Chapter 4, a model for wave-driven in-canopy flow is implemented into an existing (open-source) coastal engineering model, validated using data obtained in a large-scale wave flume, and applied to study wave evolution over submerged vegetation canopies.

In Chapter 2, drag coefficients are experimentally derived for a range of emergent and submerged canopies subject to a steady current using direct measurements of the drag force and the velocity profile. We find that the constricted cross-section velocity provides a better description of canopy drag than the commonly used pore velocity for both emergent and submerged canopies. Contrary to the (spatially averaged) pore velocity, the constricted cross-section velocity accounts for the spatial variability of the flow within the canopy and can be directly computed from the pore velocity for a known canopy density. Using a combination of the extended theory and data obtained from literature it is confirmed that the constricted cross-section velocity is a suitable
velocity scale in the drag parameterization for both emergent and submerged canopies, even showing potential in applications with randomly organized and flexible vegetation.

In Chapter 3, the focus is on wave-dominated (oscillatory) flows, where we find that waves are attenuated when propagating over a submerged canopy and a characteristic mean flow is generated with its peak located just above the canopy in onshore direction. Drag coefficients are experimentally measured for a range of wave conditions using a unique combination of direct force measurements, the water surface elevation, and the velocity profile. A momentum budget analysis is performed to explain the mean velocity profile, which is based on results from a high-resolution (non-hydrostatic) wave model, SWASH, to complement the measured data. The results show that the mean hydrodynamic forcing is governed by canopy drag balanced by the spatial gradients in wave and turbulent Reynolds stresses. These terms are usually neglected in coastal scale modelling studies. The derivation of parameterizations that can be used in models is not trivial, hence highlighting the need for additional theoretical work in this field.

Chapter 4, combines the findings regarding the spatial variability of flows inside canopies (Chapter 2) with our findings regarding the vertical variation of wave-induced flows (Chapter 3). It describes the implementation of a sub-model for the in-canopy flow velocity in an existing open-source depth-averaged wave model, XBeach, to provide an improved canopy drag description for wave attenuation over vegetation canopies while maintaining computational efficiency and feasibility at field scales over full 3D models. The model is validated for the measured wave evolution, wave-induced velocities and drag forces using the same experimental dataset as used in Chapter 3. The results show that the extended model provides a considerable improvement in accuracy over current state-of-the-art coastal models by resolving more detailed physics while maintaining computational efficiency of a depth-averaged wave-flow model.

Overall, this thesis provides a step towards a better systematic understanding of nearshore hydrodynamics induced by vegetation canopies. It provides a generic description of canopy drag that is applicable across a range of canopy geometries, and can directly be adopted in coastal engineering models. Although the results are based on idealized vegetation canopies, they provide value and potential for realistic applications, as the key governing processes are similar across more complex canopies (e.g., based on flexible elements).
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### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_0$</td>
<td>wave orbital excursion length above the canopy</td>
</tr>
<tr>
<td>$A_v$</td>
<td>plan surface area of a single canopy element</td>
</tr>
<tr>
<td>$C_{1e}$</td>
<td>turbulence closure model coefficient</td>
</tr>
<tr>
<td>$C_{2e}$</td>
<td>turbulence closure model coefficient</td>
</tr>
<tr>
<td>$C_{d}, C_{D}$</td>
<td>(general) drag coefficient</td>
</tr>
<tr>
<td>$C_{d,c}$</td>
<td>canopy drag coefficient based on constricted cross-section velocity</td>
</tr>
<tr>
<td>$C_{d,b}$</td>
<td>canopy drag coefficient based on bulk velocity</td>
</tr>
<tr>
<td>$C_{d,m}$</td>
<td>canopy drag coefficient based on measured velocity</td>
</tr>
<tr>
<td>$C_{d,p}$</td>
<td>canopy drag coefficient based on pore velocity</td>
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<tr>
<td>$C_{d,rep}$</td>
<td>representative canopy drag coefficient</td>
</tr>
<tr>
<td>$C_{f}, c_{f,c}$</td>
<td>canopy friction coefficient</td>
</tr>
<tr>
<td>$c_{f,b}$</td>
<td>bed friction coefficient</td>
</tr>
<tr>
<td>$C_{f,k}$</td>
<td>turbulence closure model coefficient (vegetation production)</td>
</tr>
<tr>
<td>$C_{f,c}$</td>
<td>turbulence closure model coefficient (vegetation dissipation)</td>
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<tr>
<td>$C_m$</td>
<td>added mass coefficient</td>
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<tr>
<td>$d_c$</td>
<td>cylinder diameter</td>
</tr>
<tr>
<td>$d_v$</td>
<td>plant / canopy element diameter</td>
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<tr>
<td>$f_{d}, f_{d,cyl}$</td>
<td>drag force per unit length of a cylinder</td>
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<tr>
<td>$f_{d,can}$</td>
<td>canopy drag force per unit bed area</td>
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</tr>
<tr>
<td>$f_{v,x}$</td>
<td>vegetation force in $x$-direction</td>
</tr>
</tbody>
</table>
\( F_d \) plant / canopy total drag force
\( F_v \) plant / canopy total vegetation force
\( g \) gravitational acceleration
\( H \) wave height
\( H_0 \) wave height offshore of vegetation
\( H_v \) wave height onshore of vegetation
\( h \) water depth
\( h_v, h_c \) plant / canopy height
\( h_{vd} \) deflected plant / canopy height
\( KC \) Keulegan-Carpenter number
\( k \) turbulent kinetic energy
\( k_p \) wave number based on wave peak period
\( k_{u,1-d}, k_{w,1-d} \) horizontal and vertical increments in particle tracking model
\( L_v, L_c \) canopy length
\( L_d \) canopy drag length scale
\( L_s \) canopy shear length scale
\( n_p \) canopy porosity
\( N_c, N_v \) number of plants / canopy elements per unit bed area
\( p \) total pressure
\( p_h \) hydrostatic pressure
\( P_k \) turbulence production due to shear
\( p_{nh} \) non-hydrostatic pressure
\( P_v \) turbulence production due to vegetation
\( Q \) flow rate / discharge
\( Re \) (general) Reynolds number
\( Re_c \) Reynolds number (canopy) based on constricted cross-section velocity
\( Re_b \) Reynolds number (canopy) based on bulk velocity
\( Re_m \) Reynolds number (canopy) based on measured velocity
\( Re_p \) Reynolds number (canopy) based on pore velocity
\( S_{v,l} \) lateral distance between two canopy elements at the same streamwise (x) location
\( S_{v,s} \) streamwise distance between two canopy element rows
\( t \) time
\( T \) wave period
\( u \) horizontal velocity
$u'$  
 turbulent velocity fluctuation in x direction

$\tilde{u}$  
 wave orbital horizontal velocity component

$\hat{u}$  
 representative in-canopy horizontal velocity

$\langle u \rangle$  
 wave-averaged horizontal flow velocity

$\langle u \rangle^E$  
 Eulerian mean horizontal velocity

$\langle u \rangle^L$  
 Lagrangian mean horizontal velocity

$\langle u \rangle^S$, $u_{st}$  
 Stokes drift horizontal velocity

$u_*$  
 friction velocity based on canopy shear stress

$U_0$  
 wave horizontal velocity amplitude

$U_\infty$  
 free stream flow velocity

$U_{bem}$  
 bulk velocity for emergent canopy

$U_{bsub}$  
 bulk velocity for submerged canopy

$U_{cem}$  
 constricted cross-section velocity for emergent canopy

$U_{csub}$, $\tilde{u}_c$  
 constricted cross-section velocity for submerged canopy

$U_{mem}$  
 measured depth-averaged velocity for emergent canopy

$U_{msub}$  
 measured depth-averaged velocity for submerged canopy

$U_{mag}$  
 velocity magnitude

$U_{pem}$  
 pore velocity for emergent canopy

$U_{psub}$, $\tilde{u}_p$  
 pore velocity for submerged canopy

$u_{p,n}$  
 particle horizontal velocity for particle $p$ at timestep $n$

$U_{ref}$, $u_{ref}$  
 reference velocity

$u_{rms,\infty}$  
 above-canopy root-mean-square velocity

$w$  
 vertical velocity

$w'$  
 turbulent velocity fluctuation in z direction

$\tilde{w}$  
 wave orbital vertical velocity component

$\langle w \rangle$  
 wave-averaged vertical flow velocity

$w_{st}$  
 vertical stokes velocity

$W$  
 channel width

$x$  
 streamwise direction

$x_0$  
 canopy flow adjustment length

$x_c$  
 computed values in skill analysis

$x_m$  
 measured values in skill analysis
\( x_{p,n} \)  particle horizontal location for particle \( p \) at timestep \( n \)

\( z \)  vertical elevation measured from bottom

\( z_{p,n} \)  particle vertical location for particle \( p \) at timestep \( n \)

\( a_H \)  wave height attenuation factor

\( a_U \)  canopy flow attenuation factor

\( \beta \)  ratio between lateral and streamwise canopy spacing \((S_v/lS_{v,s})\)

\( \varepsilon \)  turbulence dissipation

\( \zeta \)  (wave-induced) water surface elevation

\( \eta \)  (mean) water surface elevation

\( \lambda_f \)  canopy (frontal) density / element frontal area per unit bed area

\( \lambda_p \)  canopy (plan) density / element plan area per unit bed area

\( \rho \)  water density

\( \sigma_k \)  turbulence closure model coefficient

\( \sigma_{xx} \)  wave-averaged normal stress

\( \sigma_{\varepsilon} \)  turbulence closure model coefficient

\( \tau_{xz} \)  wave-averaged shear stress

\( \nu \)  kinematic viscosity of water

\( \nu_h \)  horizontal eddy viscosity

\( \nu_v \)  vertical eddy viscosity

\( \omega \)  vorticity or wave radian frequency
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I know it is tradition to thank one’s partner last in PhD theses, but I think their immense support, at least in the case of my wife, deserves to be acknowledged first. So Cláudia, thank you very much for all your unconditional support, your patience, your dedication, your encouragements, and your love during the ups and downs of this journey.

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AUTHORSHIP DECLARATION

INCLUDED PUBLICATIONS DURING CANDIDATURE

This thesis is presented as a series of papers in accordance with standards set by The University of Western Australia. The chapters that contain work that is published or currently in preparation for publication are listed below, including my contribution to the manuscript and the contributions of my co-authors.

Details of the work:

Location in thesis: Forms the entirety of Chapter 2

Student contribution to work: I designed the experiments, acquired the data, performed the data analysis, and wrote the manuscript. Co-authors Ryan Lowe and Marco Ghisalberti provided support in the experimental design, data interpretation and the development of the manuscript. Co-authors Mario Conde-Frias and Liming Tan provided support in data acquisition during the experiments. All co-authors provided editorial feedback on the manuscript.

Co-author signatures and dates:
Ryan Lowe
Date: 29 Apr 2019

Marco Ghisalberti
Date: 01 May 2019

Mario Conde-Frias
Date: 30 April 2019

Liming Tan
Date: 30 April 2019
Details of the work:

Location in thesis: Forms the entirety of Chapter 3

Student contribution to work: I designed the physical and numerical experiments, acquired the experimental data, performed the analysis of experimental and numerical results, and wrote the manuscript. Co-authors Ryan Lowe and Marco Ghisalberti provided support in the experimental design, data and model interpretation and the development of the manuscript. Co-authors Dirk Rijnsdorp, Robert McCall and Niels Jacobsen provided support in the numerical experiments and the interpretation of the numerical model results. All co-authors provided editorial feedback on the manuscript.

Co-author signatures and dates:

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Details of the work:


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**Co-author signatures and dates:**

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RELATED PUBLICATIONS DURING CANDIDATURE (NOT INCLUDED IN CANDIDATURE)

In addition, I have co-authored the following related publication (partly) during candidature (publication not included in candidature):


CONFERENCE CONTRIBUTIONS DURING CANDIDATURE

Finally, part of my research has been presented at international conferences:

i) Australasian Fluid Mechanics Conference, Perth, Australia, December 2016,


ii) Australasian Coasts & Ports Conference, Cairns, Australia, June 2017,


iii) International Conference on Coastal Engineering, Baltimore, USA, July 2018,

Student signature

Date: 25 April 2019

I, Ryan Lowe, certify that the student statements regarding their contribution to each of the works listed above are correct.

Coordinating supervisor signature:

Date: 29 April 2019
INTRODUCTION

1.1 Background

Canopies formed by aquatic vegetation, such as mangroves, seagrass and kelp can be found along many of the world’s coastlines. They play a critical role in shaping many coastal ecosystems including by providing shelter and food for numerous species, thereby helping to enhance marine biodiversity [e.g., Duarte, 2002]. Aquatic plants have also been found to be efficient in long-term storage of carbon [e.g. Fourquean et al., 2012] and can play an important role in stabilizing sediments [e.g., Hendriks et al., 2008] and limiting coastal erosion. These plants reduce the risk of coastal hazards such as flooding [e.g. Temmerman et al., 2013], making them potentially valuable components in nature-based coastal protection schemes [Narayan et al., 2016; Morris et al., 2018]. At the same time, aquatic ecosystems are under pressure worldwide due to anthropogenic impacts (e.g., increasing coastal population and economic activity, pollution). As a consequence, the global areal extent of seagrass has for instance declined by 29% since 1879, while the rate of loss has accelerated to about 110 km²/year [Waycott et al., 2009]. Similar alarming rates in areal decline have been the case of both mangroves [Giri et al., 2011] and kelp forests [Krumhansl et al., 2016].

Over the past decade, the interaction of aquatic canopies with waves and currents has been the focus of many studies, which have led to a better fundamental understanding
of current- and wave-induced flow-canopy interactions [see reviews by Nepf, 2012a,b and Mullarney and Henderson, 2018]. For instance, canopies subject to a steady current may affect local current magnitudes and reduce downstream water levels [e.g., Tanino and Nepf, 2008]. Attenuation of wave energy has been observed both experimentally [e.g., Möller et al., 2014] and in the field [e.g., Möller and Spencer, 2002; Paul and Amos, 2011], resulting in a reduction of wave run-up (the maximum wave-driven water level at a coastline) [e.g., Tang et al., 2013]. In case of emergent vegetation or submerged vegetation subject to nonlinear waves, vegetation can contribute to a reduction in wave-induced water level setup [Dean and Bender, 2006]. Finally, aquatic canopies have also been found to reduce wind-induced nearshore storm surge levels by slowing the storm surge advance through friction [e.g., Wamsley et al., 2010]. The ability of aquatic vegetation to reduce both wave energy and mean water levels (wave setup and wind-driven surge) makes it a potentially valuable component in coastal protection by reducing loads on coastal structures [Vuik et al., 2016].

With sea levels predicted to rise in the coming decades, more emphasis has been placed on understanding and predicting the impact of aquatic vegetation on nearshore (physical) processes. However, due to the complexity involved with waves and currents in and near aquatic canopies, the governing physics are still relatively poorly understood compared to nearshore processes along bare-bed sandy coastlines. It is known that for typical nearshore ocean conditions the hydrodynamics in and around aquatic canopies are almost entirely controlled by vegetation drag, but a conclusive physics-based description of drag for canopies subject to coastal flows is currently lacking. This greatly diminishes the predictive capability of coastal hydrodynamic models, as they currently rely on model calibration or empirical relationships from literature.

1.2 Current-induced flows in aquatic vegetation

The current-induced (unidirectional) flow in aquatic canopies is governed by the drag force exerted by the current on the individual canopy elements (plants), which has been the focus of numerous studies in the past three decades. Due to the high level of complexity in natural aquatic plant morphology and spatial heterogeneity, plants are usually idealized as rigid cylinders. The drag force per unit length of a cylinder in isolation is given by:
1.2 CURRENT-INDUCED FLOWS IN AQUATIC VEGETATION

\[ f_{d,\text{cyl}} = \frac{1}{2} \rho d_c C_d |u_{ref}| u_{ref} \]  

(1-1)

where \( \rho \) is the water density, \( d_c \) is the cylinder diameter, \( C_d \) is the drag coefficient and \( u_{ref} \) is a reference (horizontal) flow velocity (which is equal to the upstream velocity in stationary unidirectional flow). The drag coefficient for a cylinder in isolation is historically well-established, and depends on the Reynolds number \( Re = u_{ref} d_c \nu^{-1} \), where \( \nu \) is the kinematic viscosity of water. The wake formed by a smooth cylinder subject to a steady flow becomes turbulent for \( Re > ~200 \), while for \( Re > ~3 \times 10^5 \) the transition to turbulence occurs in the boundary layer as well [Sumer and Fredsøe, 2006]. For typical coastal flows \( (u_{ref} = 0.1 \text{ to } 1 \text{ m/s}) \) around vegetation stems with typical diameter \( (d_c = 0.001 \text{ to } 0.01 \text{ m}) \), the Reynolds number generally ranges from \( 10^2 < Re < 10^4 \) for which the drag coefficient is typically \( C_d \sim 1 \) [Schlichting and Gersten, 2016].

When multiple cylinders are organized in arrays (i.e., forming a canopy), the total canopy drag per unit height is usually expressed per unit area by simply summing the drag force for all individual canopy elements per unit area:

\[ f_{d,\text{can}} = N_c f_{d,\text{cyl}} = \frac{1}{2} \rho N_c d_c C_d |u_{ref}| u_{ref} \]  

(1-2)

where \( N_c \) is the number of canopy elements per unit area. Within a canopy, the interaction between individual elements may cause substantial spatial variations in local velocities. For instance, the wakes generated by upstream elements may reduce the local flow velocity magnitude and subsequent drag on downstream elements (sheltering effect). On the other hand, the flow velocity may be locally increased due to the reduced cross-sectional area caused by the presence of upstream canopy elements resulting in increased drag (blockage effect). In addition, this effect may also limit the width of the wake formed downstream of an element [e.g., Etminan et al., 2017]. The sheltering effect becomes more dominant when the spacing between elements becomes small relative to the element diameter [Zdravkovich, 1987], but is considered to be of minor importance for arrays that fall within the typical range observed in natural vegetation canopies [Mullarney and Henderson, 2018]. The considerable horizontal variability in flow velocity caused by the combined effects of sheltering and blockage complicate the estimation of velocity scale \( u_{ref} \), which is usually compensated by a variation in the drag coefficient [Etminan et al., 2017].
For emergent vegetation canopies, laboratory observations have most commonly been obtained by measuring the water surface slope and assuming a force balance of canopy drag and hydraulic pressure \cite{Liu2008, Tanino2008}:\[ F_{d,can} = -n_p \rho g \frac{dn}{dx} h_c \] (1-3)
where \( n_p \) is the canopy porosity, \( g \) is the gravitational acceleration, \( \eta \) is the water surface elevation and \( h_c \) is the canopy height. The drag coefficient is subsequently obtained from Eq. (1-2) by assuming a depth-uniform, spatially averaged velocity \( u_{ref} \). This has resulted in a large range of empirical formulations where \( C_d \) is related to plant shape, flow regime (i.e., Reynolds number) and canopy properties (e.g., density). As for the case of isolated cylinders, the drag coefficient in canopies is generally found to exponentially decrease for increasing Reynolds number \cite[e.g., Liu and Zeng, 2017]{Liu2017}. Whereas most studies have found a positive correlation between \( C_d \) and \( \lambda_p \) \cite[e.g., Tanino and Nepf, 2008]{Tanino2008}, some studies have observed opposite trends \cite[e.g., Nepf, 1999]{Nepf1999}. Overall, the dependency on canopy density is inconclusive which is related to the use of a spatially averaged reference velocity (bulk velocity), sometimes accounting for the fluid volume (pore velocity). Using such a velocity scale neglects the spatial variability in flow velocity induced by the sheltering and blockage effects \cite{Etminan2017}, and affects the resulting drag coefficients obtained from Eq. (1-2) considerably. Etminan et al., \cite{Etminan2017} used 3D Large Eddy Simulations to study unidirectional flow through an emergent canopy and found that the “constricted cross-section velocity”, the average velocity in the constriction between two adjacent canopy elements, is the key velocity scale that governs the wake pressure around a cylindrical element within an array. They concluded that, when combined with the well-established theory for drag on isolated cylinders, it provides a more accurate and more generic description for drag compared to previously derived formulations.

Although the model by Etminan et al. \cite{Etminan2017} provides a more robust and physics-based description for current-induced canopy drag than previous studies, to date it has been validated only for a limited number of experimental observations. Furthermore, it provides a description for canopy drag in emergent vegetation but not for submerged canopies. In case of submerged canopies, the flow dynamics are similar although more complex since a strong vertical variation in the horizontal flow velocity may occur \cite[e.g. Lowe et al., 2005]{Lowe2005}, where reduction in flow velocity inside the canopy...
leads to a reduction in canopy drag. Due to this complexity, the processes governing drag for submerged canopies are relatively understudied, and most studies used the spatially averaged (bulk) velocity as velocity scale in drag estimations [e.g., Wu et al., 1999; Lopez and Garcia, 2001]. Consequently, (bulk) drag coefficients that are derived through this method are generally (unphysically) low and highly variable.

1.3 Wave-induced flows in aquatic canopies

For vegetation canopies in wave-induced (oscillatory) flows, both the drag and inertial force may be important. The total force per unit length of a cylinder in isolation is described by the so-called Morison equation:

\[ \mathbf{f}_{\text{vcyl}} = \mathbf{f}_{\text{d,cyl}} + \mathbf{f}_{\text{i,cyl}} = \frac{1}{2} \rho d_c C_M |u_{\text{ref}}| u_{\text{ref}} + \rho \frac{\pi d_c^2}{4} C_M \frac{\partial u_{\text{ref}}}{\partial t} \]

[Morison et al., 1950], where \( C_M \) is the inertia coefficient (\( C_M = 1 + C_m \), where \( C_m \) is the added mass coefficient). Whereas for current-induced flows, \( C_d \) is known to depend on \( Re \) (see above), in wave-induced flows it is known to depend on the Keulegan-Carpenter number (\( KC = U_0 T d_c^{-1} \), where \( U_0 \) is the wave horizontal velocity amplitude, and \( T \) is the wave period) as well. The total force per unit area in wave-dominated environments is usually obtained by summing the force on the individual canopy elements over the area (equivalent to Eq. (1-2)).

