Drag forces on vegetation due to waves and currents

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COVER FIGURE: Spartina alterniflora (Saltmarsh Cordgrass), From Wikipedia
Drag forces on vegetation due to waves and currents

MASTER OF SCIENCE THESIS

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This report is regarded as the final requirement for completion of the master degree in Hydraulic Engineering of the Faculty of Civil Engineering and Geosciences, Delft University of Technology. The research focused on the variation trend of drag coefficient with Keulegan-Carpenter number in vegetation mimics in pure wave and combined current-wave flow conditions. Experiments were carried out in the Environmental Fluid Mechanics Laboratory at Delft university of Technology.

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Summary

Vegetation in coastal areas plays an important role in its environment. In addition, vegetation can also be utilized for coastal protection. Incoming wave energy could be effectively attenuated by the upstanding vegetation plants. The reduced wave energy results in stabilized seabed and harmonious environment in coastal zones. Nowadays, an increasing number of projects have been carried out to apply vegetation as a soft measure for coastal protection.

Wave energy dissipation by vegetation is primarily induced by the work done by drag force acting on the vegetation. A drag coefficient \((C_D)\) is introduced to characterize the flow resistance from the plant stems. Knowledge of \(C_D\) is of great importance for understanding and predicting the wave dissipation process. In previous studies, relations between \(C_D\) and Reynolds number \((Re)\) have been proposed in pure current or pure wave. In addition, relations between \(C_D\) and the Keulegan-Carpenter number (abbreviated as \(KC\) and \(KC=U_w^*T_w/d,\) \(T_w\) is the wave period and \(d\) is the plant stem diameter) have also been suggested. In Keulegan-Carpenter number, the wave period \(T_w\) is also considered. Since waves are oscillatory flow, it would be preferable to use the \(KC\) number to describe the behaviour of \(C_D\) in wave-present conditions.

However, contradictory conclusions are found in the literature on the \(C_D-KC\) relation in pure wave condition. Monotonous decreasing of \(C_D\) with \(KC\) has been reported for multiple vegetation mimics. On the contrary, the rise-and-fall variation trend has been observed in pure wave, but only for single cylinder. It is noted that the transition point (from rise to fall) occurs when \(KC\) value is small, which is often left out in the experiment with multiple vegetation mimics in previous studies. Hence, it is necessary to investigate the variation trend of \(C_D-KC\) for multiple vegetation mimics in pure wave with a wider \(KC\) range. Moreover, background tidal currents may also play a role in the wave dissipation process. It is often the case that when the tide penetrates the coastal wetlands during flooding phase, waves propagate in the same direction as the tidal currents. The underlying current may affect the behaviour of oscillatory wave flow during the energy-damping process and the \(C_D-KC\) relation. Yet, the \(C_D-KC\) relation in combined current-wave flow has not been reported in previous studies.

In order to fill the knowledge gap in the \(C_D-KC\) relation, an experimental approach was adopted by using the laboratory flume to replicate such complicated hydrodynamics. The flume is 40m long and 0.8m wide, with a patch of rigid wooden cylinders as vegetation mimics installed over the entire channel width over a 6m long test section. Pure wave can be generated by the wave generator. The underlying current can be made by using a water circulation system in the flume. After the generation of underlying current, waves could be generated afterwards and propagate together with the underlying current in the flume. The velocity was measured using EMS within the vegetation patch. Direct measurement data of the force on individual rods within the array were collected by attaching the rods to the force sensors and embedding them in the false bottom of the flume. Three densities of the vegetation mimics were investigated for two water depths in this study.

The results of the experiments reveal a rise-and-fall variation trend of \(C_D-KC\) for multiple vegetation mimics in pure wave. The rise-part occurs when \(KC\) is small, around \(KC=3\) to 10 and this phenomenon could be physically explained based on the changes in vortexes shedding directions. In this range of \(KC\), the vortexes motions would change its propagation direction from lateral to oblique and longitudinally parallel with the incoming flow. It is the changes in vortexes directions that lead to the increase of flow resistance experienced by the cylinder. Beyond this range of \(KC\), the vortexes motion
would keep moving longitudinally parallel and behave much the same way as in steady current. Naturally, similar to the behaviour found in steady current conditions, the values of $C_D$ would decrease gradually and converge to 1.

In the combined current-wave flow conditions, it is necessary to make a distinction between oscillatory-dominated flow and unidirectional-dominated flow. For small underlying current applied in this study, the flow could be regarded as oscillatory