Most studies have considered canopy drag in relation to wave attenuation, assuming the rate of wave energy dissipation due to vegetation is proportional to the work performed by the waves on the plants [e.g., Dalrymple et al., 1984]. The work is equal to the product of the total force and the horizontal velocity averaged over a wave cycle, hence the inertial force contribution becomes negligible (i.e., \( \bar{u} \partial u/ \partial t \approx 0 \), where the overbar denotes averaging over a wave period). Several theoretical models have been developed based on conservation of wave energy to quantify wave decay through a given aquatic vegetation canopy [e.g., Mendez and Losada, 2004]. The theory has been used in combination with wave height observations in numerous studies across a range of canopies in laboratory and field to estimate \( C_d \) [e.g., Mazda et al., 1997; Bradley and Houser, 2009; Paul and Amos, 2011; Ozeren et al., 2014; Möller et al., 2014]. The wave height evolution is sometimes assumed to be exponential [e.g., Kobayashi et al., 1993], and laboratory and field measurements are used to estimate a decay coefficient, rather
than a drag coefficient [e.g., Anderson and Smith, 2014]. Since these studies generally lack measurements of the velocity, the reference velocity is usually based on linear wave theory and assumed to be depth-uniform. However, although wave-induced flow is typically less attenuated than current-induced flow, the presence of submerged aquatic canopies may still result in considerable vertical gradients in the wave velocity [Lowe et al., 2005; Zeller et al., 2015]. In addition, several studies reported a characteristic depth-varying wave-averaged horizontal flow with its peak just above the top of the canopy [e.g. Luhar et al., 2010; Abdolahpour et al., 2017]. It is known that this wave-averaged flow is forced by a nonzero wave stress that appears when the horizontal and vertical wave velocities are no longer 90° out of phase [Luhar et al., 2010, 2013]. However, the vertical structure of this mean flow is not well understood, and has thus far only been explained partly using an empirical relation [Abdolahpour et al., 2017].

Many state-of-the-art coastal (wave) models now include formulations to account for canopy-induced wave attenuation. Phase-averaged wave models such as SWAN and XBeach-Surfbeat typically use the wave-energy-based model by Mendez and Losada [2004], while phase-resolving wave models such as SWASH and XBeach-Non-hydrostatic include a description of canopies based on Eq. (1-4). Phase-resolving models have the advantage that they are able to resolve nonlinear wave-canopy interactions [e.g. van Rooijen et al., 2016] but are computationally more expensive, particularly when used in 3D mode. Although these models are valuable tools in understanding wave dynamics in coastal areas with aquatic vegetation, the simplified description of canopy hydrodynamics within these models greatly hinders their predictive capability, and modellers rely on observations or empirical relationships from literature for calibration. Moreover, for model applications in coastal regions with aquatic vegetation that rely on an accurate description of the velocity (e.g. sediment transport), the current model implementations do not suffice.

1.4 Motivation and aims

The complex hydrodynamics inside and around aquatic vegetation canopies, particularly submerged canopies, are often neglected and compensated for by using over-simplified empirical formulations to describe canopy drag forces. This is partly due to the complexity associated with plant morphology and spatial heterogeneity, and partly due to
the lack of detailed systematic measurements of drag in aquatic canopies. This thesis aims to provide an improved understanding of canopy flow dynamics in the nearshore ocean region that can be applied to coastal engineering practice. Although the global research field has largely shifted to more complex (e.g., flexible) vegetation canopies, idealized vegetation canopies are currently still predominantly used in applications, including state-of-the-art numerical models. Moreover, even for idealized canopies, theory presents considerable knowledge gaps, and formulations that have been derived are inconclusive. Although results obtained with complex vegetation canopies may be closer to nature, the value of idealized representations is the ability to isolate key physical processes, and reach in-depth understanding of the driving mechanisms.

In this thesis, the overall aim is to derive a canopy flow parameterization that is valid across the range of (idealized) canopies (i.e., irrespective of canopy geometry) in both current- and wave-dominated coastal environments, and that can be used to improve existing coastal modelling tools for simulating coastal hydro- and (eventually) morphodynamics. The specific aims of this study are:

i. **Extend the theoretical model by Etminan et al. [2017] for application in submerged canopies, and validate the model using high-resolution drag observations for a range of hydrodynamic conditions and canopies (Chapter 2).**

Coastal regions are generally dominated by wave-driven (oscillatory) flows, however, unidirectional flows such as wind- or tide-driven coastal currents can often not be neglected. Moreover, the hydrodynamics for canopies subject to a unidirectional flow are still relatively poorly understood, particularly for submerged canopies. In order to improve understanding of (more complex) oscillatory flows in canopies, good understanding of unidirectional flows is required. Prior studies have generally ignored the spatial variability in flow induced by aquatic canopies. In addition, empirical drag relations are often based on bulk canopy parameters such as the horizontal gradient in water level (in unidirectional flow) or waves (in oscillatory flow). In Chapter 2, the theoretical model proposed by Etminan et al. [2017] is extended for submerged canopies, unlocking the model for the full range of natural vegetation canopies. Newly obtained
high-resolution laboratory observations of the drag forces exerted on a single canopy element are used to better understand current-induced drag on the canopy scale and to validate the model.

ii. Investigate the three-dimensional wave-driven flow dynamics induced by submerged vegetation canopies using a combination of high-resolution laboratory observations and detailed numerical modelling (Chapter 3).

Recent studies have shown how the presence of wave-current interactions within submerged vegetation canopies drive relatively strong mean currents. A strong vertical structure has been observed, but the physical mechanisms responsible for these flows are still not well understood. In this thesis, direct laboratory observations of the combined drag and inertial force are obtained for a single canopy element in combination with high-resolution velocity measurements, and used to better understand the wave-induced currents generated within submerged canopies. The experimental data is used in combination with results from a high-resolution three-dimensional wave model to quantify the governing hydrodynamic forcing around submerged canopies, in order to provide guidance for improving existing coastal models.

iii. Develop a robust and computationally efficient numerical model for predicting and understanding canopy-induced hydrodynamics on coastal spatial scales (Chapter 4).

To date, authors have typically used phase-averaged wave models to study wave attenuation by aquatic canopies on field scale that are usually based on linear wave theory and assume the effect of the canopy on the wave-induced velocity is negligible. To account for nonlinear wave effects and the vertical variation in velocity, an existing wave model (XBeach) is extended with a canopy flow subgrid model based on the findings from Chapter 2 and 3 to provide a better estimate of the canopy induced wave dynamics while maintaining computational feasibility on coastal spatial (~km) scales.
This thesis contains a general introduction (Chapter 1) followed by three chapters that are presented in manuscript format (Chapter 2, 3 and 4) and a general discussion (Chapter 5). In Chapter 2, the theoretical drag model proposed by Etminan et al. [2017] is extended to submerged canopies, and is validated using newly obtained laboratory observations of the current-induced drag force on a single canopy element, as well as a large dataset compiled from literature. In Chapter 3, newly obtained laboratory observations of the wave-induced vegetation force on a single canopy element are used in combination with results from a high-resolution numerical wave model (SWASH) to better understand the mean flow dynamics in submerged canopies, and provide guidance for coastal model improvements. In Chapter 4, the numerical wave model XBeach is extended with a subgrid canopy flow model that is used to estimate a representative reference velocity for canopy drag. The model is verified using the observations presented in Chapter 3. Lastly, Chapter 5 provides a synthesis of the findings from the previous chapter and discusses the broader implications of this work.
2.1 Introduction

It is widely recognised that aquatic vegetation, such as seagrass, reeds, kelp and mangroves, greatly influences hydrodynamic processes within rivers, estuaries and coastal regions [e.g. Nepf, 2012b]. The drag exerted by emergent and submerged vegetation impacts the local hydrodynamics, morphodynamics and ecology over a range of spatial scales [Koch et al., 2007]. The canopies formed by vegetation can affect the local flow environment at the smallest scale (i.e. the plant scale, mm to cm) to the larger-scale (> 1 km) flows that occur across benthic ecosystems. Canopy drag forces contribute to reducing flow velocities within canopies [Lopez and Garcia, 2001; Luhar and Nepf, 2013] and enhancing local turbulence [Nepf and Vivoni, 2000]. In areas with significant wave action, such as in coastal regions and large lakes, the rate of work done by canopy drag forces also results in wave energy attenuation [e.g. Fonseca and Chalan, 1992]. The flow reduction induced by canopy drag can, in turn, influence a number of morphodynamic and biophysical processes [Koch et al., 2007]. For example, canopies can modify local bed shear stresses [James et al., 2004], thereby affecting sediment transport, deposition [Hendriks et al., 2008, 2010] and resuspension [Widdows et al., 2008]. Similarly, canopy drag also indirectly influences other particle dynamics, affecting...
pollination [Ackerman, 1995], establishment of seedlings [Balke et al., 2013], and recruitment and settlement of larvae, spores and fauna [Kenyon et al., 1999]. The effect of the reduced in-canopy flow on the diffusive boundary layer around plant leaves [Koch et al., 2007] also governs nutrient uptake [Morris et al., 2008] and can influence the growth of epiphytes [Cornelisen and Thomas, 2002]. Under strong flow conditions, the drag forces exerted on canopy elements can result in their physical removal from the seabed [Duarte, 2002; Edmaier et al., 2011]. Globally, aquatic ecosystems are under increasing pressure from anthropogenic and climate change impacts [Duarte, 2002], and it is crucial we increase our understanding of canopy drag as it directly influences many important biophysical processes in aquatic environments.

To be able to quantify the influence of aquatic canopies on the local hydrodynamics, a comprehensive understanding of the mechanics governing canopy drag is required. Given the diversity of plant morphologies in natural environments, individual plants are often schematized as uniform, rigid cylinders to establish a general knowledge framework for the processes governing drag [see review by Vargas-Luna et al., 2016]. The drag force per unit length of a cylinder in isolation is given by:

\[ f_d = \frac{1}{2} \rho d_c C_d U_{ref}^2 \]  

(2-1)

where \( \rho \) is the water density, \( d_c \) is the cylinder diameter, \( C_d \) is the drag coefficient, and \( U_{ref} \) is a reference flow velocity (which, in the case of an isolated cylinder, is equal to the upstream velocity). Predicting the drag coefficient for a cylinder in isolation is historically well-established, and it can be robustly predicted as:

\[ C_d = 1 + 10 Re^{-2/3} \]  

(2-2)

[White, 1991], where the Reynolds number is defined as \( Re = U_{ref} d_c / \nu \), with \( \nu \) is the kinematic viscosity. For real-world application, considering plants rather than cylinders, temporal fluctuations in the drag force (due to turbulence) and vertical variation of the drag are often of less interest than the mean drag force, which governs the range of biophysical processes described earlier. As the plant biomass and flow velocity may vary significantly over the height of the plant, the total mean drag force on the plant is usually defined as:
2.1 INTRODUCTION

\[ \bar{F}_d = \frac{1}{2} \rho \int_{z=0}^{h_v} d_v C_d U_{ref}^2 \, dz \]  

(2-3)

where the drag force is integrated over the vertical dimension \((z)\) and averaged over time (denoted by the overbar), \(h_v\) is the vegetation (cylinder) height (with \(z = 0\) at the bed), and \(d_v\) is the vegetation stem (cylinder) diameter.

In the case of a single plant, the upstream velocity is usually weakly vertically varying over most of the water column and the depth-averaged velocity is an obvious choice for the reference velocity \((U_{ref})\) needed to estimate the drag force in Eq. (2-3). However, in the case of multiple plants forming a canopy, the flow throughout the canopy (and therefore the ‘upstream’ velocity for each plant) is spatially non-uniform. It is thus unclear which actual velocity governs drag and could be used as the appropriate reference velocity. In emergent canopies (denoted hereafter with the superscript ‘em’), previous studies have chosen the reference velocity to be either: 1) the bulk velocity (i.e. \(U_{b,em}^m = Q/W_h\), where \(Q\) is the flow discharge, \(W\) is the channel width and \(h\) is water depth) [e.g. Wu et al., 1999] or, more commonly, 2) the pore velocity \((U_{p,em}^m = U_{b,em}^m/(1 - \lambda_p))\), where \(\lambda_p\) is the canopy density that is equivalent to the canopy element plan area per unit bed area) [e.g. Tanino and Nepf, 2008], representing the spatially averaged velocity inside the fluid spaces within a canopy. However, through Large Eddy Simulation, Etminan et al. [2017] found that the ‘constricted cross-section velocity’, the average velocity in the constriction between adjacent canopy elements, is the velocity scale that actually governs wake pressure and thus canopy drag. The relationship between the pore velocity and the constricted cross-section velocity \((U_{c,em}^m)\) is dependent on the arrangement of canopy elements, and is obtained through conservation of mass (i.e. \(U_{c,em}^m (1 - d_v/S_{v,l}) = U_{p,em}^m (1 - \lambda_p)\)). Here, \(S_{v,l}\) is the lateral spacing between adjacent elements at the same streamwise \((x)\) location, and can only be strictly defined for regular arrays (such as linear or staggered arrangements). This relationship between the constricted cross-section velocity and the pore velocity can be written as a function of the canopy density:

\[ U_{c,em}^m = \frac{1 - \lambda_p}{1 - \beta \frac{S_{v,l}}{\pi}} U_{p,em}^m \]  

(2-4)

[Stone and Shen, 2002; Etminan et al., 2017]. In (2-4), \(\beta\) represents the ratio between \(S_{v,l}\) and the distance between two rows of canopy elements in the streamwise direction \((S_{v,s})\).
For random arrays, as can be found in nature, the constricted cross-section velocity can be computed from the bulk velocity:

\[ U_{c}^{em} = \frac{1}{1-d_{w}/N_{v}} U_{b}^{em} = \frac{1-\frac{2}{\pi}N_{v}d_{v}^{2}}{1-d_{w}/N_{v}} U_{p}^{em} \]  

(2-5)

where \( N_{v} \) is the total number of plants per unit area. Note that this will result in a canopy-average value of \( U_{c}^{em} \), and local values may vary significantly.

In the case of submerged canopies, the shear layer present at the top of the canopy results in strong vertical variations in the spatially averaged flow, further complicating canopy drag predictions. In many cases, the reference velocity used to predict the drag in submerged canopies is based on the bulk velocity \( U_{b}^{sub} = Q/Wh \), where the superscript ‘\( sub \)’ refers to a velocity scale used for submerged canopies [Wu et al., 1999, Lopez and Garcia, 2001]. However, this approach does not account for the attenuation of flow within the canopy that will significantly influence canopy drag. An exception is the study of Liu and Zeng [2017] who proposed a more representative in-canopy flow velocity that accounts for vertical variation in the spatially averaged flow. However, their approach did not account for the local (horizontal) spatial variation in the mean flow inside the canopy.

In emergent canopies, experimental measurements of drag coefficients have most commonly been obtained by measuring the surface slope and assuming a force balance of canopy drag and hydraulic gradient [Tanino and Nepf, 2008; Liu et al. 2008]. The drag force of an individual plant within the canopy is then given by:

\[ \bar{F}_{d} = -(1-\lambda_{p}) \rho g \frac{dn}{dx} h_{w} N_{v}^{-1} \]  

(2-6)

where \( g \) is the gravitational acceleration, and \( h \) is the (measured) water surface elevation. By combining Eq. (2-3) and (2-6), the drag coefficient can be obtained when assuming a depth-uniform velocity profile. For emergent canopies, this is relatively straight-forward, although the choice of reference velocity may greatly affect the calculated \( C_{d} \) values [Etminan et al., 2017]. A large range of empirical relations have been established to relate canopy drag coefficients to plant shape, the flow regime (i.e. Reynolds number) and canopy properties (e.g. density). The drag coefficient is generally found to decrease exponentially with increasing Reynolds number [e.g. Liu and Zeng, 2017], following a similar trend to the isolated cylinder case (Eq. (2-2)). In terms of canopy geometry, some
studies have found that the drag coefficient decreases with increasing canopy density [e.g. Nepf, 1999], while many others obtained conflicting results [e.g. Wu et al., 1999; Tanino and Nepf, 2008; Wang et al., 2014]. Relatively few studies have directly measured the forces on canopy elements using force sensors either mounted at the top [e.g. Kothyari et al., 2009] or at the base of a canopy element [e.g. Schoneboom et al., 2010].

Furthermore, the majority of studies have focused on emergent canopies, such that there are still significant knowledge gaps in predicting the drag of submerged canopies. This is largely due to the more complex vertical flow structure within submerged canopies [e.g., Luhar and Nepf, 2013]. The in-canopy flow velocity is often significantly lower than the freestream velocity and, as for emergent canopies, horizontal variation in the flow field are expected to play a significant role in canopy drag. Even with accurate measurements of submerged canopy drag forces, it is still unclear how to predict the constricted cross-section velocity within a submerged canopy when velocity measurements are lacking. The main reason for this is that the in-canopy flow velocity is dependent on the drag itself [Lowe et al., 2005], so that \( C_d \) is a function of \( U_{ref} \), and vice versa.

This paper aims to reduce the uncertainty in canopy drag estimation through direct measurements of the drag force in aquatic vegetation canopies subject to unidirectional flow. The experimental program includes both emergent and submerged canopies with varying densities, and a range of hydrodynamic conditions covering a broad range of natural conditions that can be found in aquatic systems. In addition, a theoretical canopy drag model for emergent canopies is extended to submerged canopies and validated for the first time using direct force measurements, and then more broadly assessed using a compilation of data reported in previous studies.

### 2.2 Canopy drag model

For both emergent and submerged canopies, the mean drag force exerted on a single plant or canopy element is governed by Eq. (2-3). For emergent canopies, the mean horizontal flow velocity is often assumed to be depth-uniform. For submerged canopies, the horizontal flow profile can be approximated as a two-layer flow with depth-uniform velocities both above and inside the canopy [e.g. Lowe et al., 2005; Lui et al., 2008] (see Figure 2-1 for a definition sketch and relevant velocity definitions).
Figure 2-1: Open channel flows with (A) an emergent canopy and (B) a submerged canopy. In emergent canopies, the depth-averaged velocity ($\bar{U}$) is often used as the representative in-canopy velocity.

2.2.1 Emergent canopies

For emergent canopies, Etminan et al. [2017] proposed the use of the theory of drag for isolated cylinders (i.e. Eq. (2-2)) as the basis to compute the drag coefficients associated with emergent canopy. Their model employs the constricted cross-section velocity ($U_{ce}^{em}$) as the reference velocity ($U_{ref}$) to determine the drag coefficient through the Reynolds number (Eq. (2-2)) and to compute the drag force (Eq. (2-3)), and was validated through Large Eddy Simulation [Etminan et al., 2017].

2.2.2 Submerged canopies

For a given in-canopy flow, one can hypothesize that an analogous method to emergent canopies can be applied to submerged canopies, i.e. the in-canopy constricted
2.2 Canopy drag model

cross-section velocity \( U_{\text{c,sub}} \) can be computed using Eq. (2-4) or (2-5). However, as discussed in Section 2.1, the estimation of \( U_{\text{p,sub}} \) is not straightforward due to the vertical variation in the mean velocity profile (Figure 2-1); the magnitude of the in-canopy velocity both governs, and depends on, the canopy drag. Here, we propose the use of a canopy flow model to predict the in-canopy pore velocity \( U_{\text{p,sub}} \) based on the (undisturbed) above-canopy flow velocity \( U_{\infty} \). This model takes the form:

\[
U_{\text{p,sub}} = U_{\infty} \sqrt{L_d / L_s}
\]  

[2-7] [Lowe et al., 2005]. In (2-7), \( L_d \) is the drag length scale, given by

\[
L_d = \frac{2h_u(1-\lambda_p)}{C_d \lambda_f}
\]  

[2-8] [Lowe et al., 2005; Ghisalberti, 2009], and represents the flow resistance of the canopy. \( \lambda_f \) is the canopy element frontal area per unit bed area (=\( h, d, N_c \)). \( L_s \) is the shear length scale, given by

\[
L_s = \frac{2h_u}{C_f}
\]  

[2-9] [Lowe et al., 2005] (where \( C_f \) is a friction coefficient), which parameterizes the magnitude of the shear stress at the top of the canopy. This shear stress is generated by the velocity difference between the flow within and above the canopy. If velocity measurements are available, the friction coefficient can be estimated based on the peak in the Reynolds stress profile near the top of the canopy \( (z \approx h_c) \):

\[
C_f = 2 \frac{u_*^2}{U_{\infty}^2} = 2 \frac{\overline{u'w'}_{z=h_c}}{U_{\infty}^2}
\]  

[2-10] [Lowe et al., 2005], where \( u_* \) is the friction velocity and \( u' \) and \( w' \) are the horizontal and vertical turbulent velocity fluctuations, respectively. It is assumed a similar estimation could be obtained for more natural canopies with irregular elements, in which case the turbulence peak shifts upward by approximately the standard deviation of the heights of the canopy elements [Horstman et al., 2018]. Data from a wide range of canopies indicates that \( u_*/U_{\infty} \) tends to be consistently \( O(0.1) \), which corresponds to \( C_f = O(0.01) \) [e.g. Harman and Finnigan, 2007; Lowe et al., 2008; Luhar et al., 2010; Moltchanov et al., 2011; Weitzman et al., 2015]. Therefore, for a given canopy geometry and above-canopy flow velocity \( U_{\infty} \), the in-canopy pore velocity \( U_{\text{p,sub}} \) can be estimated from Eqs. (2-7) to (2-10). Subsequently, the constricted cross-section velocity inside a submerged canopy
can be obtained through Eq. (2-4) or (2-5), and is used as the reference velocity \( U_{\text{ref}} \) to calculate the drag coefficient through the Reynolds number (Eq. (2-2)) and to compute the drag force (Eq. (2-3)).

**Figure 2-2:** Flow diagram for the canopy drag model. The model can be used to estimate the drag force on an individual element within an emergent or submerged canopy or the bulk canopy drag. As input, it requires above-canopy velocity \( U_\infty \) that can be estimated from the flow rate \( Q \) or bulk velocity \( U_b \) for submerged and emergent canopies resp., local water depth \( h \), and the canopy properties: height \( h_v \), stem diameter \( d_v \), and canopy density \( \lambda_p, N_v \). For submerged canopies, an initial value of \( C_d = 1 \) (to calculate \( L_d \)) is suggested.

In summary, the model that is proposed here relies on information on above-canopy flow velocity \( U_\infty \) or bulk velocity (for emergent canopies), the local water depth
(h), and the canopy properties: height (h), stem diameter (d), and canopy density (λ, N). It includes one empirical parameter (namely, C) in the case of a submerged canopy. It is important to emphasize that given the drag coefficient C_d is also needed in Eq. (2-8) to predict the in-canopy flow (hence the drag forces and in-canopy flow are inherently coupled), for submerged canopies the model involves an iterative process. A flow diagram summarizing the model is provided in Figure 2-2. In the following sections, the model is validated using newly obtained velocity and drag force data, as well as a large dataset covering a broad range in canopy geometries and flow conditions obtained from literature.

2.3 Experimental Methods

Experiments were carried out in a 20-m-long, 0.6-m-wide and 0.6-m-deep recirculating flume using emergent (Table 2-1) and submerged (Table 2-2) model vegetation. To accommodate the drag force sensor, a 10-cm-high false bottom was placed over a length of 10 m. Model canopies were constructed using perforated PVC sheets and two sets of 6.4-mm-diameter dowels with heights of 30 cm (emergent) or 9 cm (submerged). Dowels were distributed in a staggered arrangement over the entire width of the flume. The dowel diameter used in this study has been used previously in numerous studies to represent a generic aquatic vegetation canopy [e.g. Nepf, 1999] and was originally based on actual observed stem diameters of cordgrass (Spartina alterniflora, see Zavistoski, [1994]). An important design parameter for experimental studies with canopies is the canopy length (L). Lowe et al. [2005] found a canopy flow adjustment length (x0) of 3 to 5 times the drag length scale (L_d) in their experiments. Hence, to ensure fully developed canopy flow, it was required that L_v >> x0 resulting in L_v ranging between 2.4 m (λ = 0.1) and 3.6 m (λ = 0.025).

The drag force exerted on a representative aluminium dowel (canopy element) was measured using a load cell with 2 N capacity (Uxcell, Hong Kong) connected to a load cell amplifier (RW-ST01A, SMOWO, China). The load cell was mounted vertically onto the underside of the false bottom in the flume, ensuring the bottom end of the load cell was fixed but allowing the upper end to move slightly with the bending moment (M_y) generated by the drag force acting on the dowel (Figure 2-3). Data was obtained from the load cell using a National Instruments data acquisition system (NI-DAQ PCI-6009) and
LabVIEW software. This experimental setup relies on the linear relationship between drag force and the instrument voltage output. To confirm the load cell’s linearity, the load cell was placed at the edge of a table and the voltage output recorded for cases with both no weight and a weight of (approx.) 1.9 N. The (linear) calibration coefficient was derived by calculating the ratio between the change in voltage output and the change in applied weight. The linear response was subsequently verified using 9 (smaller) weights ranging from 0.01 to 1.2 N ($R^2 > 0.99$). Prior to each individual experimental run, the load cell was re-calibrated using a set of three known weights ranging between 0 and ~0.3 N.

Figure 2-3: Schematic view of the load cell, which was attached to a single aluminum dowel and placed under the false bed. The drag force ($F_x$) due to the flow acting on the dowel translates into a moment ($M_y$) around the base of the load cell.

For emergent canopies, the water level was measured using a point gauge at three locations both upstream and downstream of the canopy. The water level gradient ($d\eta/dx$) was then obtained by averaging the water level in time at the upstream and downstream locations and dividing by the canopy length. To calculate the flow rate, velocity measurements were obtained several meters upstream of the canopy using a Nortek Vectrino Acoustic Doppler Velocity (ADV) Profiler, resulting in 3-cm-tall velocity
profiles with 1 mm resolution. The vertical position of the ADV was varied to obtain a full velocity profile extending from the bottom to ~5 cm below the water surface. In a similar manner, the velocity profile in and above the canopy was obtained for the submerged cases, and extended from the base of the canopy up to ~5 cm below the water surface. The ADV was positioned within the constricted cross-section in between two canopy elements at a lateral distance of approximately 0.25S_{v,l} from one of the elements. This was based on the modelling of Etminan et al. [2017], who found that the velocity at this point in a staggered canopy was similar to the constricted cross-section value. Experimental runs were repeated several times to obtain the full velocity profile over depth within and above the canopy. Both the load cell and ADV were placed at a distance of ~2/3 of the canopy length downstream from the leading edge, which is at least 10 times the drag length scale (L_d) for all cases.

The experimental program included a range of canopy densities (λ_p = 0.025, 0.05 and 0.10), canopy submergence ratios (h/h_v = 1, 2 and 3, where h is the water depth at still water and h_v is the canopy height) and flow rates (Table 2-1 and 2-2). The upstream flow velocity ranged between approximately 0.05 and 0.35 m/s, which in combination with the range in canopy density and submergence ratio covers a broad range of conditions that can be found in aquatic canopies. The drag force and velocity data were processed and the drag coefficient was subsequently computed using Eq. (2-3).

Following Taylor [1997], measurement uncertainties were propagated, with an estimated velocity uncertainty of 0.1 cm/s and drag force uncertainty of 0.4 mN. For the model-data comparison the model skill was quantified using scatter index (SCI), and the relative bias. The scatter index is a relative measure of the scatter between computed (x_c) and measured data (x_m) and is computed by normalizing the root-mean-square error \( \sqrt{\langle (x_c - x_m)^2 \rangle} \) with the maximum of the root-mean-square-value of the data \( \sqrt{\langle x_m^2 \rangle} \) and the absolute value of the mean of the data \( |\langle x_m \rangle| \). The relative bias is a relative measure of the bias or mean error \( \langle (x_c - x_m) \rangle \) and is normalized in the same way as the scatter index.
Table 2-1: Experimental emergent vegetation conditions: canopy density ($\lambda_p$), canopy height ($h_v$), water depth ($h$), flow rate ($Q$), bulk velocity ($U_{bem}$), pore velocity ($U_{pem}$), constricted cross-section velocity ($U_{cem}$), measured in-canopy velocity averaged over the canopy / dowel height ($U_{mem}$) and the measured time-averaged drag force acting on an isolated cylinder ($F_d$).

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<th>$\lambda_p$ [%]</th>
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<th>$h$ [m]</th>
<th>$Q$ [L s$^{-1}$]</th>
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Table 2-2: Experimental submerged vegetation conditions: canopy density ($\lambda_p$), canopy height ($h_v$), water depth ($h$), flow rate ($Q$), bulk velocity ($U_{b\text{ sub}}$), pore velocity ($U_{p\text{ sub}}$), constricted cross-section velocity ($U_{c\text{ sub}}$), measured in-canopy velocity averaged over the canopy / dowel height ($U_{m\text{ sub}}$) and the measured time-averaged drag force acting on an isolated cylinder ($F_d$).

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<td>5</td>
<td>0.09</td>
<td>0.27</td>
<td>25.9</td>
<td>0.16</td>
<td>0.04</td>
<td>0.05</td>
<td>0.06</td>
<td>0.19</td>
</tr>
<tr>
<td>S3-05-30</td>
<td>5</td>
<td>0.09</td>
<td>0.27</td>
<td>31.5</td>
<td>0.19</td>
<td>0.05</td>
<td>0.06</td>
<td>0.07</td>
<td>0.23</td>
</tr>
<tr>
<td>S3-05-35</td>
<td>5</td>
<td>0.09</td>
<td>0.27</td>
<td>36.7</td>
<td>0.23</td>
<td>0.06</td>
<td>0.07</td>
<td>0.08</td>
<td>0.21</td>
</tr>
<tr>
<td>S2-025-20</td>
<td>2.5</td>
<td>0.09</td>
<td>0.18</td>
<td>20.5</td>
<td>0.19</td>
<td>0.08</td>
<td>0.10</td>
<td>0.10</td>
<td>0.09</td>
</tr>
<tr>
<td>S2-025-25</td>
<td>2.5</td>
<td>0.09</td>
<td>0.18</td>
<td>25.9</td>
<td>0.24</td>
<td>0.10</td>
<td>0.12</td>
<td>0.13</td>
<td>0.14</td>
</tr>
<tr>
<td>S2-025-30</td>
<td>2.5</td>
<td>0.09</td>
<td>0.18</td>
<td>36.7</td>
<td>0.34</td>
<td>0.14</td>
<td>0.17</td>
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</tr>
<tr>
<td>S2-05-10</td>
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<td>0.18</td>
<td>10.2</td>
<td>0.09</td>
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<td>0.03</td>
<td>0.05</td>
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</tr>
<tr>
<td>S2-05-15</td>
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<td>0.09</td>
<td>0.18</td>
<td>15.2</td>
<td>0.14</td>
<td>0.04</td>
<td>0.05</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>S2-05-20</td>
<td>5</td>
<td>0.09</td>
<td>0.18</td>
<td>20.5</td>
<td>0.19</td>
<td>0.06</td>
<td>0.07</td>
<td>0.09</td>
<td>0.16</td>
</tr>
</tbody>
</table>

To date only relatively few studies have used load cells to measure canopy drag, hence a comparison is made between the drag force measured directly using the current
methodology \( (F_{d,\text{direct}}) \) and the drag force obtained through an indirect measuring method commonly used in previous studies \( (F_{d,\text{momentum}}, \text{from } \text{Eq. (2-6)}) \). The indirect estimate \( (F_{d,\text{momentum}}) \) for the emergent cases (E05 and E10, see Table 2-1) shows the same trend \( (R^2 = 0.99) \) as the drag force directly measured with the load cell \( (F_{d,\text{direct}}, \text{see Figure 2-4}) \). Although measured drag forces with magnitudes above 0.01 N are very similar for both methods (up to 8% difference), for drag forces < 0.01 N the discrepancy between both methods increases (with an average 22% difference). For these low flow cases the percentage uncertainty associated with the measured water level gradient increases (with the water level dropping only ~3 mm over the length of the canopy) leading to larger errors. Given the high instrument linearity, the force sensor is able to provide more accurate measurements for these cases and is therefore preferred.

Figure 2-4: The strong agreement in estimated drag forces on an individual element in an emergent canopy using two methods: (i) measured directly using the force sensor \( (F_{d,\text{direct}}) \) and (ii) derived indirectly from the water surface gradient \( (F_{d,\text{momentum}}). \) Marker color indicates canopy density (black: \( \lambda_p = 0.05; \) grey: \( \lambda_p = 0.10 \)). The size of the markers indicates the associated measurement uncertainty. The dashed line represents the line of perfect agreement.
2.4 Results and Discussion

2.4.1 Measurement of drag coefficients

Isolated cylinder

Although the focus in this study is on assessing canopy drag, a limited number of experiments were conducted with isolated emergent (Table 2-1) and submerged (Table 2-2) cylinders. The isolated cylinder drag coefficients were then compared to theory (Eq. (2-2)) to gain confidence in the experimental methodology (particularly the drag force data obtained from the load cell). For the emergent case, there is excellent agreement between the directly measured drag on an isolated cylinder and Eq. (2-2) (Figure 2-5, squares). For the submerged case (with same height as the submerged canopy), the value of $C_d$ derived from the measured drag force and measured in-canopy velocity (averaged over the cylinder height) is consistent with isolated cylinder theory (Figure 2-5, triangles). In other words, despite the single vertical cylinder occupying a fraction of the water column in a boundary layer flow, its forces can be predicted by Eq. (2-2) originally developed for a cylinder in a uniform cross-flow.

Emergent canopies

As discussed in Section 2.1, for emergent canopies, both the bulk velocity and pore velocity are often used as the reference velocity in Eq. (2-3) to relate a given flow condition to the canopy drag force through a drag coefficient (i.e., $C_{d,b}$ and $C_{d,p}$, respectively). Here, when using both the bulk velocity ($U_b^{em}$) and pore velocity ($U_p^{em}$) are used as the drag reference velocity, there are large discrepancies with values for isolated cylinders (Eq. (2-2)), similar to results reported in other studies [e.g. Liu and Zeng, 2017]. For the highest density canopies ($\lambda_p=0.1$), there is an exponential decrease in the drag coefficient with Reynolds number using both the bulk velocity $U_b^{em}$ (Figure 2-6A, squares) and pore velocity $U_p^{em}$ (Figure 2-6B). For the 5% density emergent canopies, the drag coefficient shows a slight decrease with $Re$ using both reference velocities. When considering both $U_b^{em}$ and $U_p^{em}$, the drag coefficient appears to take an approximately constant value at high $Re$ (i.e. $Re >1000$), consistent with other studies [e.g. Tang et al.,
2014]. Given that the pore velocity accounts for the volume of water being occupied by the canopy, \(C_{d,p}\) is always smaller than \(C_{d,b}\), but still deviates substantially from isolated cylinder values. To account for these discrepancies, previous studies have arrived at highly empirical \(C_{d,p}-Re_p\) relationships that are parameterized as a function of canopy density [Tanino and Nepf, 2008] and (sometimes) stem diameter [Sonnenwald et al., 2018].

![Figure 2-5: Drag coefficients derived from the drag force measurements for the isolated cylinder and cases using the measured velocity \(C_{d,m}, Re_m\) as the reference velocity for emergent and submerged canopies. Theoretical values for an isolated cylinder (Eq. (2-2)) are denoted by the dashed line.](image)

The direct experimental measurements support the canopy drag model proposed by Etminan et al. [2017] – when the constricted cross-section velocity \((U_c^{em})\) is used as the reference velocity, calculated drag coefficients closely match the isolated cylinder values (Figure 2-7, squares). Therefore, while the drag coefficients derived using the bulk and pore velocities exhibit significant scatter (Figure 2-6), the use of \(U_c^{em}\) in the drag coefficient \((C_{d,c})\) calculations serves to collapse the data onto the isolated cylinder curve.
For the range of Reynolds numbers investigated \((Re_c = 380 - 1680)\), the drag coefficients for the emergent cases show relatively little scatter and approaches a canonical isolated cylinder value of \(C_{d,c} \approx 1\).

![Figure 2-6: Drag coefficients derived from the drag force measurements using (A) the bulk velocities \(U_{b,em}\) and \(U_{b,sub}\) and (B) the pore velocity \(U_{p,em}\) as the reference velocity for the emergent (squares) and submerged (circles: \(h/h_v = 2\); triangles: \(h/h_v = 3\)) cases. The marker color represents the canopy density (black: \(\lambda_p = 0.1\); white: \(\lambda_p = 0.05\); grey: \(\lambda_p = 0.025\)), with theoretical values for an isolated cylinder (Eq. (2-2)) denoted by the dashed line.](image)

**Submerged canopies**

The velocity exhibits more vertical variation in submerged canopies than in emergent canopies due to the drag discontinuity and resulting shear layer present at the top of the canopy. When using the bulk velocity \(U_{b,sub}^{\text{sub}}\) as the reference velocity to derive \(Re_b\) and \(C_{d,b}\), relatively low drag coefficients (that substantially deviate from the isolated cylinder values) are obtained (Figure 2-6A, circles and triangles). This approach neglects the effect of canopy drag on reducing the in-canopy velocity, which is significant at higher canopy densities. Hence, we use measured \(U_{c,sub}^{\text{sub}}\) obtained approximately within the constricted cross-section area and derive the associated drag coefficients. For the submerged canopy cases, the measured values of \(C_{d,c}\) (i.e., evaluated using the constricted cross-section velocity \(U_{c,sub}^{\text{sub}}\)) generally follow a similar trend as isolated cylinder theory.
(Figure 2-7). There is more scatter at $Re_c < 500$, which can be attributed to the greater uncertainty associated with measuring flow and forces at such low Reynolds numbers. Therefore, analogous to the emergent canopy observations in Figure 2-6, where $C_d$ evaluated using bulk and pore velocities deviates markedly from isolated cylinder theory, these results indicate that the constricted cross-section velocity $U_{csub}$ is the optimal reference velocity for evaluation of drag of a submerged canopy (Figure 2-7).

![Graph showing drag coefficients against Re_c](image)

**Figure 2-7:** Drag coefficients derived from the drag force measurements for all canopies using the constricted cross-section velocity $U_c$ as the reference velocity for the emergent and submerged cases. Theoretical values for the drag coefficient of an isolated cylinder (Eq. (2-2)) are denoted by the dashed line.

### 2.4.2 Canopy drag model assessment

**Emergent canopies**

The canopy drag model for emergent canopies, based on Eqs. (2-2) to (2-4) using the computed constricted cross-section velocity $U_{cem}$ (see Section 2.1), was used to
predict the drag force on a single canopy element in all experimental cases (Table 2-1). These predictions were then compared to the time-averaged drag force measured by the force sensor (Figure 2-8, squares). Using only the bulk flow velocity, which was derived from the known flow rate, and canopy geometry as model input, the canopy drag forces are accurately predicted over the full range of experimental cases. The results provide direct experimental validation of the finding of Etminan et al. [2017] that the constricted cross-section velocity $U_{c}^{em}$ is the most appropriate reference velocity to parameterize canopy drag.

Figure 2-8: The strong agreement between predicted and measured drag forces, including the line of perfect agreement (dashed). The predictive model skill is described by the relative bias and scatter index (bottom right corner).

**Submerged canopies**

To assess the ability of the model to predict the drag of submerged canopies, we first compared the predicted in-canopy velocities with the experimental measurements. Specifically, we compared the measured time-averaged constricted cross-section velocity integrated over the canopy height ($U_{m}^{sub}$) with predicted $U_{c}^{sub}$ values, which generally reveals good agreement (Figure 2-9). The model (with above-canopy velocity and canopy
geometry as input) is subsequently applied to calculate the drag force for all submerged canopy cases (Table 2-2). Canopy friction coefficient values were derived for each case through Reynolds stress profiles (Eq. (2-10)), resulting in a range of $C_f$ values between 0.01 and 0.04. However, due to the experimental setup in this study, that used a downward facing ADV, the velocity measurement was limited to measuring only ~6 cm below the water surface. The above-canopy velocity is therefore likely underestimated, particularly in the $h/h_v=2$ cases, and actual $C_f$ values are expected to be lower. Due to this uncertainty, here we opt the use of a conventional value of 0.01 for all experimental cases (see Section 2.2). Compared to emergent canopies, there is greater scatter in the relationship between measured and predicted forces (particularly at low $Re$), but overall there is still relatively good agreement (Figure 2-8). Given the complexity involved with submerged canopies (including the uncertainty involved with measurements under low $Re$), and the range in submergence ratio and density investigated, the model error averages about 11% ($SCI =0.114$), and suggests that the whole model outlined in Figure 2-2 can serve as a useful tool to obtain robust estimates of canopy drag forces.

![Figure 2-9: Comparison between the measured depth-averaged in-canopy flow velocity ($U_{m}^{sub}$) and the estimated in-canopy constricted cross-section velocity ($U_{c}^{sub}$) in submerged canopies.](image)

$R^2=0.84$
2.4.3 Model application to other submerged canopy datasets

To date, the canopy drag model has been validated for emergent canopies [Etminan et al., 2017] (albeit using only numerical simulations); here we have provided direct experimental validation for both emergent and submerged canopies for the first time. Nevertheless, the experiments only covered a relatively small range of possible canopy geometry and flow conditions. To further assess the validity of the model across a large range of flow conditions and canopy properties (e.g. density, submergence ratio, flexibility), the model was tested against a large number of existing datasets. Experiments were limited to those with submerged canopies in which the energy slope was reported.

**Rigid vegetation**

For rigid vegetation, experiments that employed either staggered (as in the present study), linear or random arrangements were selected here (Table 2-3). Although on the individual canopy element scale, the velocity distribution may vary significantly among these arrangements, we hypothesize that the model can still be used to estimate bulk canopy drag. Indeed, the work of Etminan et al. [2017] suggested that in the case of randomly distributed canopy elements, the constricted cross-section velocity can still be considered as the velocity scale governing canopy drag, indicating that the model can be applied here without modification. Hence, using provided values of flow rate and canopy properties, the bulk drag was computed and compared with the measured drag (Figure 2-10A). Using a constant $C_f$ value of 0.01 (as before), the model shows a similar trend as the measurements ($R^2 = 0.74$) with reasonably low bias and scatter (rel. bias = 0.02, $SCI = 0.45$). It should be emphasized that the main uncertainty is likely to be attributed to the schematization of relatively complex three-dimensional canopy hydrodynamics into a relatively simple (two-layer) model.
Table 2-3: Overview of experimental studies on drag in submerged rigid canopies from which data was obtained. All experiments either used staggered (stag.), linear (lin.) or random (rand.) canopy setups.

<table>
<thead>
<tr>
<th>reference</th>
<th>$d_c$ [mm]</th>
<th>$h_c$ [cm]</th>
<th>$h/v$</th>
<th>$f_p$ [%]</th>
<th>stem type</th>
<th>canopy setup</th>
<th>runs</th>
<th>$U_{sub}$ [cm/s]</th>
<th>$Re_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dunn et al. ['96]</td>
<td>6.4</td>
<td>11.8</td>
<td>1.4-3.3</td>
<td>0.14-1.23</td>
<td>cyl.</td>
<td>stag.</td>
<td>12</td>
<td>30-85</td>
<td>1890-5420</td>
</tr>
<tr>
<td>Stone &amp; Shen ['02];</td>
<td>3.2-12.7</td>
<td>12.4</td>
<td>1.2-2.5</td>
<td>0.55-6.10</td>
<td>cyl.</td>
<td>stag.</td>
<td>128</td>
<td>3-63</td>
<td>126-5400</td>
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<td>Stone ['97]</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cheng ['11]</td>
<td>3.2-8.3</td>
<td>10</td>
<td>1.3-2</td>
<td>0.43-11.9</td>
<td>cyl.</td>
<td>stag.</td>
<td>23</td>
<td>8-34</td>
<td>540-2130</td>
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<tr>
<td>Shimizu et al. ['91]</td>
<td>1-1.5</td>
<td>4.1-4.6</td>
<td>1.1-2.6</td>
<td>0.44-0.79</td>
<td>cyl.</td>
<td>lin.</td>
<td>28</td>
<td>6-33</td>
<td>65-500</td>
</tr>
<tr>
<td>Poggi et al. ['04]</td>
<td>4</td>
<td>12</td>
<td>5</td>
<td>0.08-1.35</td>
<td>cyl.</td>
<td>lin.</td>
<td>5</td>
<td>~30</td>
<td>~1200</td>
</tr>
<tr>
<td>Nezu &amp; Sanjou ['08]</td>
<td>8</td>
<td>5</td>
<td>1.25-4</td>
<td>0.39-1.54</td>
<td>strips</td>
<td>lin.</td>
<td>9</td>
<td>10-12</td>
<td>800-960</td>
</tr>
<tr>
<td>Murphy et al. ['07]</td>
<td>6</td>
<td>7-14</td>
<td>1.3-4.3</td>
<td>1.18-3.77</td>
<td>cyl.</td>
<td>rand.</td>
<td>24</td>
<td>1.5-18</td>
<td>90-1060</td>
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<tr>
<td>This study</td>
<td>6.4</td>
<td>9</td>
<td>2.3</td>
<td>2.5-10</td>
<td>cyl.</td>
<td>stag.</td>
<td>23</td>
<td>9-34</td>
<td>310-2180</td>
</tr>
<tr>
<td>Overall</td>
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<td>4.1-14</td>
<td>1.1-5</td>
<td>0.08-11.9</td>
<td></td>
<td></td>
<td>252</td>
<td>1.5-85</td>
<td>65-5420</td>
</tr>
</tbody>
</table>

Flexible elements

Although most studies so far have represented vegetation canopies using rigid elements, aquatic vegetation in natural systems is often flexible (e.g. seagrasses, kelp), adapting its shape and thereby frontal area in response to the flow. Hence, there is now increased experimentation with flexible mimics in hydraulic experiments [e.g. Abdolahpour et al., 2017]. The canopy drag model presented in this study does not explicitly account for flexibility, but it is hypothesized that it could still be used as a tool provided the deflected vegetation height (i.e. the height of the vegetation under stationary flow condition) rather than the actual length of the element is used. Hence, data was obtained from three studies that investigated drag in submerged flexible canopies and reported the deflected canopy height (Table 2-4). From these studies, both Dunn et al.
2.4 RESULTS AND DISCUSSION

[1996] and Järvelä [2003] observed swaying motions of their flexible plants (cylindrical) elements, resulting in a time-varying deflected canopy height. Okamoto and Nezu [2010] reported both swaying and the more organized monami-type motions [Ackerman and Okubo, 1993] in their experiments. Here, we use the time-averaged deflected canopy height as input for the model. Furthermore, for the experiments by Okamoto and Nezu [2010] we use the width of the flexible strip as a proxy for $d$, given that it is equivalent to the frontal area.

Figure 2-10: Validation of canopy drag model for submerged canopies against previous experimental results with (A) rigid and (B) flexible vegetation (listed in Tables 2-3 and 2-4, respectively).

For the flexible canopies, the model is able to predict the bulk drag relatively well (Figure 2-10B, $R^2 = 0.69$, rel. bias = 0.04, $SCI = 0.53$). This is surprising to some extent, as the complexity associated with flexible elements is only accounted for to some extent by the (deflected) plant height. Both the measurements by Okamoto and Nezu [2010] and Järvelä [2003] are consistently underpredicted, which may be related to the plant geometries that involved flat strips and real plants respectively. Dunn et al. [1996], on the other hand, used flexible cylinders in their experiments which provide more similarity with rigid cylinders, and may therefore better be represented by model.

Overall, with limited information (above-canopy velocity derived from flow rate, canopy properties) the relatively simple canopy drag model is able to provide...
reasonably accurate estimates of the bulk canopy drag for both rigid and flexible vegetation canopies. Given the fact that the model performs well over such a broad range of hydrodynamic conditions \((U_b = 1.5 – 85 \text{ cm/s}, Re = 65 - 5420)\) and canopies \((h/h_v = 1.1 – 5, \lambda_p = 0.08 – 11.9\%, \text{ both rigid and flexible vegetation})\), and is based on theory rather than empirical relations, it is thus expected the model can robustly predict hydraulic resistance of aquatic canopies, including in field setting with natural vegetation (e.g. where stem diameters are often of order 0.1 – 1 cm and current velocities of order 0.05 – 0.5 m/s, which translates to \(Re\) ranging between 50 and 5000).

Table 2-4: Overview of experimental studies on drag in submerged flexible canopies from which data was obtained.

<table>
<thead>
<tr>
<th>reference</th>
<th>(d_v) [mm]</th>
<th>(h_v) [cm]</th>
<th>(h_{vd}) [cm]</th>
<th>(h/h_{vd})</th>
<th>(\lambda_p) [%]</th>
<th>stem type</th>
<th>canopy setup</th>
<th>runs</th>
<th>(U_{sub}) [cm/s]</th>
<th>(Re_b)</th>
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<tr>
<td>Dunn et al. ['96]</td>
<td>6.4</td>
<td>17</td>
<td>9.7 – 16</td>
<td>1.7 – 2.4</td>
<td>0.1 – 1.2</td>
<td>cyl.</td>
<td>stag.</td>
<td>6</td>
<td>30-85</td>
<td>1950-5430</td>
</tr>
<tr>
<td>Järvelä ['03]</td>
<td>2.8-3</td>
<td>28 – 30</td>
<td>16 – 29.5</td>
<td>1.4 – 3.3</td>
<td>0.4 – 7.4</td>
<td>real</td>
<td>stag.</td>
<td>12</td>
<td>7-33</td>
<td>200-990</td>
</tr>
<tr>
<td>Okamoto &amp; Nezu ['10]</td>
<td>8</td>
<td>5 – 10.5</td>
<td>3 – 9.6</td>
<td>3 – 5.3</td>
<td>4.78</td>
<td>strip</td>
<td>lin.</td>
<td>28</td>
<td>10 - 35</td>
<td>800-2800</td>
</tr>
</tbody>
</table>

Overall | 2.8–8        | 5 – 30       | 3 – 29.5        | 1.4 – 5.3    | 0.1 – 7.4       | 46        | 7-85          | 200-5430 |

2.5 Summary and Conclusions

In this study we present new direct experimental measurements of canopy drag forces using emergent and submerged canopies with a broad range of flow conditions and canopy properties (i.e. density and submergence ratio). Drag coefficients were derived using direct measurements of the drag force on a dowel within the canopy. We found that if the constricted cross-section velocity is used as the reference velocity, the drag coefficient of both emergent and submerged canopies is equal to that of an isolated cylinder. Comparison between canopy drag model predictions and current and existing
experimental data shows that the model is able to robustly and accurately predict canopy drag across the field range of flow conditions and canopy characteristics, including flexible canopies. The model can thus be used to predict drag forces in emergent and submerged canopies and is considered a simple and practical tool for estimating the hydraulic resistance of aquatic canopies.
3.1 Introduction

Improving predictions of wave-vegetation interactions has been an increasing focus of coastal research over the past decade [e.g., see review by Nepf, 2012b], which is often motivated by the desire to quantify the coastal protection services provided by aquatic vegetation [e.g., Borsje et al., 2011; Tang et al., 2013]. Attenuation of wave energy due to different species of vegetation has been studied both experimentally [e.g., Möller et al., 2014] and in the field [e.g., Möller and Spencer, 2002; Paul and Amos, 2011], while theoretical models have been developed based on conservation of wave energy to predict wave attenuation across a given aquatic vegetation canopy for monochromatic [Dalrymple et al., 1984; Kobayashi et al., 1993] and irregular waves [Mendez and Losada, 2004; Jacobsen et al., 2019]. In the case of emergent vegetation and/or nonlinear waves, vegetation can contribute to a reduction in wave setup (wave-induced mean water levels) [Dean and Bender, 2006], and aquatic canopies have also been found to reduce wind-induced storm surge levels by slowing the storm surge advance [e.g., Sheng et al., 2012]. Although wave-induced flows are typically assumed to be depth-uniform in shallow coastal waters, the presence of submerged aquatic canopies generally results in strong vertical gradients in the wave velocities [Lowe et al.,
2005; 2008; Pujol et al., 2013] and localised increases in turbulence production [e.g., Neumeier and Amos, 2006].

Wave-induced mean currents near aquatic vegetation canopies have received relatively little attention to date. The vertical gradients in wave-driven mean flow within submerged canopies are thought to enhance vertical mixing of nutrients between the canopy and its surroundings [e.g., Abdolahpour et al., 2016], and on longer timescales drive local morphological changes to seabeds with canopies. Luhar et al. [2010; 2013] observed a wave-averaged net mean flow inside a submerged canopy with flexible vegetation, and derived a theoretical model to quantify the magnitude of the depth-integrated wave-averaged in-canopy velocity. Their model proposes that the mean flow is induced by a nonzero wave stress, similar to streaming observed in wave boundary layers [e.g., Longuet-Higgins, 1953]. The wave stress \( \langle u_w w_w \rangle \), where \( \langle \ldots \rangle \) denotes time average) becomes nonzero when the horizontal \( u_w \) and vertical \( w_w \) wave velocities are no longer perfectly out of phase due to the difference in horizontal wave velocity inside and above the canopy. The model assumes that wave energy is predominantly transferred from the above canopy region into the canopy through the work done by the wave-induced pressure at the top of the canopy, and that it is balanced by the in-canopy energy dissipation dominated by work done due to drag. Using linear wave theory, the governing energy balance for a canopy is then given by:

\[
\rho \langle u_w w_w \rangle = -\frac{k}{\omega} \int_0^{h_v} f_d u \, dz,
\]

[3-1]

[Luhar et al., 2010], where \( \rho \) is the water density, \( k \) is the wave number, \( \omega \) is the wave radian frequency, \( h_v \) is the vegetation height, \( f_d \) is the vegetation drag force, \( u \) is the horizontal velocity, and \( z \) is the vertical coordinate. Furthermore, Luhar et al. [2010] derived a time-averaged horizontal momentum balance by assuming that the momentum transfer into the canopy is balanced by the time-averaged drag force. To derive a formulation for the mean in-canopy flow magnitude, they further assumed that, i) the drag force can readily be decomposed in a mean and wave component with drag coefficients of comparable magnitude, ii) wave energy dissipation is dominated by the wave component of the drag, iii) the mean canopy drag is dominated by the mean current in the canopy, and iv) the mean flow magnitude is constant over the height of the canopy. With
3.1 **Introduction**

these assumptions, they derived the following formulation for the depth-integrated in-canopy mean flow magnitude \( (u_{m,can}) \):

\[
    u_{m,can} = \sqrt{\frac{4}{3\pi} \frac{C_{ Dw} k}{C_{ Dc} \omega} u_{w,can}^3},
\]

[3-2] [Luhar et al., 2010], where \( C_{ Dw} \) and \( C_{ Dc} \) are drag coefficients associated with waves and currents respectively, and \( u_{w,can} \) is the in-canopy wave velocity magnitude.

While the model by Luhar et al. [2010] assumes the wave-induced mean flow inside a canopy is depth-uniform, Abdolahpour et al. [2017] found relatively strong vertical gradients in the wave-induced mean velocity for submerged canopies. They proposed a Lagrangian framework and kinematic arguments to derive an empirical relation to predict the peak value of the mean velocity near the top of a submerged canopy. Their model relies on a moving (Lagrangian) reference frame and thus accounts for the additional depth-varying mass flux (Stokes drift) that appears when accounting for vertical variation in the wave orbital particle motion [e.g., Phillips, 1977]. Although it is well established that the total (Lagrangian) mass flux governs the transport of dissolved and particulate material, it is difficult to measure Stokes drift as it requires particle tracking or use of tracers. Instead, Abdolahpour et al. [2017] validated their model using measurements from fixed (Eulerian) instruments and found a good agreement, hence suggestion the Stokes drift contribution was relatively small. However, due to the nature of their model, a clear distinction between the (Eulerian) streaming and (Lagrangian) Stokes drift influence is missing. Consequently, a general description of the Stokes drift profile in case of submerged canopies, as well as the relative contribution to the overall wave-averaged flow dynamics is still lacking.

Some studies have also investigated the mean flow generated by waves interacting with submerged canopies using numerical simulations [e.g., Ma et al., 2013; Chen et al., 2019]; however, these studies generally focused on validating the performance of a given model, and not a detailed description or explanation of the driving mechanisms. A comprehensive understanding of the hydrodynamic forces that governs wave-driven mean flows in submerged canopies is currently lacking.

This paper aims to increase understanding of wave-averaged canopy hydrodynamics, based on a combination of experimental observations and numerical
modelling. We focus particularly on the stress distributions and forces that control the mean (wave-averaged) horizontal momentum balance to obtain a physical description of the depth-varying wave-induced current and to support future numerical model developments.

### 3.2 Background: the mean horizontal momentum balance

The two-dimensional cross-shore (2DV) wave-averaged horizontal momentum equation governing the mean flow through a canopy can be derived by applying averaging operations to the Navier-Stokes equations [e.g., Nielsen, 1992]. First the velocity signal is decomposed, which for the horizontal component is defined as

\[
\mathbf{u} = \langle \mathbf{u} \rangle + \mathbf{u} \bar{} + \mathbf{u}' ,
\]

where \( \langle \mathbf{u} \rangle \) is the wave-averaged flow velocity, \( \tilde{\mathbf{u}} \) is the wave orbital velocity and \( \mathbf{u}' \) is the turbulent velocity component. Next, the terms in the Navier-Stokes equations are time-averaged over the wave cycle (denoted by \(<...>\)) and then spatially averaged over the fluid region (i.e., neglecting the solid canopy elements), yielding:

\[
\frac{\partial}{\partial x} \langle u \rangle + \frac{\partial}{\partial x} \langle u \rangle \langle w \rangle + \frac{\partial}{\partial x} \langle u \rangle \langle w \rangle + \frac{\partial}{\partial x} \langle u \rangle \langle w \rangle - \frac{\nu}{\rho} \left( \frac{\partial^2 \langle u \rangle}{\partial x^2} + \frac{\partial^2 \langle u \rangle}{\partial z^2} \right) + \frac{1}{\rho} \frac{\partial p}{\partial x} - \frac{1}{\rho} \langle f_{v,x} \rangle = 0
\]

where \( x \) and \( z \) are the horizontal and vertical coordinates, respectively, \( \nu \) is the kinematic viscosity, \( \rho \) is the density, \( p \) is the (total) pressure and \( \langle f_{v,x} \rangle \) is the wave-averaged vegetation force. The wave-averaged pressure contains a hydrostatic and non-hydrostatic component (\( \langle p \rangle = \langle p_h \rangle + \langle p_{nh} \rangle \)), where the hydrostatic part is given by:

\[
\langle p_h \rangle = \rho g \langle (\zeta) - z \rangle ,
\]

where \( g \) is the acceleration due to gravity, and \( \zeta \) is the mean (wave-averaged) water surface elevation. Spatial gradients in hydrostatic pressure, i.e. \( \partial \langle p_h \rangle / \partial x \), are therefore associated with a mean water level (e.g., wave setup) gradients. The non-hydrostatic pressure comprises a contribution due to the flux of vertical momentum from the vertical fluid motion and a contribution from the wave-averaged horizontal derivative of the vertically integrated shear stresses:

\[
\langle p_{nh} \rangle = -\rho \left( \langle \omega^2 \rangle + \langle w'^2 \rangle \right) + \frac{2}{\partial x} \langle f_{x} \rangle \rho \langle \tilde{u} \tilde{w} + u' w' \rangle dz ,
\]

which is obtained through a vertical integration of the vertical momentum equation.
3.2 BACKGROUND: THE MEAN HORIZONTAL MOMENTUM BALANCE

[Svendsen, 2006]. For clarity, all terms contributing to the wave-averaged normal ($\sigma_{xx}$) and shear stress ($\tau_{xz}$) can be aggregated as:

$$\begin{align*}
\sigma_{xx} &= \rho \left( v \frac{\partial \bar{u}}{\partial x} - \langle \bar{u}^2 \rangle - \langle u'^2 \rangle \right) - \langle p_{nh} \rangle, \\
\tau_{xz} &= \rho \left( v \frac{\partial \bar{w}}{\partial z} - \langle \bar{u}\bar{w} \rangle - \langle u'w' \rangle \right),
\end{align*}$$

where each of the first three terms in Eqs. (3-7) and (3-8) represent the viscous, wave-driven and turbulent contributions to the normal and shear stress, respectively. Based on these definitions, Eq. (3-4) can be rewritten as:

$$\frac{\partial \langle u^2 \rangle}{\partial x} + \frac{\partial \langle uw \rangle}{\partial z} - \frac{1}{\rho} \left( \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \tau_{xz}}{\partial z} - \frac{\partial \langle p_{nh} \rangle}{\partial x} + \langle f_{dx} \rangle \right) = 0.$$

The mean horizontal momentum balance (i.e., Eq. 4 and 9) represents the force balance that governs the mean (wave-averaged) flow.

Both viscous stresses and the turbulent normal stress $\langle u'^2 \rangle$ are generally expected to be relatively small in cross-shore (2DV) coastal applications [e.g., van der Werf et al., 2017]. The wave contribution to the normal stress $\langle \bar{u}^2 \rangle$ is directly related to momentum associated with wave orbital motions and is often represented as the wave radiation stress through depth-integration. The wave shear stress $\langle \bar{u}\bar{w} \rangle$ (also referred to as the wave Reynolds stress) is zero for irrotational waves and is therefore often neglected in coastal models. However, in many cases waves become rotational (for example, within wave boundary layers) as a result of horizontal and vertical orbital velocities being no longer 90° out of phase, leading to a nonzero wave Reynolds stress [Longuet-Higgins, 1953]. Turbulence generated by vertical gradients in the mean flow generate turbulent shear stresses $\langle u'w' \rangle$ (also known as the turbulent Reynolds stresses). The mean horizontal vegetation force $\langle f_{v,x} \rangle$, is generally described by the (wave-averaged) Morison equation, where the wave-average of the inertial force equals zero (i.e., $\langle \partial u/\partial t \rangle = 0$), such that:

$$\langle f_{v,x} \rangle = \langle f_{d,x} \rangle = \frac{1}{2} \rho C_D d_v N_v \langle |u| \rangle$$

where $\langle f_{d,x} \rangle$ is the wave-averaged drag force, $C_D$ is the drag coefficient, $d_v$ is the canopy element diameter, and $N_v$ is the number of canopy elements per unit area.
3.3 Methods

3.3.1 Wave flume experiments

Experiments were conducted in a 35-m-long, 1.2-m-wide and 1.2-m-deep wave flume at the University of Western Australia (Figure 3-1). The flume was equipped with a piston-type wave maker positioned at the upstream end of the flume with a 1:10 slope at the downstream end. The slope was covered by dense polyurethane filter foam sheets, anti-fatigue rubber mats with holes and finally flat hollow concrete elements. With this approach, the slope was used as a passive wave energy absorber as waves experience progressively decreasing porosity, thereby gradually losing their energy. In a similar study in the same facility, it was found that this approach ensures wave reflections from the downstream slope are sufficiently small, with reflection coefficients < 6% [Abdolahpour et al., 2016].

![Figure 3-1: Schematic diagram of experimental setup (with vertical scale exaggerated) with location of Nortek Vectrino Acoustic Doppler Velocimeter (ADV) and load cell (LC).](image)

A rigid submerged canopy was constructed using a staggered array of dowels (6.4 mm diameter) that were 30 cm high at a density of ~3100 units per m², representing a relatively high-density canopy ($\lambda_p=0.1$, where $\lambda_p$ is the canopy element plan area per unit bed area). To ensure fully developed canopy flow conditions, the length of the canopy ($L_c = 2.5$ m) was chosen such that $L_c >> A_\infty^c$, where $A_\infty = \bar{u}_{max,\infty} \omega$ is the wave orbital excursion length above the canopy, $\bar{u}_{max,\infty}$ is the maximum free-stream horizontal wave orbital velocity and $\omega = 2\pi/T$ is the angular wave frequency based on the wave period.
3.3 Methods

Furthermore the length of the canopy was much greater than the canopy drag length scale \((L_d)\) defined as
\[
L_d \sim 2 h_v (1 - \lambda_p) \lambda_f^{-1},
\]
where \(h_v\) is the vegetation height and \(\lambda_f\) is the canopy element frontal area per unit bed area [e.g., Lowe et al., 2005]. Preliminary numerical modelling (presented in Section 3.4) indicated that, in all cases, edge effects were negligible at a point 1 m into the canopy, further validating the choice of canopy length.

The experimental program included six regular wave conditions with varying wave height and wave period (Table 3-1) in constant water depth \((h = 0.75 \text{ m})\). The Keulegan-Carpenter number \((KC = \hat{U}_{max,\infty} T d_v^{-1})\) is a commonly used parameter in wave-canopy interaction studies, and is often used to distinguish characteristic canopy flow regimes and to provide an indication of the relative contribution from canopy drag over inertial forces [e.g., Etminan et al., 2019]. Moreover, several studies have shown that canopy drag coefficients depend on \(KC\) [e.g., Ozeren et al., 2014]. We therefore ensured that the experimental wave conditions covered a wide range of \(KC\) to cover the field range as much as possible within the capacities of the experimental facility. The resulting \(KC\)-values (51-230, see Table 3-1) are considered representative for many coastal wave conditions and aquatic vegetation commonly found in nature (e.g., assuming \(\hat{U}_{max,\infty} \sim 0.1 - 0.4 \text{ m/s, } T \sim 3 - 8 \text{ s and } d_v \sim 0.01 \text{ m resulting in } KC \sim 30 - 320\)). In addition, the wave conditions cover a range of nonlinear shallow to intermediate water waves that are representative for areas with aquatic vegetation that can be described with cnoidal wave theory [Le Méhauté, 1976]. Hence, the wave maker was forced using prescribed time series of the horizontal displacement of the wave paddle following the cnoidal wave generation method outlined by Goring [1979] and Cho [2003].
Table 3-1: Experimental conditions for all cases: offshore wave height ($H$) upstream of the canopy, wave period ($T$), Reynolds number ($Re$), Keulegan-Carpenter number ($KC$), drag coefficient ($C_d$) derived from combined force sensor and velocity measurements (Section 3.1), the above-canopy root-mean-square velocity ($\bar{u}_{rms,c}$), the measured depth-integrated in-canopy mean flow velocity ($\langle u \rangle_{can}$), and the depth-integrated in-canopy mean flow velocity as predicted by Luhar et al. [2010] ($\langle u \rangle_{can,Luhar}$).

<table>
<thead>
<tr>
<th>Run ID</th>
<th>$H$ [m]</th>
<th>$T$ [s]</th>
<th>$Re = \frac{u_{max,in} d_w}{v}$</th>
<th>$KC = \frac{u_{max,in} T}{d_w}$</th>
<th>$C_d$</th>
<th>$\bar{u}_{rms,\infty}$ [m s$^{-1}$]</th>
<th>$\langle u \rangle_{can}$ [m s$^{-1}$]</th>
<th>$\langle u \rangle_{can,Luhar}$ [m s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>0.14</td>
<td>2</td>
<td>1043</td>
<td>51</td>
<td>2.00</td>
<td>0.14</td>
<td>0.003</td>
<td>0.019</td>
</tr>
<tr>
<td>R2</td>
<td>0.10</td>
<td>3</td>
<td>1009</td>
<td>74</td>
<td>1.84</td>
<td>0.13</td>
<td>-0.007</td>
<td>0.014</td>
</tr>
<tr>
<td>R3</td>
<td>0.21</td>
<td>3</td>
<td>1845</td>
<td>135</td>
<td>1.14</td>
<td>0.28</td>
<td>-0.005</td>
<td>0.025</td>
</tr>
<tr>
<td>R4</td>
<td>0.20</td>
<td>4</td>
<td>1727</td>
<td>169</td>
<td>0.95</td>
<td>0.29</td>
<td>-0.008</td>
<td>0.017</td>
</tr>
<tr>
<td>R5</td>
<td>0.09</td>
<td>5</td>
<td>1182</td>
<td>144</td>
<td>1.22</td>
<td>0.13</td>
<td>-0.014</td>
<td>0.008</td>
</tr>
<tr>
<td>R6</td>
<td>0.21</td>
<td>5</td>
<td>1887</td>
<td>230</td>
<td>0.85</td>
<td>0.26</td>
<td>-0.017</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Velocity measurements (25 Hz) were obtained above and within the canopy by vertically traversing a Nortek Vectrino Acoustic Doppler Velocimeter (ADV) at a location at the cross-shore mid-point of the canopy region (Figure 3-1). To accommodate the ADV within the canopy, a small (<5 cm diameter) area was cleared. Velocity measurements were conducted at 20 vertical positions, each for the duration of 150 wave periods. The velocity signals were decomposed by averaging the velocity signal over the total experimental duration to obtain the mean component, and subsequently ensemble averaging the velocity signal over the wave period to obtain the wave component. The turbulent component was obtained by subtracting the mean and wave components from the total velocity signal. To assess the convergence properties (uncertainties) in the flow statistics, the flow statistics were analysed over a running interval over the experiment duration [e.g. Ting and Kirby, 1994]. For cases in which the mean ($\langle u \rangle$, $\langle w \rangle$) or turbulent ($\sqrt{\langle u^2 \rangle}$, $\sqrt{\langle w^2 \rangle}$) flow statistics did not converge sufficiently (i.e., >5 % difference after 100 wave periods compared to statistics obtained after 150 wave periods) the data points were not included in the subsequent analysis. The time-series of horizontal forces exerted on a representative aluminum dowel (canopy element) was measured at 25 Hz using a one-dimensional load cell with 2 N capacity (Uxcell, Hong Kong) connected to a load...
3.3 METHODS

cell amplifier (RW-ST01A, SMOWO, China). The load cell itself was placed in a circular hole that was drilled inside the wave tank concrete floor. The force measurement procedure and instrument calibration are explained in detail in Chapter 2.

Figure 3-2: Instantaneous vegetation force (ensemble-averaged by wave phase) from direct force measurement ($F_m$) and reconstructed using velocity measurements based on the optimal force coefficients $C_D$ and $C_M$ ($F_r = F_{r,d} + F_{r,i}$), including the separate contributions of the drag ($F_{r,d}$) and inertial ($F_{r,i}$) forces, shown for case R3.

The measured time-varying depth-integrated vegetation force ($F_{x,m}$) acting on an individual canopy element was evaluated by the vertically integrated Morison equation over the height of the canopy element. Bulk (i.e., averaged over time and canopy element height) values for the drag ($C_D$) and inertia ($C_M$) coefficients were obtained by applying the least-squares method (e.g. Sumer and Fredsøe [2006]). To verify whether the use of constant coefficients are able to explain the variation in vegetation force within a wave cycle (as is assumed in the numerical modelling below), the ensemble-averaged force signal was reconstructed using the measured velocity and the derived constant drag and inertia coefficients. The reconstructed force signal shows a good agreement with the measured signal ($R^2 > 0.93$ for all cases), particularly during periods of maximum force (Figure 3-2). The estimated bulk drag coefficient ($C_D$) decreases with increasing $Re$ and $KC$ (Figure 3-3; Table 3-1), consistent with many other studies [e.g., Ozeren et al., 2014]. The optimal inertia coefficients ($C_M$), showed a relatively large scatter (mean value of
3.05, standard deviation of 2.06). This was attributed to the relatively small contribution from the inertial force to the total vegetation force (Figure 3-2), generally <10%, leading to relatively high uncertainty in reconstructing the inertial force. In fact, additional analysis showed that the least-square error value is nearly insensitive to variations in $C_M$; therefore, a constant value of $C_M = 2$ was assumed in this work.

Figure 3-3: Drag coefficients ($C_D$) derived from drag force and velocity measurement as function of (A) Reynolds number, and (B) Keulegan-Carpenter number.

3.3.2 Numerical model description

**Governing equations**

The non-hydrostatic (RANS-based) wave-flow model SWASH (version 5.01) was used, which is effectively a direct numerical implementation of the three-dimensional mass and momentum equations within a terrain following framework [Zijlema et al., 2011; Smit et al., 2013; Rijnsdorp et al., 2017]. Here, the model was used in 2DV mode, for which the governing equations (momentum and continuity) are given by:

\[
\frac{\partial u}{\partial t} + \frac{\partial uu}{\partial x} + \frac{\partial uw}{\partial z} + \frac{1}{\rho} \frac{\partial p_h}{\partial x} + \frac{1}{\rho} \frac{\partial p_{nh}}{\partial x} = \frac{\partial}{\partial x} \left( \frac{\partial}{\partial x} (u_h \frac{\partial u}{\partial x}) + \frac{\partial}{\partial z} (u_v \frac{\partial u}{\partial z}) + \frac{1}{\rho} f_{v,x} \right),
\]

(3-11)

\[
\frac{\partial w}{\partial t} + \frac{\partial uw}{\partial x} + \frac{\partial ww}{\partial z} + \frac{1}{\rho} \frac{\partial p_{nh}}{\partial z} = \frac{\partial}{\partial x} \left( u_h \frac{\partial w}{\partial x} \right) + \frac{\partial}{\partial z} \left( u_v \frac{\partial w}{\partial z} \right),
\]

(3-12)
\[ \frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0, \quad (3-13) \]

\[ \frac{\partial \zeta}{\partial t} + \frac{\partial \int u}{\partial x} = 0, \quad (3-14) \]

where \( f_{v,x} \) is the (instantaneous) vegetation force, and \( \zeta \) is the water surface elevation.

Within the canopy, the horizontal vegetation force \( (f_{v,x}) \) is computed using the Morison equation based on the known vegetation canopy properties and the local instantaneous horizontal velocity [Suzuki et al., 2019]:

\[ f_{v,x} = \frac{1}{2} \rho C_d d_v N_v |u| + \rho C_M N_v A_v \frac{\partial u}{\partial t}, \quad (3-15) \]

where \( C_M \) is the inertia coefficient \( (C_M = 1 + C_m) \), where \( C_m \) is the added mass coefficient, and \( A_v \) is the plan surface area of a single element (for cylindrical elements, \( A_v = \pi d_v^2 / 4 \)). The canopy porosity is accounted for by using a pore velocity inside the canopy, i.e., the spatially averaged velocity takes into account the space occupied by the canopy [see Suzuki et al., 2019, for details].

In SWASH, the turbulent stresses (i.e., first and second terms on the RHS of Eqs. (3-11) and (3-12)) are approximated using the eddy viscosity concept, where \( \nu_v \) and \( \nu_h \) are the vertical and horizontal eddy viscosity, respectively. The vertical eddy viscosity \( (\nu_v) \) is obtained using a turbulence closure \( (k-\epsilon) \) model extended with vegetation effects. The \( k-\epsilon \) equations (which include vegetation effects) are given by:

\[ \frac{\partial k}{\partial t} + \frac{\partial kw}{\partial z} = \frac{\partial}{\partial z} \left( \alpha_k \frac{\partial k}{\partial z} \right) + P_k + C_f P_v - \epsilon , \quad (3-16) \]

\[ \frac{\partial \epsilon}{\partial t} + \frac{\partial \epsilon w}{\partial z} = \frac{\partial}{\partial z} \left( \alpha_\epsilon \frac{\partial \epsilon}{\partial z} \right) + C_1 \frac{\epsilon}{k} \left( P_k + C_f \nu_v \right) - C_2 \epsilon^2 \frac{\epsilon^2}{k} , \quad (3-17) \]

where the vertical eddy viscosity is computed as:

\[ \nu_v = C_\mu \frac{k^2}{\epsilon} , \quad (3-18) \]

The turbulence production consists of a component due to shear \( (P_k) \) and due to vegetation \( (P_v) \):

\[ P_k = \nu_v \left( \frac{\partial u}{\partial z} \right)^2 , \quad (3-19) \]

\[ P_v = f d u = \frac{1}{2} C_d d_v N_v |u|^3 . \quad (3-20) \]

The model contains a number of universal constants \( (i.e., C_\mu = 0.09, C_{ke} = 1.44, C_{2e} = 1.92, \sigma_k = 1 \text{ and } \sigma_\epsilon = 1.3) \) which were derived by Launder and Spalding [1974]. The coefficients
related to vegetation drag \((C_f k \text{ and } C_f \varepsilon)\), can be set by the user and are discussed in the next section. To allow for horizontal turbulent mixing, the Prandtl mixing length approximation is used to estimate the horizontal eddy viscosity \(\nu_h\), where the wave height is used as approximation for the mixing length \([\text{e.g., } Zijlema \text{ et al.}, 2011]\).

In this study, the traditional cell-centred arrangement for the non-hydrostatic pressure variables combined with the central difference scheme for the vertical non-hydrostatic pressure gradient was used. This approach is preferable over the alternative Keller-Box method \([\text{e.g., } Zijlema \text{ et al.}, 2011]\) in the case of fine vertical resolutions (>10 layers) as it accounts for the advective contributions to the non-hydrostatic pressure, and it is able to capture the wave characteristics (e.g., wave dispersion and wave nonlinearity) with sufficient accuracy \([\text{e.g., Smit \text{ et al.}, 2013}\].

**Model schematization**

A horizontally uniform computational grid resolution of 0.1 m was used along the model domain (32 m) to ensure a minimum of 50 grid points per wavelength were resolved when simulating each experimental case. The water column was discretized using 40 vertical computational layers with a varying resolution of 0.06 m (near bottom) to 0.001 m (near the top of the canopy interface). To minimize interpolation inaccuracies during the post-processing of the model results when computing the contributions to the mean momentum balance, the vertical profile was discretized using a combination of layers with fixed (i.e., z-layers) and variable thicknesses (i.e., sigma-layers). A total of 36 z-layers were located between the bottom \((z = 0 \text{ m})\) and \(z = 0.5 \text{ m} (\text{i.e., } 0.2 \text{ m above the canopy})\), and the remaining part of the water column was resolved using 4 equidistant sigma-layers. Extensive grid sensitivity testing showed that this vertical resolution was required for accurate results, while a higher resolution did not improve the results substantially.

The canopy was specified within the SWASH vegetation module by replicating the canopy height \((h_v = 0.3 \text{ m})\), canopy element diameter \((d_v)\) and density \((N_v)\) that were used in the experiments. The drag force coefficients were obtained from the experimental measurements, while for the inertia coefficients we assumed default values \((C_M = 2)\) given the small relative magnitude of inertial forces that made quantifying \(C_M\) in the
experiments difficult (see Section 3.3.1). The turbulence model requires two empirical coefficients ($C_{f_{k}}$ and $C_{f_{ε}}$) related to the energy transfer from mean and oscillatory flow into turbulent energy due to vegetation drag. Here, we used the values as recommended by López and García [1997; 1998] for vegetated flows (i.e. $C_{f_{k}} = 1$ and $C_{f_{ε}} = 1.33$), which is consistent with Ma et al. [2013a] who used a (similar) non-hydrostatic wave-flow model to study turbulence and wave damping induced by submerged canopies.

**Boundary conditions and modelling procedure**

To reproduce the waves within the experiment, second-order cnoidal wave theory was used to force the model wave maker, consistent with the method used for the physical wave maker. At the bottom boundary the logarithmic wall law option was used assuming a smooth bed. The model was subsequently run for each experimental case (Table 3-1) for a simulation duration equal to 150 wave periods (equal to the measurement duration). To allow the hydrodynamics to spin up to a steady state, only the last 100 wave periods were used for analysis of both measurements and model results.

**Lagrangian particle tracking model**

In order to study the Eulerian and Stokes drift contribution to the Lagrangian transport, we used high-resolution output from SWASH in combination with an offline coupled particle tracking model (described in Appendix A) to simulate the Lagrangian particle trajectories. Over 100 particles were released across the water column with highest density around the top of the canopy for a fixed (mid-canopy) horizontal location. The time step was set at 0.01 s to obtain accurate simulation of particle trajectories. The wave-averaged (horizontal) Lagrangian velocity profile was obtained by computing the vector displacement of each particle over a wave cycle. The resulting mean velocity profile was mildly sensitive to the moment of particle release with respect to the wave phase. Hence, to provide a robust measure of the mean transport, each particle tracking simulation was repeated 50 times (with release times distributed uniformly over the wave cycle), with results from the 50 simulations subsequently averaged.
3.4 Results

3.4.1 Mean, wave and turbulent velocities

The measured and modelled velocities were decomposed into (wave-averaged) mean, wave and turbulence contributions, and normalised by $\bar{u}_{rms,\infty}$, i.e., the measured root-mean-square wave velocity at a reference elevation $z = 2h_v$ above the canopy (Table 3-1). The measured mean velocity profile $\langle u \rangle$ was generally well-captured by the model (Figure 3-4, top panels) and shows a characteristic shape with enhanced onshore flow near the top of the canopy as found in previous experimental studies [e.g., Abdolahpour et al., 2017]. Within the canopy, mean flow velocities are nearly zero (R1-R3) to slightly negative (offshore directed, R4-R6), while far above the canopy an offshore directed mean current is found in all cases. Near the top of the canopy, the mean flow velocity is relatively high in direction of wave propagation, reaching values of up to 20 to 50% of $\bar{u}_{rms,\infty}$. For reference, the measured in-canopy depth-integrated mean velocities are compared to the values predicted by Eq. (3-2) [Luhar et al., 2010], see Table 3-1. For all cases the in-canopy mean flow velocity is overestimated, while for case R2-R5 the depth-integrated mean flow is even offshore directed. This may be due to the generation of a return current (undertow) in the wave flume, which was found negligible in the experiments by Luhar et al. [2010]. Another explanation may be the fact that their model does not have any dependencies on canopy properties, such as canopy density. The current experiments consider a relatively high canopy density, which may be violating some of the assumptions in the derivation of Eq. (3-2). The vertical structure of the unsteady wave component of the horizontal velocity (represented by the root-mean-square value $\bar{u}_{rms}$) modelled with SWASH agrees well with the observations (Figure 3-4, bottom panels). The wave orbital velocities are substantially attenuated within the canopy, whereas there is a localised peak in velocity located just above the canopy characteristic for oscillatory boundary layer flow.

The spatial distribution of the cross-shore mean velocity field across the canopy is further explored using the model results for case R3 (see Figure 3-5). Both offshore and onshore of the canopy, the mean flow was directed opposite to the direction of wave propagation and is mostly uniform over the depth. At the leading edge of the canopy, a counter-clockwise eddy forms (centred 0.2 m offshore the canopy) that causes an upward
flow at the leading edge. At about 0.5 m upstream of the canopy, the mean flow changes direction and increases in strength, while far above the canopy the flow is still directed against the direction of wave propagation. Within 1 m downstream of the canopy leading edge, the relatively strong mean flow on top of the canopy is formed which persists until the trailing edge of the canopy. At this trailing edge, a clockwise rotating eddy forms with opposite direction and with a centre slightly below the top of the canopy.

Figure 3-4: Dimensionless wave-averaged (top) and root-mean-square velocity (bottom) for cases R1 – R6 obtained from measurements (markers) and model (line).
3.4.2 Lagrangian transport and the effect of Stokes drift

Based on the particle motions computed by the particle tracking routine, the mean Lagrangian velocity profile \( \langle u \rangle^L \) follows a similar pattern to the fixed-reference (Eulerian) mean velocity profile \( \langle u \rangle^E \) (Figure 3-6). This indicates the Langrangian transport is dominated by the Eulerian contribution, whereas the Stokes drift effect \( \langle u \rangle^S \) (obtained by subtracting the Eulerian from the Lagrangian mean velocity) is relatively small. The Stokes drift velocity generally shows a slightly increasing magnitude from bottom to the water surface, except for the area near the top of the canopy. Just below the top of the canopy a peak in the Stokes drift is found, which is consistent throughout all six cases. For reference, the maximum mean flow velocity as predicted by Abdolahpour et al. [2017] is plotted as well (Figure 3-6). Their model is able to accurately predict the maximum mean velocity for case R1-R3 and R5, while it substantially overestimates the flow for case R4 and R6. For both of these cases, the return current is relatively strong within the canopy compared to the other cases (where the return flow is relatively strong above the canopy), and it appears that this current may be responsible for diminishing the streaming just above the canopy.
3.4 Results

Since the total (Lagrangian) mass flux is dominated by the Eulerian contribution (which is the direct output from both measurements and the wave model), the subsequent analysis focuses on investigating the Eulerian mean flow dynamics in further detail.

![Simulated Eulerian, Lagrangian, and Stokes drift mean velocity profiles for all cases R1-R6, as well as the values for the peak mean velocity as predicted by Abdolahpour et al. (2017, triangles).](image)

3.4.3 Contributions to the wave-mean horizontal momentum balance

To investigate the mechanisms responsible for the wave-induced mean (Eulerian) velocity profile, we evaluated all terms in the momentum balance per Eq. (3-9). Since our experimental measurements do not contain measurements at different horizontal locations across the canopy, and hence quantify terms that depend on horizontal gradients, we use the validated model results to interrogate the spatial distribution of the individual momentum terms. The spatially varying wave-averaged
normal stress $\sigma_{xx}$ is computed using Eq. (3-7). In the following, case R3 is used to highlight results representative for all cases. Offshore of the canopy, the normal stress shows relatively little variation over depth, while at the canopy there is considerable variations over the depth (Figure 3-7A). Within the canopy, the mean normal stress is small compared to the region above the canopy. In all cases, the mean normal stress onshore of the canopy is substantially lower than that offshore, which can be attributed to a reduction in wave orbital velocities due to wave attenuation across the canopy. The magnitude of the wave-averaged shear stresses $\tau_{xz}$ (Eq. (3-8)) is an order in magnitude smaller than the mean normal stress (Figure 3-7B), but shows a somewhat similar spatial pattern with largest values above the canopy and near zero stress inside the canopy. The shear stress appears to be relatively uniform between the top of the canopy and the water surface, except near the leading edge of the canopy.

To assess the relative contribution from the wave-averaged force terms (which depend on the gradients of the stress terms), all terms in Eq. (3-4) are computed and plotted over depth at a mid-canopy location (Figure 3-8). Note that spatial gradients in the normal and shear stresses create forces that drive the flow (see Eq. (3-9)), and these gradients may not share the same patterns as the stresses [e.g., van der Werf et al., 2017]. For all cases, the shear stress gradient $\partial \tau_{xz} / \partial z$ is dominant over the normal stress gradient $\partial \sigma_{xx} / \partial x$, and is comprised of both wave and turbulent Reynolds stress gradients ($-\partial \langle \tilde{u}\tilde{w} \rangle / \partial z$ and $-\partial \langle u'w' \rangle / \partial z$, respectively). The two dominant force contributions (i.e. the Reynolds stress gradients) are balanced by the wave-averaged drag forces within the canopy while balancing each other above the canopy (Figure 3-8). While the residual mean momentum in this analysis is considerably smaller than each of the dominant momentum terms, it is not exactly zero, which is likely due to a combination of numerical inaccuracies and vertical interpolation in the post-processing.
3.4 RESULTS

Figure 3-7: Modelled dimensionless wave-averaged (A) normal stress $\sigma_{xx}$ and (B) shear stress $\tau_{xz}$ around the canopy (dashed line) as function of $x$ (where the leading edge of the canopy is at $x = 0$ m) and $z$ (focused on the lower portion of the water column, i.e. below the wave troughs) for case R3.
After dividing the water column into an area within the canopy and above the canopy, the momentum budgets are integrated over the depth of each region and normalized with the total mean drag force providing a clear summary of the governing forces in the wave-averaged momentum balance for all six cases (Figure 3-9). Although there is some variation among the cases, generally it is found that the drag within the canopy is almost completely balanced by the shear stress gradient (consisting of a wave and a turbulent Reynolds stress gradient). Above the canopy the wave Reynolds stress gradient is equal and opposite to the turbulent Reynolds stress gradient. Other momentum terms that play a role in some of the cases are the normal stress gradient (case R2 and R3), and both the hydrostatic (R1 and R3) and non-hydrostatic pressure gradients (R1). No clear pattern regarding these terms was found though, and they change sign depending on the case (Figure 3-9). The hydrostatic pressure term (substantial in case R1 and R3) is related to a gradient in the mean water level along the length of the canopy (i.e. any gradients in wave setup).
Figure 3-9: Dimensionless wave-averaged mid-canopy momentum budget terms (following Eq. (3-1), and normalising with the wave-averaged depth-integrated canopy drag force) integrated over different regions of the water column (A) above canopy (z > h_c) and (B) inside canopy (z < h_c).

3.5 Discussion

The results provided insight into the dominant stress distributions and resulting forces that are responsible for determining the mean wave-driven flows generated through interactions with the canopy. The analysis revealed that the force balances within the canopy were dominated by three terms: the wave and turbulent Reynolds stress gradients and the mean canopy drag forces, equivalent to:

$$\frac{\partial \langle \bar{u}\bar{w} \rangle}{\partial z} + \frac{\partial \langle u'w' \rangle}{\partial z} - \frac{1}{\rho} \langle f_{v,x} \rangle = 0.$$  (3-21)

This balance is analogous to the balance found for unidirectional flow [e.g., Ghisalberti, 2010], but with the inclusion of a wave Reynolds stress gradient term. In the following sections the physical significance of each force term will be discussed in more detail.
Although the wave Reynolds stress gradient was found to be the dominant driving force, the turbulent Reynolds stress gradient was often still important and hence included.

3.5.1 The wave Reynolds stress: relationship to vertical wave motions and vorticity at the canopy interface

The wave Reynolds stress is the predominant driver of the mean flow in a submerged canopy. Luhar et al. [2010] derived their expression for depth-integrated in-canopy mean flow by assuming that the turbulent stress is negligible and that linear wave theory is valid. By combining expressions for $\langle \tilde{u} \tilde{w} \rangle$ from energy and force balances (i.e., assuming that the wave Reynolds stress gradient balances drag), their method does not require explicit computation of the wave Reynolds stress gradient to determine the wave-averaged velocity. This method only provides a prediction for the depth-integrated mean velocity (and wave Reynolds stress), and does not predict the vertical profile, and hence the maximum observed near the top of the canopy. In order to be able to predict the vertical variation in wave-averaged canopy flow, i.e. $\partial \langle \tilde{u} \rangle / \partial z$, the vertical distribution of the mean wave Reynolds stress ($\partial \langle \tilde{u} \tilde{w} \rangle / \partial z$) is needed.

The appearance of the wave Reynolds stress gradient as dominant term is directly related to the vorticity generated when wave orbital motions become rotational once they interact with the discontinuity in drag at the canopy interface. Rivero and Arcilla [1995] derived a general analytical expression for the vertical distribution of $\langle \tilde{u} \tilde{w} \rangle$ in relation to the (wave) normal stresses ($\langle \tilde{u}^2 \rangle$ and $\langle \tilde{w}^2 \rangle$) and the vorticity of the oscillatory flow ($\tilde{\omega}$):

$$\frac{\partial \langle \tilde{u} \tilde{w} \rangle}{\partial z} = \langle \tilde{w} \tilde{\omega} \rangle - \frac{1}{2} \frac{\partial (\langle \tilde{u}^2 \rangle - \langle \tilde{w}^2 \rangle)}{\partial x},$$  \hspace{1cm} (3-22)

where the oscillatory vorticity is given by:

$$\tilde{\omega} = \frac{\partial \tilde{u}}{\partial z} - \frac{\partial \tilde{w}}{\partial x}.$$  \hspace{1cm} (3-23)
Figure 3-10: Relationship between the (A) wave Reynolds stress and vorticity around the canopy (dashed line) as function of $x$ and $z$ for case R3, with (B, C) the two components on the RHS of Eq. (19) and (D, E) the two components on the RHS of Eq. (3-24).
Several studies have used the relationship in Eq. (3-22) to predict mean velocity profiles (e.g. due to undertow [e.g., Garcez Faria et al., 2000; Guannel and Özkan-Haller, 2014]). However, expressions are typically derived by assuming that linear wave theory is valid and that waves are irrotational, hence \( \tilde{\omega} \approx 0 \), which allows for the vorticity term (first term on RHS of Eq. (3-22)) to be neglected. The remaining term (i.e., the second term on the RHS of Eq. (3-22)) can then readily be obtained from any wave theory (e.g., linear wave theory).

Since by definition the wave-averaged values \( \langle \tilde{u} \rangle \) and \( \langle \tilde{w} \rangle \) equal zero, the wave-averaged value of the oscillatory vorticity \( \langle \tilde{\omega} \rangle \) equals zero as well. However, as seen in Eq. (3-22), it is the quantity \( \langle \tilde{w} \tilde{\omega} \rangle \) that is directly related to the vertical distribution of the wave Reynolds stress [Rivero and Arcilla, 1995]. The vorticity term determines the wave Reynolds stress gradient near the top of the canopy, while the contribution from the wave normal stress (second term on RHS of Eq. (3-22)) is negligible (Figure 3-10A-C, representative for all cases). So in order to further study the contributions to the vorticity effect in case of a submerged canopy, Eq. (3-22) can be rewritten as:

\[
\frac{\partial \langle \tilde{u} \tilde{w} \rangle}{\partial z} \approx \langle \tilde{w} \tilde{\omega} \rangle = \langle \tilde{w} \frac{\partial \tilde{u}}{\partial z} - \tilde{W} \frac{\partial \tilde{u}}{\partial x} \rangle = \langle \tilde{w} \frac{\partial \tilde{u}}{\partial z} \rangle - \langle \tilde{W} \frac{\partial \tilde{u}}{\partial x} \rangle.
\] (3-24)

As may be expected for canopy flows with strong vertical gradients in the horizontal orbital velocity (Figure 3-4), the first term on the RHS of Eq. (3-24) dominates the vorticity effect on the wave shear stress (Figure 3-10D,E). Hence, this shows that the vertical gradient in wave stress can be approximated by:

\[
\frac{\partial \langle \tilde{u} \tilde{w} \rangle}{\partial z} \approx \langle \tilde{w} \tilde{\omega} \rangle \approx \langle \tilde{w} \frac{\partial \tilde{u}}{\partial z} \rangle.
\] (3-25)

where the horizontal and vertical orbital velocity components may be obtained from 1DV models [e.g., Zeller et al., 2015; Jacobsen, 2016], which can therefore provide a means to predict wave-driven mean flow profiles within coupled (phase-averaged) wave ocean circulation models (see section 3.5.4).

3.5.2 Turbulent Reynolds stress

For unidirectional flows, the vertical gradient in turbulent Reynolds stress is generated by the shear at the top of the canopy and is known to drive the in-canopy flow together with the horizontal pressure gradient [Nepf and Vivoni, 2000]. In this present
study of wave-driven flows, we found that the turbulent Reynolds stress was consistently smaller than the wave Reynolds stress, but is still an important force that contributes to the wave-averaged canopy flow structure. However, we also acknowledge that these results may depend to some degree on the $k$-$\varepsilon$ turbulence closure model in SWASH that relies on two empirical vegetation coefficients. Prior studies have generally used two different sets of coefficients to account for vegetation effects in $k$-$\varepsilon$ models [see discussion by Defina and Bixio, 2005]. Some authors use the values recommended by Lopez and Garcia [1997, 1998] where $C_{fr} = 1$ and $C_{fc} = 1.33$ (as in this study), others apply the values as proposed by Shimizu and Tsujimoto [1994] ($C_{fr} = 0.07$ and $C_{fc} = 0.16$). To study the sensitivity of the model results to these coefficients, simulations were repeated for two additional cases: (i) with the alternative coefficients suggested by Shimizu and Tsujimoto [1994], and (ii) without the turbulence model. The resulting mean and RMS velocity in case of the alternative set of coefficients are nearly identical to the results obtained when not using a turbulence model at all (see example for case R3 in Figure 3-11). The above-canopy peak in the mean velocity using the original turbulence settings is smaller and overall the turbulent Reynolds stress appears to diminish the peak velocity (Figure 3-11A). The peak in RMS velocity just above the canopy is also smaller compared to the peak obtained for the alternative turbulence settings or no turbulence model at all (Figure 3-11B). In all cases, the mean momentum balance is dominated by the wave Reynolds stress gradient (Figure 3-11C) balanced by the canopy drag forces (Figure 3-11E), while the turbulent Reynolds stress gradient is relatively small (Figure 3-11D). With the original settings a smoother transition of both wave and turbulent Reynolds stresses from the location with the largest shear (top of the canopy) to the regions inside and above the canopy is obtained, resulting in smoother velocity profiles. Although these results do not affect the overall conclusions of the present work, further research on the turbulent Reynolds stress in wave-driven canopy flows would be helpful in order to reduce uncertainty in estimating its relative contribution on canopy flow dynamics. Recent studies on wave-canopy interaction using more detailed wave models that are less reliant on turbulence parameterizations [e.g., Chakrabarti et al., 2016; Etminan et al., 2019] have the potential to partly fill this gap, particularly in combination with ever-increasing computational capabilities.
3.5.3 Wave-averaged canopy drag force

In wave-only conditions, the wave-averaged drag force in a submerged canopy is zero for linear (sinusoidal) waves and is consequently often ignored in phase-averaged wave modelling studies. However, in practice a nonzero wave-averaged drag force appears when mean flows are present or if the waves are nonlinear [Dean and Bender, 2006]. Moreover, an additional, potentially considerable wave-current interaction term emerges from the full decomposition of the mean drag force and subsequent wave-averaging (accounting for the absolute velocity functionality in the total drag formulation):

\[
\langle f_{d,x} \rangle = \beta \langle u \mid u \rangle, \\
= \beta \langle (u) + \bar{u} \rangle \langle (u) + \bar{u} \rangle, \\
= \beta \left( \langle (u) \rangle \langle (u) \rangle + \langle \bar{u} \rangle \langle \bar{u} \rangle + 2 \langle (u) \bar{u} \rangle \right), \\
\]

where \( \beta = \frac{1}{2} \rho C_D d_N v \). In previous studies on drag due to combined wave-current flows
interacting with canopies, studies have typically assumed that the interaction term (i.e., the third term on the RHS of Eq. (3-26)) is negligible and the total drag can be readily decomposed into mean and oscillatory drag components [e.g., Zhou and Graham, 2000; van Rooijen et al., 2016]. In the present work, it is found that when not accounting for the interaction components, the total simulated mean drag force may be overestimated in the lower part of the canopy and underestimated near the top of the canopy for some of the cases investigated (Figure 3-12A, B). The relative contribution from each component on the total (depth-integrated) drag \( \frac{F_{d \text{rel}}}{F_{d \text{component}} / F_{d \langle u \rangle}} \) varies among the different cases. For instance, for case R1, R2 and R3 the mean drag is dominated by the wave and the interaction terms while the component associated with mean flow is negligible (as highlighted in Figure 3-12C for R3). However, for the remaining cases, both the (depth-integrated) mean and interaction terms are negligible contributions to the total depth-integrated canopy drag compared to the wave-related term (see example for R4 in Figure 3-12D). These results indicate that the interaction terms may not always be negligible, or may even be dominant, and cannot be ignored when studying wave-averaged canopy flow dynamics.

3.5.4 Implications for coupled phase-averaged wave ocean circulation models

Although phase-resolving wave-flow models are increasingly being used on coastal scales, including those with vertical resolution, they are still computationally too expensive for many practical broad-scale coastal applications. Phase-averaged wave models coupled to ocean circulation models are therefore still widely used to predict coastal flows, and such models are also the foundation for most coastal sediment transport models. In this study, we identified three force terms that govern the vertical distribution of the momentum balances that determines the wave-driven mean flow profile. While the development of analytical formulations for embedding wave-driven canopy flow interactions within coupled wave-circulation models is beyond the scope of the present study, the results provide insight into how this hydrodynamics can be incorporated in the future. This would allow for a better description of the mean transport processes within a range of coastal ecosystems that form submerged canopies, which in turn would help to
provide more accurate prediction of processes as sediment transport and nutrient exchange.

Figure 3-12: Modelled (A, B) total mean drag force (black line) and contributions as function of depth, and (C, D) relative depth-integrated mean drag force contributions ($F_{d,rel}^{(u|u|)} = F_{d,rel}^{component} / F_{d,rel}^{(u|u|)}$) for case (A, C) R3 and (B, D) R4.

3.6 Conclusions
In this study, the wave-averaged flow dynamics for a submerged coastal canopy were investigated using a combination of wave flume experiments and numerical modelling with a multi-layered 2DV non-hydrostatic (phase-resolving) wave model,
3.7 Appendix A: Lagrangian particle tracking model

A MATLAB-based particle tracking model was developed to compute the Lagrangian flow within and above a submerged vegetation canopy (see Section 3.4.2). The model is based on a 4th order Runge-Kutta advection scheme, as commonly applied in ocean particle tracking models [e.g., North et al., 2006]. Particles were released instantaneously at > 100 vertical locations for one fixed horizontal position at mid-canopy, and the model was run for a full wave cycle with a time step of 0.01 s. To provide a robust measure of the mean transport the simulations were repeated 50 times resulting in an ensemble of simulations differing \( T/50 \) in particle release time. The resulting particle vector displacements and Lagrangian velocities were then averaged over all ensemble simulations to obtain a representative Lagrangian mean velocity profile. Some additional details regarding the interpolation scheme and advection sub-model are provided in the following sections.

The instantaneous horizontal and vertical (Eulerian) velocity computed by SWASH is used to calculate the particle trajectory after release at a certain \((x_p, z_p)\)-position within the model domain. The velocities are interpolated to the initial particle...
locations using a cubic spline method. Since the particle tracking time step (0.01 s) is smaller than the SWASH output time step (0.1 s), an interpolation in time is required as well. For this, the velocities are estimated at the particle location for the 5 consecutive SWASH output time points nearest to the current particle tracking time point. Next a cubic spline interpolation is applied to interpolate the velocities from the 5 (SWASH) time points to the time of particle motion.

To calculate the movement of particles due to advection, a 4th order Runge-Kutta scheme in space and time is used. It uses velocities calculated by SWASH at previous and future times to provide a robust estimate of the particle motion throughout a wave cycle. The location of a particle at a certain time step is determined by the location at the previous time step plus the weighted average of four increments:

\[
x_{p,n} = x_{p,n-1} + \frac{1}{6}(k_{u,1} + 2k_{u,2} + 2k_{u,3} + k_{u,4}),
\]

\[
z_{p,n} = z_{p,n-1} + \frac{1}{6}(k_{w,1} + 2k_{w,2} + 2k_{w,3} + k_{w,4}).
\]

The increments are based on the estimated slope between the previous and the current location, e.g.:

\[
k_{u,1} = \Delta t \cdot u_{p,n-1}(x_{p,n-1}, z_{p,n-1})
\]

\[
k_{u,2} = \Delta t \cdot u_{p,n-1} \left(x_{p,n-1} + \frac{k_{u,1}}{2}, z_{p,n-1} + \frac{k_{w,1}}{2}\right)
\]

\[
k_{u,3} = \Delta t \cdot u_{p,n-1} \left(x_{p,n-1} + \frac{k_{u,2}}{2}, z_{p,n-1} + \frac{k_{w,2}}{2}\right)
\]

\[
k_{u,4} = \Delta t \cdot u_{p,n-1} \left(x_{p,n-1} + \frac{k_{u,3}}{2}, z_{p,n-1} + \frac{k_{w,3}}{2}\right)
\]

and equally so for the vertical component \((k_{w,1} - k_{w,4})\). Here, \(n\) is defined as the current particle time point.
4.1 Introduction

It is widely recognized that coastal canopies formed by aquatic vegetation (e.g., seagrass, mangroves, kelp) play an important role in a range of bio-physical processes within the coastal zone [e.g. Nepf, 2012b; Mullarney and Henderson, 2018]. For example, canopies generally increase the overall flow resistance via drag forces, reduce local flow velocities [e.g., Luhar et al., 2008], and as a consequence, enhance sediment / particle trapping [e.g. Hendriks et al., 2008]. Canopies can also affect the mean water level through reduction of the wind-induced water level surge [e.g. Sheng et al., 2012] and modify the wave-induced water level setup [Dean and Bender, 2006]. Moreover, the presence of aquatic vegetation in the nearshore generally leads to increased wave energy attenuation, which has been studied extensively over the past decade in the laboratory [e.g., Løvås and Tørum, 2001; Möller et al., 2014], and field [e.g., Bouma et al., 2007; Paul and Amos, 2011]. The ability of aquatic vegetation to reduce wave energy and subsequent wave runup [Tang et al., 2013] makes it a potentially valuable component in nature-based coastal protection schemes [Narayan et al., 2016; Morris et al., 2018].

The rate of wave energy dissipation due to vegetation is proportional to the work performed by the waves on the plants, which is a function of the total drag exerted by the
waves on the canopy [e.g., Dalrymple et al., 1984]. Although a number of studies have investigated wave interaction with more complex highly three-dimensional (e.g. coral) canopies [e.g., Osorio-Cano et al., 2016] and flexible vegetation [e.g., Luhar and Nepf, 2016], the underlying theory that is commonly used is eventually based on drag associated with an isolated rigid cylinder [Morison et al., 1950; Keulegan and Carpenter, 1958]. For aquatic vegetation, this representation of the canopies as arrays of cylinders is often justifiable (e.g., for salt marsh vegetation, reeds, and mangrove pneumatophores), while it may still produce satisfying results when calibrated for more complex (e.g., flexible) vegetation [e.g., Løvås and Tørum, 2001].

For an idealized case with an array of uniform rigid cylinders, the instantaneous vertically integrated canopy vegetation force ($F_v$) is given as the sum of the drag and inertial forces:

$$F_v(t) = \int_{z=0}^{h_v} \left( \frac{1}{2} \rho C_{d,rep} d_v N_v u_{rep} |u_{rep}| + C_M \frac{nd_v^2}{4} N_v \frac{\partial u_{rep}}{\partial t} \right) dz$$  \hspace{1cm} (4-1)

[Dalrymple et al., 1984], where $t$ is time, $z$ is the vertical coordinate ($z = 0$ m at the bottom), $h_v$ is the vegetation canopy height, $C_{d,rep}$ is a representative drag coefficient, $d_v$ is the canopy element diameter, $N_v$ is the number of elements per unit area, $u_{rep}$ is a representative velocity scale (discussed further below), and $C_M$ is the inertial force coefficient (i.e., $C_M = 1+C_m$, where $C_m$ is the added mass coefficient). Note that work done is equal to the product of (vegetation) force and velocity ($F_v u$), hence the inertial force contribution becomes zero after phase-averaging for sinusoidal wave motions. This approach simplifies the complex morphology of canopies typically found in nature by representing plants as rigid cylinders with a uniform height, diameter and density, and subsequently several theoretical models have been developed in the past that can be used to provide an estimate of the effect of vegetation on the wave height [Mendez and Losada, 2004], other wave properties [Jacobsen, 2016], and subsequently wave runup and coastal erosion [Guannel et al., 2015].

Although the canopy geometry parameters (i.e., $h_v$, $d_v$, and $N_v$) in Eq. (4-1) can sometimes be estimated with reasonable confidence for aquatic vegetation (particularly for spatially relatively uniform vegetation), the estimation of a (representative) drag coefficient ($C_{d,rep}$) and establishing a corresponding representative velocity ($u_{rep}$) remains a challenge, as illustrated by the wealth of empirical formulations have been derived for
the drag coefficient [e.g., Ozeren et al., 2014]. In addition, it is often unclear for what range in natural conditions specific formulations are valid, and how specific processes are incorporated within the parameterization (e.g., vegetation flexibility, spatial variability in velocity, canopy density). Most formulations have been derived in the laboratory where linear wave theory is used to estimate $u_{rep}$ in order to derive a drag coefficient that fits the observed wave heights [e.g., Ozeren et al., 2014; Koftis et al., 2013; Anderson and Smith, 2014]. A more sophisticated approach involves the synchronized measurement of the vegetation force exerted on a single element and the horizontal velocity [e.g., Infantes, et al., 2011]. However, this method has so far predominantly been applied to (near-) emergent vegetation canopies only [Hu et al., 2014; Maza et al., 2017; Yao et al., 2018]. Although, this latter (direct) measurement technique provides a more accurate estimation of the drag coefficient, the choice of representative velocity scale in Eq. (4-1) in order to compute $C_d$ as function of the measured vegetation force and velocity is not trivial. Etminan et al. [2017] showed through LES modelling that the horizontal velocity typically shows a strong spatial variation within the canopy. They found that the so-called constricted cross-section velocity is the velocity scale that best describes drag, which was experimentally verified in this thesis (Chapter 2). Although these results were derived for unidirectional flow, it is expected they hold for oscillatory flow [Etminan et al., 2019] as it shows similar horizontal variability of the in-canopy velocity [e.g., Chakrabarti et al., 2016].

Many numerical wave models used in coastal applications now include formulations to account for vegetation-induced wave dissipation, usually based on the rigid cylinder framework discussed above. Examples include phase-averaged models as SWAN [Suzuki et al., 2012], XBeach-Surfbeat [van Rooijen et al., 2016; Phan et al., 2015], and CSHORE [Zhu et al., 2018], and phase-resolving models including Boussinesq models [e.g., Augustin et al., 2009; Karambas et al., 2015] and non-hydrostatic (NH) models as NHWAVE [Ma et al., 2013a], XBeach-NH [van Rooijen et al., 2016], and SWASH [Suzuki et al., 2019]. On coastal spatial scales, these models are generally used in depth-integrated mode assuming the wave orbital motions above a submerged canopy are equal to the velocities interacting with the canopy. However, this is often not the case [e.g., Lowe et al., 2005] and the difference between the wave-driven flow inside and above the canopy may in turn influence the canopy forces and dissipation,
particularly for relatively dense canopies. In addition, phase-averaged wave models are still mostly applied in coastal science and engineering while they do not account for nonlinear wave effects [e.g., van Rooijen et al., 2016] and typically also not for frequency-dependent flow attenuation [e.g., Lowe et al., 2007; Jacobsen et al., 2019]. To account for these unresolved processes, authors therefore often use the drag coefficient as a calibration parameter when wave observations are available [e.g., Vuik et al., 2016] or use empirical formulations obtained from literature [e.g., Garzon et al., 2019]. However, this practice greatly hinders the predictive capacity of these models when applied in nearshore areas with considerable aquatic vegetation.

In order to improve model predictions, there is a need to develop more generic canopy drag model descriptions that can be applied across the range of natural canopies. With the ever increasing computational capabilities, phase-resolving (e.g., non-hydrostatic) wave models are now increasingly being used, although for computational reasons usually not in full three-dimensional mode [e.g., Rijnsdorp et al., 2017]. In this paper, we extend the vegetation module within the non-hydrostatic mode of XBeach [van Rooijen et al., 2016] with a canopy flow subgrid model that accounts for the vertical and horizontal variation of the wave-induced velocity observed in submerged canopies. The model provides a more accurate and computationally efficient description of canopy drag and the resulting wave evolution, and is verified using a unique combination of observations of wave heights, velocities and vegetation forces obtained in the lab.

4.2 Methods

4.2.1 Physical experiments

Experiments were performed in a 35-m-long, 1.2-m-wide and 1.2-m-deep wave flume, which was equipped with a piston-type wave maker positioned at the upstream end of the flume and a 1:10 slope at the downstream end (Figure 4-1). To minimize wave reflection, the slope was covered by dense polyurethane filter foam sheets, porous rubber mats and finally flat hollow concrete elements acting as a passive wave energy absorber [see Adolahpour et al., 2017 for details]. A rigid submerged canopy was constructed using 6.4-mm-diameter and 30-cm-high dowels with at a density of ~3100 units per m², representing a relatively high-density canopy ($\lambda_p = 0.1$, where $\lambda_p$ is the canopy element
4.2 METHODS

plan area per unit bed area, i.e., \( \lambda_p = \frac{\pi d^2}{4} N_p \). The length of the canopy was \( L_c = 2.5 \) m, such that \( L_c >> A_0 \) (where \( A_0 = U_0 \omega \) is the wave orbital excursion length above the canopy, \( U_0 \) is the maximum free-stream horizontal wave orbital velocity and \( \omega \) is the wave radian frequency). In addition, \( L_c >> L_d \), where \( L_d \) is the canopy drag length scale given by \( L_d \sim 2 h_v (1 - \lambda_p) \lambda_f^{-1} \), where \( h_v \) is the vegetation height and \( \lambda_f \) is the canopy element frontal area per unit bed area [Lowe et al., 2005].

![Schematic view of experimental setup](image)

Figure 4-1: Schematic view of experimental setup (not to scale) with location of Nortek Vectrino Acoustic Doppler Velocimeter (ADV), load cell (LC), and wave gauges (triangles). The wave gauge locations were at -12 m, -5 m, -3.5 m, -2 m, -1 m, 0 m, 0.1 m, 0.4 m, 0.8 m, 1.4 m, 2.5 m, 3.5 m, 4.5 m, 5.5 m, 6.5 m, 7.5 m, 8.5 m, and 9.5 m with respect to the leading edge of the canopy. The ADV and load cell were located mid-canopy, approximately 1.5 m from the canopy leading edge.

The experimental program included six regular wave conditions with varying wave height and wave period (Table 4-1) to cover a broad range of Keulegan-Carpenter numbers \((KC = U_0 T d_c^{-1} \), where \( T \) is the wave period). The conditions cover a range of nonlinear shallow to intermediate water waves that are representative for areas with aquatic vegetation, and can be characterized using cnoidal wave theory [Le Méhauté, 1976]. The wave maker was forced using a prescribed time series of the horizontal displacement of the wave paddle which was generated for each wave condition (see Chapter 3).

High-frequency measurements of the velocity profile were obtained at the cross-shore mid-point of the canopy using a Nortek Vectrino ADV, and the drag force on a
presentative aluminium dowel was measured using a load cell. These measurements, discussed in detail in Chapter 3, were combined to derive phase-averaged depth-integrated drag coefficients (Table 4-1). Finally, the instantaneous water level was measured at 25 Hz at 19 locations along the wave flume using a capacitive wave gauge (RBR-WG50).

Table 4-1: Experimental conditions for all cases: wave height ($H$), wave period ($T$), Reynolds number ($Re$, where $v$ is the kinematic viscosity), Keulegan-Carpenter number ($KC$), and drag coefficient ($C_d$) derived from combined force sensor and velocity measurements (see Chapter 3 for details).

<table>
<thead>
<tr>
<th>Run ID</th>
<th>$H$ [m]</th>
<th>$T$ [s]</th>
<th>$Re = U_0 d_p v^{-1}$</th>
<th>$KC = U_0 T d_p^{-1}$</th>
<th>$C_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>0.14</td>
<td>2</td>
<td>1043</td>
<td>51</td>
<td>2.00</td>
</tr>
<tr>
<td>R2</td>
<td>0.10</td>
<td>3</td>
<td>1009</td>
<td>74</td>
<td>1.84</td>
</tr>
<tr>
<td>R3</td>
<td>0.21</td>
<td>3</td>
<td>1845</td>
<td>135</td>
<td>1.14</td>
</tr>
<tr>
<td>R4</td>
<td>0.20</td>
<td>4</td>
<td>1727</td>
<td>169</td>
<td>0.95</td>
</tr>
<tr>
<td>R5</td>
<td>0.09</td>
<td>5</td>
<td>1182</td>
<td>144</td>
<td>1.22</td>
</tr>
<tr>
<td>R6</td>
<td>0.21</td>
<td>5</td>
<td>1887</td>
<td>230</td>
<td>0.85</td>
</tr>
</tbody>
</table>

4.2.2 Numerical model

**Governing equations**

XBeach was originally developed as a coastal storm impact model that resolves the sea-swell waves on the wave group scale using a wave action balance that is coupled to the nonlinear shallow water equations to solve for infragravity waves and mean currents [Roelvink et al., 2009, 2018]. Although initially developed for sandy beach and dune systems, the application range has now broadened widely including the application to study hydrodynamic around coastal canopies, e.g. coral reefs [e.g., Quataert et al., 2015] and vegetation [e.g., van Rooijen et al., 2016]. Moreover, a non-hydrostatic wave mode was developed that is able to fully resolve the surface (sea-swell) waves [Smit et al., 2010], which is essentially a depth-averaged version of the SWASH wave model.
4.2 METHODS

[Zijlema et al., 2011]. In this mode, the depth-averaged nonlinear shallow water equations are extended with a non-hydrostatic pressure term following Stelling and Zijlema [2003]:

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial hu}{\partial x} = 0, \tag{4-2}
\]

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + \nu h \frac{\partial^2 u}{\partial x^2} = \frac{\partial (\rho \zeta + \bar{q})}{\partial x} - c_{f,b} \frac{u|u|}{h} + \frac{F_v}{h}, \tag{4-3}
\]

[van Rooijen et al., 2016], where \( t \) and \( x \) are the temporal and horizontal coordinates, \( \zeta \) is the water surface elevation, \( h \) is the local water depth, \( u \) is the depth-averaged horizontal velocity, \( v_h \) is the horizontal eddy viscosity, \( g \) is the gravitational acceleration, \( \bar{q} \) is the depth-averaged dynamic pressure, \( c_{f,b} \) is the bed friction coefficient, \( \rho \) is the density of water, and \( F_v \) is the depth-integrated canopy force, given by the sum of drag and inertia:

\[
F_v = \frac{1}{2} C_d h_v d_v N_v \bar{u} |\bar{u}| + C_M h_v \lambda_p \frac{\partial \bar{u}}{\partial t}, \tag{4-4}
\]

where the overhat is used to emphasize the use of a representative (in-canopy) value for drag coefficient and velocity, respectively (see next section).

**Canopy flow subgrid model**

To account for the vertical variation in wave-driven flow in submerged canopies, a two-layer subgrid canopy flow model is implemented to calculate the depth-integrated in-canopy velocity. The in-canopy momentum equation is given by:

\[
\frac{\partial \bar{u}}{\partial t} = \frac{\partial u}{\partial t} + \frac{1}{2} c_{f,c} u |u| - \frac{1}{2} C_d h_v d_v N_v \bar{u} |\bar{u}| - \left( \frac{C_M \lambda_p}{1 - \lambda_p} \right) \frac{\partial \bar{u}}{\partial t} \tag{4-5}
\]

[Lowe et al., 2005], where we assumed that the velocity sufficiently far above the canopy (i.e., unaffected by the canopy roughness) can be approximated by the depth-averaged velocity \( u \) predicted by the governing momentum Eq. (4-3), and where \( c_{f,c} \) is a friction coefficient that is used to parameterize the shear stress at the top of the canopy. The in-canopy flow is driven by a combination of the instantaneous pressure gradient (first term on the RHS of Eq. (4-5)) and the shear stress on top of the canopy (second term RHS), while both drag (third term RHS) and inertia (fourth term RHS) act to reduce the in-canopy flow.

By using Eq. (4-5) the in-canopy velocity that is used to compute the canopy drag essentially represents a pore velocity \( \bar{u}_p \) (i.e. the velocity averaged spatially over the
fluid region). The constricted cross-section velocity can be directly computed from $\hat{u}_p$ based on the canopy geometry:

$$\hat{u}_c = \frac{1-\lambda_p}{1-\sqrt{\frac{\lambda_p}{\beta \pi}}} \hat{u}_p$$  \hspace{1cm} (4-6)

(see Chapter 2), where $\beta$ is the ratio between the element spacing in lateral and streamwise direction in case of (lab) canopies organized in linear or staggered structures. For random canopies (as in nature), it is assumed that the representative lateral and streamwise spacing is equal, hence $\beta = 1$.

For oscillatory flow, numerous studies have shown a dependence of the canopy drag coefficient on Reynolds number and (particularly) Keulegan-Carpenter number [e.g., Sarpkaya, 1986] resulting in a large number of empirical relationships [e.g., Ozeren et al., 2014]. However, when using the constricted cross-section velocity as the representative velocity, the drag coefficient may be approximated with (well-established) isolated cylinder theory for drag dominated cases, i.e. $KC \geq 20$ [Etminan et al., 2019]. This threshold is usually met in typical coastal settings, for example when assuming $U_0 \geq 0.05$ m/s, $T \geq 4$ s, and $d_v \leq 0.01$ m. For these cases, where inertial force effects are considered insignificant, the drag coefficient can be estimated using existing formulations for isolated cylinders in unidirectional flow [White, 1991]:

$$C_d = 1 + 10Re^{-2/3}$$  \hspace{1cm} (4-7)

As shown by Etminan et al. [2019], Eq. (4-7) may even be applied in inertia-dominated conditions, i.e., relatively low $KC$, where the mean drag coefficient of an array of cylinders is close to that of an isolated cylinder [e.g., Tong et al., 2015]. To avoid numerical instabilities, constant values are prescribed within XBeach on the lower side of the function for $Re < 100$. For typical submerged vegetation canopies, e.g. $d_v \sim O(0.01$ m), in typical coastal hydrodynamic conditions (e.g., $U_0 \sim 0.05 – 1$ m/s, $T \sim 2 – 20$ s), the range in $Re$ and $KC$ is expected to be $500 < Re < 10,000$ and $10 < KC < 2000$ respectively.
4.2 METHODS

Model setup

All experimental cases (Table 4-1) were simulated for the full experimental duration (150 wave periods) in (1D) profile mode using a spatially uniform computational grid resolution of 0.1 m. Waves were generated in the model by applying time series of the (depth-averaged) horizontal velocity and water surface elevation based on second-order cnoidal wave theory, including a mass flux compensation [following Smit et al., 2013]. A flat bottom was used with an open onshore absorbing boundary as we found the model overpredicted wave reflection from the slope by failing to represent the passive wave energy absorber in the experiments, even with additional roughness on the slope. Input parameters for the vegetation canopy were chosen based on the height ($h_v$), element diameter ($d_v$) and density ($N_v$) of the canopy elements used in the experiments, while for the representative drag coefficient and velocity scale different approaches were tested. The inertial force component ($C_M$) was set to the theoretical value of 2, as the measured inertia coefficients presented considerable uncertainty (see Chapter 3 for details).

Modelling procedure and skill quantification

The model is verified using the measured wave heights, velocities and vegetation forces. To identify how the proposed method compares to more traditional methods, the model was run with different combinations of drag coefficients and velocities (Table 4-2). For case 1, the model was run with the canopy flow model turned off, hence using the depth-integrated horizontal velocity as the representative velocity when computing the canopy drag (i.e., following the original implementation by van Rooijen et al., [2016]). In practical applications and in absence of observations, a drag coefficient needs to be estimated and is often assumed to be ~1. Here, we opt for single cylinder theory (Eq. (4-7)) to provide a reasonable estimate for $C_d$. This case is considered as current common practice in coastal applications. Case 2, 3 and 4 utilize the in-canopy orbital velocity as calculated by the canopy flow model. For case 2, the in-canopy (spatially averaged) pore velocity is used as representative velocity in combination with the drag coefficient derived from the measurements. Case 3 also applies the measured drag coefficients, but uses the constricted cross-section velocity (Eq. (4-6)) as representative velocity scale.
Finally, case 4 combines the constricted cross-section velocity with the drag coefficient obtained from single cylinder theory (Eq. (4-7)).

Table 4-2: Overview of representative drag coefficient and velocity combinations tested in this study.

<table>
<thead>
<tr>
<th>Case</th>
<th>$C_{d,rep}$</th>
<th>$\bar{u}_{rep}$</th>
<th>Canopy drag description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Eq. (4-7) ($C_{d,Re}$)</td>
<td>$u$</td>
<td>depth-averaged velocity, in combination with drag coefficient obtained from theory (current XBeach implementation)</td>
</tr>
<tr>
<td>2</td>
<td>Measured ($C_{d,Meas}$)</td>
<td>$\bar{u}_{p}$</td>
<td>in-canopy pore velocity in combination with measured drag coefficients</td>
</tr>
<tr>
<td>3</td>
<td>Measured ($C_{d,Meas}$)</td>
<td>$\bar{u}_{c}$</td>
<td>in-canopy constricted cross-section velocity in combination with measured drag coefficients</td>
</tr>
<tr>
<td>4</td>
<td>Eq. (4-7) ($C_{d,Re}$)</td>
<td>$\bar{u}_{c}$</td>
<td>in-canopy constricted cross-section velocity in combination with drag coefficient obtained from theory (proposed in this study)</td>
</tr>
</tbody>
</table>

The predictive skill of the model for each of the cases is quantified using the root-mean-square percent error [e.g., Apotsos et al., 2008]:

$$RMSPE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left( \frac{X_{c,i} - X_{m,i}}{X_{m,i}} \right)^2} \times 100\%$$

(4-8)

where $n$ is the number of observations, $X_{c,i}$ is the computed value and $X_{m,i}$ is the measured value. Although a relative model skill is preferred, the (absolute) root-mean-square error ($RMSE$) was used for the time-averaged velocities as the measured values are found to be relatively small thereby having a relatively large (unrealistic) effect on the computed $RMSPE$ scores. In addition, for comparison of the vegetation force the correlation coefficient ($R^2$) was computed as:
\[ R^2 = 1 - \frac{\sum_n (x_c - x_m)^2}{\sum_n (x_m - \bar{x}_m)^2} \]  

(4-9)

where the overbar represents averaging in time.

4.3 RESULTS

4.3.1 Wave height evolution

To highlight the influence of using the canopy flow model, the wave evolution for two runs with a relatively low (R5) and high (R3) wave height with and without canopy flow (CF) model is shown in Figure 4-2. The observed wave height offshore of the canopy shows considerable periodic variation which is likely due to wave reflection of the canopy leading edge. Across the canopy itself the wave height is reduced due to canopy-induced wave attenuation resulting in lower wave heights onshore of the canopy. With the original model implementation (case 1, see Table 4-2), the canopy-induced wave attenuation is overpredicted resulting in an underprediction of the wave height onshore of the canopy, particularly in case of relatively high waves. In practice, \( C_d \) is then often used as tuning parameter (which would have resulted here in an unphysically low average drag coefficient of 0.5), but this practice greatly diminishes the model’s predictive capabilities as it would require wave observations or an empirical relation from literature.

The model with CF (case 4, Table 4-2), however, is able to simulate the wave height evolution across the canopy accurately without any calibration. Similar results are obtained for the other runs (Figure 4-3), where the modelled wave height across the canopy agrees well with the measurements as long as the canopy flow model is used (case 2, 3 or 4, Table 4-2). In comparison with the original implementation (case 1), the RMSPE skill score reduces from 15% towards 6 to 8 % (Table 4-3). Best results are obtained when using the constricted cross-section velocity as representative velocity scale, either in combination with the measured (case 3) or theoretical (case 4) drag coefficients.
Figure 4.2: Comparison between measured and modelled wave height along wave tank and across the canopy without (dashed line) and with (solid line) canopy flow model for case R3 and R5 (using the single cylinder relationship, Eq. (4.7)).

Figure 4.3: Comparison between measured and modelled relative wave height along wave tank and across the canopy for the different \( C_d \alpha \) combinations as specified in Table 4.2. Note that for case R5 the yellow line sits below the blue line.
4.3 RESULTS

4.3.2 Wave-driven velocity

The measured wave-driven horizontal velocity inside and above the canopy shows a clear vertical variation with higher root-mean-square orbital velocities above the canopy and lower (~ 50%) velocities inside the canopy (Figure 4-4). It is evident that the original model implementation based on the depth-averaged velocity (case 1, Table 4-2) cannot account for this. All three cases that include the canopy flow subgrid model (case 2-4), however, are able to represent this well. Using a pore velocity as representative velocity scale generally leads to slightly higher above canopy velocities, although the variation among the different cases is expected to fall within the measurement uncertainty. The canopy flow subgrid model being able to provide such good approximation of the measured in-canopy velocity (i.e., \( \text{RMSPE} < 10\% \), see Table 4-3) is encouraging with the prospect of future applications around aquatic ecosystems that include processes in which an accurate description of the near-bed orbital velocity is important (e.g., sediment transport). For those cases, the depth-averaged approach would clearly lead to an overprediction of the near bed orbital velocity (Figure 4-4).

In the following the modelled mean velocity is verified. Previous research has shown that currents (e.g. tide or river flows) may substantially influence wave attenuation processes [e.g., Paul et al., 2012], although the relation with wave-induced mean currents is subject of ongoing research. Nonetheless, it is important to be able to accurately predict wave-driven mean flows for a range of applications, e.g. sediment transport [e.g., van Rijn, 2007]. The mean velocity profile across a submerged canopy presents considerable variation over depth though (see Chapter 3), which cannot be accounted for with a (quasi) two-layer approach. Hence, the measured in-canopy mean velocity is averaged over the canopy height and compared with the mean in-canopy velocity derived from the model. For visual clarity, a comparison is made between case 1 (no canopy flow model) and case 4 (with canopy flow model) only, for which the latter shows considerable improvement in the computed near bed (in-canopy) mean velocity (Figure 4-5). The model error is relatively high for all cases examined here with \( \text{RMSE} \)-values with similar order of magnitude compared to the actual velocities (Table 4-3), but it is expected that the relative error (e.g. \( \text{RMSPE} \)) decreases for sparser canopies with relatively high mean velocity magnitudes.
CHAPTER 4 QUASI-3D MODELLING OF CANOPY FLOWS AND WAVE ATTENUATION OVER SUBMERGED VEGETATION CANOPIES

Figure 4-4: Comparison between measured (markers) and modelled (lines) root-mean-square horizontal velocity over depth for run R1-R6 and the different $C_d\tilde{u}$ combinations as specified in Table 4-2. Note that for case R5 the yellow line sits below the blue line.

Figure 4-5: Comparison between measured (horizontal axis) and modelled (vertical axis) mean horizontal velocity integrated over the canopy height for run R1-R6 with $C_d\tilde{u}$ combinations following case 1 (triangles) and case 4 (squares), see Table 4-2.
Finally, to assess the spatial variation of the wave-induced flow, the computed depth-averaged and in-canopy mean and root-mean-square (RMS) velocities along the horizontal model domain are shown for run R3 in Figure 4-6. The decrease in wave energy due to canopy-induced dissipation directly results in reduced depth-averaged orbital (RMS) velocities over the length of the canopy from about 0.3 to 0.23 m/s. The in-canopy orbital velocity slightly decreases from 0.12 to 0.1 m/s. At the same time, the net depth-averaged (Eulerian) return flow magnitude decreases due to reduced Stokes drift. The results for the other runs are qualitatively similar and therefore not shown here.

Figure 4-6: (A) Mean and (B) root-mean-square depth-averaged and in-canopy velocity across submerged canopy (dotted lines) for case R3.

4.3.3 Vegetation force

To verify the model capability in computing the depth-integrated vegetation force the instantaneous measured and modelled drag forces are ensemble-averaged by wave phase. With the original implementation (case 1, Table 4-2), it is expected the vegetation force will be overpredicted due to the use of the depth-averaged velocity and the overestimation found in the modelled canopy-induced wave attenuation (Figure 4-3). This is indeed the case for run R3, R4 and R6, however, for run R1, R2 and R5 the model is able to calculate the vegetation force reasonably well (Figure 4-7). The fact that for those runs the model overpredicts the wave attenuation can thus only be attributed to the overestimation of the velocity when computing the work done ($F_vu$). For the case using
the in-canopy pore velocity (case 2), the vegetation force is underpredicted, while both cases using the constricted cross-section velocity (case 3 and 4) generally agree reasonably well with the data. Overall, the vegetation force is best captured using the constricted cross-section velocity in combination with the theoretical drag coefficient with $RMSPE$ of 23 % and $R^2$ of 0.97 (Table 4-3).

Figure 4-7: Comparison of measured (dashed line) and modelled (solid lines) vegetation force ensemble-averaged by wave phase for run R1-R6 and the different $C_d\hat{u}$ combinations as specified in Table 4-2. Note that for case R5 the yellow line sits below the blue line.
Table 4-3: Overview of model skill for all drag representations used in the model. For the mean velocity (absolute) RMSE-values are reported as the observed values were relatively small, resulting in relatively large RMSPE values. The error metrics for vegetation force were obtained by comparing the on- and offshore directed peak values.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Skill statistic</th>
<th>Model drag representation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$C_{d,Re}$ $u_{dev}$</td>
</tr>
<tr>
<td>Wave height</td>
<td>RMSPE (%)</td>
<td>15</td>
</tr>
<tr>
<td>RMS velocity</td>
<td>RMSPE (%)</td>
<td>70</td>
</tr>
<tr>
<td>Mean velocity</td>
<td>RMSE (m/s)</td>
<td>0.010</td>
</tr>
<tr>
<td>Vegetation force</td>
<td>RMSPE (%)</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.85</td>
</tr>
</tbody>
</table>

4.4 Discussion

4.4.1 The new subgrid modelling approach

Phase-resolving wave models are increasingly being used for field applications at coastal (~km) scales as computational resources are increasing rapidly [e.g., Rijnsdorp et al., 2015; Ma et al., 2013b; Roelvink et al., 2018; Chakrabarti et al., 2017]. Most studies adopt a depth-integrated (2DH) approach, since including multiple computational layers in a phase-resolving wave model is computationally expensive, even when using high performance computing systems. Usually, this is acceptable as the vertical variation in wave-driven flow dynamics is much smaller than the horizontal variation. However, as shown in this study, coastal canopies may create a strong vertical gradient in the wave-induced velocities that is not accounted for by depth-integrated models. The main motivation for opting a subgrid (quasi-3D) approach over a fully coupled two-layer approach to estimate the in-canopy velocity is to ensure computational times are manageable when using XBeach in typical coastal scale applications.

To illustrate this, we compare the results for a typical coastal scale application with results from the SWASH model [Zijlema et al., 2011]. The governing equations in
XBeach (in non-hydrostatic mode) and SWASH are identical, and include the effect of aquatic vegetation based on the same theory [Suzuki et al., 2019]. The main difference is that SWASH allows for a user-defined number of computational layers, whereas XBeach can only be run in depth-averaged mode. Models were run for a hypothetical field scale case with waves propagating over a nearshore submerged coastal canopy (Figure 4-8B). The model domain was 1.5 x 1 km, and was discretized using a spatially uniform grid size of 2 m and 5 m in cross- and alongshore direction respectively to ensure sufficient grid points (>50) per wave length. A time series of 100 regular waves was generated at the offshore boundary with wave height of 0.5 m and wave period of 12 s, resulting in a total simulation period of 1200 s. The canopy was placed in the nearshore in 5 m water depth with vegetation height of 0.5 m (hence $h/h_v = 10$), element diameter of 0.01 m and density of 1000 units/m$^2$. To allow for direct comparison between both models default values were used for the canopy coefficients: $C_d = 1$, $C_M = 2$, and $C_f = 0.01$. Although XBeach and SWASH are based on the same theoretical framework, the numerical implementation is slightly different and therefore both models were run in depth-averaged mode (here denoted as XBeach, and SWASH respectively) and with canopy flow subgrid model (XBeach-CF) or in two-layer mode (SWASH-2V). For the latter the reduced two-layer model option was used [Cui et al., 2014] to maximize computational efficiency.

In the following we compare results from XBeach with SWASH under the assumption that the latter provides a more accurate representation as it is able to resolve the three-dimensional wave dynamics. The wave field computed with SWASH-2V shows a gradual increase in wave height along the profile due to shoaling and a decrease in wave height at the vegetation patch (Figure 4-8A). With the original implementation, XBeach considerably overestimates the canopy-induced wave attenuation (Figure 4-8C) leading to substantially lower wave heights at and onshore of the canopy with a difference of up to 0.4 m (Figure 4-8D). In fact, onshore of the canopy the waves have been nearly fully dissipated in the model. As discussed before, in practice modellers may account for this by tuning the drag coefficient, but this greatly diminishes the predictive capability of the model. When the canopy flow model is used (XBeach-CF), very similar results for the wave evolution over the submerged canopy are obtained, with nearly identical spatial patterns as SWASH (Figure 4-8E), and differences in wave heights are in the order of centimetres only (Figure 4-8F). Regarding the vertical variation in wave-driven flow,
XBeach-CF provides an orbital (root-mean-square) velocity profile similar to SWASH-2V (Figure 4-9).

Figure 4-8: Comparison of computed wave height \( H_{rms} \) normalized by the offshore wave height \( H_{rms,0} \) using (A) SWASH with 2 vertical layers, (C) XBeach without canopy flow model, and (E) XBeach with canopy flow model, for a theoretical coastal application with (B) constant slope and submerged canopy. Wave height difference plots are generated by subtracting XBeach results from SWASH results for the case (D) without and (F) with canopy flow model.
Although, XBeach-CF provides a more accurate representation of wave dynamics in and above submerged canopies over the original model, computational costs remain the same, whereas SWASH-2V requires approximately three times more computational time compared to a depth-averaged model (Table 4-4). In case of fully resolving the 3D hydrodynamics (e.g., with >10 computational layers), SWASH computational times are expected to be even an order of magnitude higher [e.g., Rijnsdorp et al., 2017]. The current results show that the subgrid canopy model provides an accurate description of the in-canopy wave-driven flow dynamics at negligible computational cost. It is therefore considered an efficient and effective alternative over 3D models for wave studies in coastal ecosystems.

Figure 4-9: Comparison of the orbital (root-mean-square) velocity over depth computed using XBeach without canopy flow model, SWASH (depth-averaged), XBeach with canopy flow model (XBeach-CF), and SWASH in reduced 2 layer mode (SWASH-2V).
Table 4-4: Ratio of the computational time relative to the depth-averaged XBeach for XBeach extended with canopy flow model (XBeach-CF), SWASH in depth-averaged mode, and SWASH in reduced two-layer mode (SWASH-2V).

<table>
<thead>
<tr>
<th>Model</th>
<th>Runtime relative to XBeach (without canopy flow model)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XBeach-CF</td>
<td>1</td>
</tr>
<tr>
<td>SWASH (depth-averaged)</td>
<td>1</td>
</tr>
<tr>
<td>SWASH-2V</td>
<td>3.1</td>
</tr>
</tbody>
</table>

4.4.2 Model sensitivity to canopy coefficients

The model presented in this study includes three coefficients related to the canopy (drag \( C_d \), inertia \( C_M \) and friction \( C_f \) coefficient, respectively). For relatively uniform rigid aquatic vegetation species (e.g., salt marsh vegetation, reeds, and mangrove pneumatophores), the currently implemented drag relation based on \( Re \) (Eq. (4-7)) is expected to be sufficient for estimating \( C_d \). For other species, however, \( C_d \) may still require adjustment to account for more complex morphologies (e.g., mangrove trees) or flexibility. In this section a brief sensitivity analysis is performed on all three coefficients to study their influence on the model outcome, and to verify if using default values can be justified when additional information (e.g. local wave observations) is lacking. A set of simulations was set up based on experimental case R3 with base values \( C_d = 1 \), \( C_M = 2 \), and \( C_f = 0.01 \). All other simulations include either a slightly lower or higher coefficient, with the following variation: \( C_d = [0.5, 1.5] \), \( C_M = [1.5, 2.5] \), and \( C_f = [0.001, 0.1] \). To study the effect of these coefficients on different canopies, all (7) simulations were carried out for canopies with a range of densities \( \lambda_p = [0.01, 0.05, 0.1] \). Model results are compared through both the wave height attenuation factor

\[
\alpha_H = \frac{1}{\lambda_p} \left( \frac{H_v}{H_0} - 1 \right)
\]  

[Dalrymple et al., 1984], and the canopy flow attenuation factor

\[
\alpha_U = \frac{\bar{u}_{rms}}{u_{rms}}
\]  

[Lowe et al., 2005] respectively, where \( H_v \) is the average wave height at the back of the canopy, \( H_0 \) is the wave height at the leading edge of the canopy with length \( L_c \), and where
\( \alpha_u \) is averaged over the canopy length. The resulting attenuation factors are shown in Figure 4-10.

The effect of \( C_d \) on the wave height attenuation is directly accounted for in the computed drag force, but also indirectly through the in-canopy velocity (which is also input for the drag force). For a canopy with relatively high density (\( \lambda_p = 0.1 \)) as used in this study, the effect of the variation in \( C_d \) on the canopy flow attenuation is relatively small (Figure 4-10D). However, the wave height attenuation factor varies with nearly factor 2 between the lowest (0.5) and highest (1.5) value tested (Figure 4-10A). Although this is a considerable difference, it is smaller compared to conventional models in which the attenuation scales linearly with \( C_d \). For the sparser canopies, the differences in wave height attenuation factor become smaller (Figure 4-10B, C) although the effect on the canopy flow attenuation factor is relatively high for the sparsest case (Figure 4-10F). Both attenuation factors are relatively insensitive to the inertia and friction coefficient across the range of canopy densities tested here. Given the variation range of all coefficients used, these results shows that the model is relatively insensitive to any changes in the coefficients. Although the variation in wave height attenuation due to varying \( C_d \) is considerable, it is likely that modellers would opt for a drag coefficient closer to 1 than tested here (i.e., unless it accounts for complex vegetation morphology e.g. flexibility). Hence, the default values (i.e., \( C_d = 1 \), \( C_M = 2 \), and \( C_f = 0.01 \)) generally provide an acceptable first approximation.
4.4 Discussion

Figure 4-10: Sensitivity of simulated (A, B, C) wave attenuation and (D, E, F) canopy flow attenuation to a variation in drag coefficient ($C_d = [0.5, 1, 1.5]$), inertia coefficient ($C_M = [1.5, 2, 2.5]$) and canopy friction coefficient ($C_f = [0.001, 0.01, 0.1]$) for $\lambda_p = 10\%, 5\%$, and $1\%$.

4.4.3 Importance of accounting for canopy flow dynamics in wave attenuation predictions

The results showed how the inclusion of an in-canopy flow subgrid model increases the accuracy in wave height attenuation prediction in a phase-resolving wave model. In general, the reduced in-canopy flow velocities lead to lower drag forces and subsequently lower wave attenuation rates. However, it is unclear to what extent this effect is relevant across the range of wave conditions and canopy characteristics that may be found in nature. To investigate this, and to provide an indication when a canopy flow model is needed, a cascade of XBeach simulations were set up for a typical field scale setting, based on a 1D version of the model setup used in Section 4.4.1 (see Figure 4-8B). Each simulation is run with and without the canopy flow model, and the results are compared through the wave attenuation factor (Eq. (4-10)), which can be approximated by:
\[ \alpha_H = \frac{1}{3\pi} \frac{H}{h^2} C_d h v d v N_v \]  

(4-12)

[National Academy of Sciences, 1977]. This relation contains a clear hydrodynamic \((H/h^2)\) and a canopy \((h, d, N_v)\) component (assuming the variation in \(C_d\) is relatively small), from which the latter equals the frontal canopy area per unit bed area \((\lambda_f)\). Hence, these relations were used to obtain a broad range in wave conditions and canopies. Finally, a variation in wave period was applied with runs with relatively short (5 s), medium (10 s) and long waves (15 s). In all runs the implemented \(C_d\)-model (Eq. (4-7)) is used.

Without the canopy flow model, there is a clear increase in wave attenuation for both increasing \(H/h^2\) and increasing \(\lambda_f\) (Figure 4-11). The increase in canopy drag due to either increased wave height, decreased water depth or increased roughness results in more wave attenuation. Wave attenuation also increases for decreasing wave period. When the canopy flow model is used, the attenuation rates are an order of magnitude smaller particularly for the 10 and 15 s wave conditions (Figure 4-12, note the different colour scale). The difference in wave height attenuation factor provides an indication for which conditions a canopy flow model is required. Here, the results show that for relatively low wave heights or deep water in combination with relatively sparse canopies the difference in attenuation factor is < 0.01 (Figure 4-13). However, with increasing wave height, decreasing water depth and increasing canopy density the canopy flow model gets increasingly important.
Figure 4-11: Wave height attenuation factor across a range of wave conditions (vertical axis) and canopy characteristics (horizontal axis) for waves with (A) 5 s, (B) 10 s, and (C) 15 s wave period, computed with XBeach without canopy flow model.
Figure 4-12: Wave height attenuation factor across a range of wave conditions (vertical axis) and canopy characteristics (horizontal axis) for waves with (A) 5 s, (B) 10 s, and (C) 15 s wave period, computed with XBeach with canopy flow model.
Figure 4-13: Difference in wave height attenuation factor across a range of wave conditions (vertical axis) and canopy characteristics (horizontal axis) for waves with (A) 5 s, (B) 10 s, and (C) 15 s wave period, between XBeach without and with canopy flow model.
4.4.4 Complex canopies

This study provides a step into the improvement of wave models in incorporating complex aquatic ecosystems by including the three-dimensional variation in wave-driven flow while maintaining computational efficiency. However, it is evident that more research is required to account for the complex morphologies associated with coastal canopies, including highly 3D structured (e.g., corals) and flexible vegetation (e.g., seagrass). Around the world, researchers are now increasingly studying more complex coastal canopies such as corals [Samuel and Monismith, 2013; Osorio-Cano et al., 2016], mangroves [Husrin et al., 2012; Maza et al., 2017], and flexible vegetation [Dijkstra and Uittenbogaard, 2010; Mularney and Henderson, 2010]. Most studies, however, only consider unidirectional flow and the translation of the measurements into a model that can be incorporated in large scale wave models is not trivial. Dedicated measurements of waves, in-canopy velocities and vegetation force for complex canopies [e.g., Paul et al., 2016; Lei and Nepf, 2019] are required to derive practical expressions for canopy drag that are equivalent to the current approach based on rigid cylinders [Morison et al., 1950], and can be incorporated in coastal models such as XBeach. At this stage we have omitted the drag coefficient as tuning parameter to account for the spatial variability in wave-driven flow. Hence, for rigid canopies well-established empirical values derived for isolated cylinders can now be used, eliminating the need for calibration. However, the complexity associated with natural canopies (e.g., in case of flexible vegetation) can still be accounted for in the model by adjusting the coefficient.

4.5 Conclusions

In this study, we extend an existing phase-resolving wave model with a subgrid canopy flow model that calculates the instantaneous in-canopy velocity used to quantify the drag exerted by waves propagating over a canopy. The model is based on well-established single cylinder theory and omits the need for calibration of the drag coefficient for rigid canopies. The model is subsequently verified using a unique combination of high resolution direct measurements of the wave height evolution, velocity inside and above the canopy and the force exerted by waves on a single canopy element. It is able to
accurately compute canopy hydrodynamics across a range of Keulegan-Carpenter numbers, and relatively insensitive to changes in (empirical) model coefficients.

The model is computationally efficient and can be used at coastal scales, where the drag coefficient may still be verified to incorporate complex (e.g., flexible) canopies. With its description of the in-canopy mean and orbital velocity, it has high potential for future applications including sediment transport in nearshore ecosystems.
5.1 Summary

The overarching aim of this thesis was to develop an improved understanding of the wave- and current-induced hydrodynamics in and around aquatic vegetation canopies. This information is required to improve predictions of hydrodynamic (e.g., wave attenuation and wave run-up along coastlines fronted by aquatic vegetation), morphodynamic (e.g., sediment transport) and biophysical processes (e.g., particle and nutrient dynamics). An additional objective of this thesis was to develop a computationally efficient numerical model that incorporates relatively complex coastal (physical) processes induced by aquatic vegetation canopies and can be practical to apply at field scale.

Coastal regions are generally dominated by wave-driven (oscillatory) flows, however, unidirectional flows such as wind- or tide-driven coastal currents can often not be neglected. Moreover, the hydrodynamics around aquatic canopies subject to a unidirectional flow are still relatively poorly understood. Hence, the work described in this thesis includes a stepwise approach in complexity; from emergent canopies in current-induced (unidirectional) flow to eventually submerged canopies in wave-induced (oscillatory) flow. The study comprised both detailed laboratory observations and numerical modelling.
Whereas most studies have traditionally used bulk measurements such as the water surface elevation or wave height to (indirectly) derive the force exerted on canopy elements, a direct measurement method for the force exerted on a single canopy element was employed here. The data was used in combination with observations of water levels and flow velocities to provide a detailed understanding of the current- and wave-induced force exerted on emergent and submerged aquatic vegetated canopies and contributed to Chapter 2 (currents) and Chapter 3 and 4 (waves) respectively. Results from a high-resolution numerical wave model, SWASH, were used to further investigate the spatial variability in wave-induced flow dynamics induced by submerged canopies, and contributed to Chapter 3. An open-source numerical wave model that is widely used by coastal scientists and engineers, XBeach, was extended based on the findings from Chapter 2 and 3 to provide a more accurate description of the in-canopy flow dynamics and resulting wave attenuation over submerged aquatic canopies (Chapter 4). This final chapter synthesizes the main findings and implications from the overall study and presents recommendations for further research.

5.2 Conclusions

Considerable spatial heterogeneity in the hydrodynamics was observed within both the submerged and emergent canopies that were assessed. The “constricted cross-section velocity” (the average velocity in the constriction between two adjacent canopy elements) in combination with well-established isolated cylinder theory was found to provide a more accurate and more robust description of canopy drag than the commonly used pore velocity (Chapter 2). Contrary to the (spatially averaged) pore velocity, the constricted cross-section velocity accounts for the horizontal variability of the flow within the canopy and can be directly computed from the pore velocity for a known canopy density. For submerged canopies, the vertical variation in flow velocity is accounted for by including a relatively simple canopy flow model. Comparison of the resulting theoretical model and newly obtained and existing data showed that the model is able to robustly and accurately predict canopy drag across the field range of (unidirectional) flow conditions and canopy characteristics (Chapter 2).

Through interaction between wave-induced flow and submerged canopies, wave energy is attenuated and a characteristic mean flow vertical profile was observed in the
experimental data and numerical results. The onshore-directed peak in mean velocity was located just above the canopy (Chapter 3), which is consistent with previous studies, but the mechanisms responsible have not yet been described in detail. The analysis in this thesis showed that the mean hydrodynamic forcing is governed by canopy drag balanced by the vertical gradients in wave and turbulent Reynolds stress. The importance of both Reynolds stress terms in wave-driven canopy flows has not been shown before, and these terms are often neglected in coastal scale modelling studies.

Finally, it was found that the horizontal and vertical variability of wave-induced flows in submerged canopies can be robustly, accurately and computationally efficiently described in a depth-averaged wave model when using a subgrid canopy flow model (Chapter 4). The resulting model provides a more generic canopy drag description for wave attenuation over vegetation canopies at field scales at negligible computational cost, while reducing the large uncertainty associated with the use of the drag coefficient as tuning parameter. In addition, this development presents high potential for future model developments that consider application in areas with aquatic vegetation requiring an accurate description of the in-canopy flow velocity (e.g. sediment transport).

5.3 Implications

This thesis provides a substantial advancement in the understanding and prediction of canopy flows in wave- and current-dominated environments. In practical applications, observations are often lacking and the understanding of the physical processes in coastal regions with aquatic vegetation relies on physics-based models. This study provides a substantial reduction in the uncertainty associated with coastal model predictions.

For current-induced canopy drag, the theoretical model described in Chapter 2 can directly be applied to both emergent and submerged canopies without calibration, and provides a robust and accurate tool that is applicable across the field range of flow conditions and canopy characteristics. For wave-dominated environments, it is well known aquatic canopies enhance wave attenuation. However, models typically rely on the drag coefficient as tuning parameter. In this study, a more generic vegetation description that accounts for the spatial variation of the wave velocity is presented and implemented in a coastal wave model. The model implementation presented in Chapter 4
eliminates the need for calibration and results in improved model accuracy at negligible computational costs.

Although this study primarily focused on coastal hydrodynamic processes, it is expected that the results of this study can also be applied to coastal morphodynamic (e.g., sediment transport) and biophysical processes (e.g., particle and nutrient dynamics). The vertical variation in orbital and wave-averaged velocities in case of a submerged canopy subject to waves discussed in Chapter 3 is expected to have a considerable effect on the net transport of material in the coastal ocean. This study showed that in addition to the canopy drag force, the wave and turbulent Reynolds stress gradients are important in driving wave-induced mean currents, and should be included in future model developments around wave-induced flows in submerged aquatic canopies.

5.4 Recommendations for future research

**Targeted high-resolution measurements in complex canopies**

This thesis considers idealized (rigid) aquatic vegetation only. Natural canopy elements may add considerable complexity to the flow dynamics. For instance, non-rigidity of canopy elements may result in bending of the element with the current- of wave-induced flow thereby reducing drag. In recent years, authors have increasingly focused on more complex vegetation representations. However, with the exception of a few studies, results have generally been obtained through bulk observations (e.g., spatial gradients in water level or wave height). In order to obtain additional insight, further research should be carried out using systematic laboratory experiments with complex vegetation canopies. Analogous to the experiments described in this thesis, this should include a combination of high-resolution measurements of vegetation forces, water levels (wave heights) and velocities across the full range of hydrodynamic conditions and canopies.

**Three-dimensional flows in spatially non-uniform canopies**

The results in this thesis were obtained for idealized canopies that are assumed to be spatially uniform while the alongshore dimension was omitted. The spatial variability in current and wave induced flow in natural aquatic vegetation canopies is expected to increase, as vegetation naturally grows in patches or meadows. To date, the
effect of patchiness on wave evolution has received relatively little attention. In order to obtain improved fundamental understanding of three-dimensional flow dynamics, further research should include systematic laboratory experiments (similar to the current study) in three-dimensional wave facilities (basins), preferably combining high-resolution measurements of vegetation forces, water levels (waves) and velocities across the full range of hydrodynamic conditions and canopies.

**Other coastal (physical) processes in aquatic canopies**

To date, numerous studies have addressed how aquatic vegetation effectively attenuates wave energy thereby reducing the risk for coastal flooding. Other influences of aquatic canopies on the nearshore hydrodynamics have received relatively little attention. For instance, nonlinear wave-vegetation interactions and the effect of vegetation canopies on flow velocities (e.g., Chapter 2 and 3 in this thesis), low-frequency (infragravity) waves, wave run-up and near bed processes (e.g., bed shear stress) have received relatively little attention to date. However, these processes require a similar level of systematic understanding in order to fully comprehend the influence of marine ecosystems in reducing coastal hazards, and in the long term coastal evolution. Further research should aim at quantifying these effects across the broad range of canopy characteristics and forcing conditions.

**Future model developments for improved predictions**

With ever increasing computational power, numerical models will become increasingly more detailed, both in resolution and in the physical processes to be resolved. However, being able to resolve the fine-scale canopy flow within an entire ecosystem will remain impractical within the coming years. Instead, coastal researchers, managers and engineers will require to rely on spatially averaged modelling methods (e.g., this thesis). At present, phase-resolving wave models that are able to resolve for nonlinear wave dynamics are increasingly being used in coastal applications (Chapter 3 and 4 in this thesis). However, in case of aquatic vegetation, these models typically rely heavily on empirical tuning parameters (e.g., drag coefficient), resulting in large uncertainty in the predictions. The current work (Chapter 4) provides a computationally efficient model for accounting for the complexity associated with flow in and around vegetation canopies but is based on idealized canopies. It is recommended for future model developments to focus
on newly obtained theoretical frameworks and parameterizations that incorporate the effect of complex flow-canopy interactions (e.g., due to element flexibility) more accurately.
REFERENCES


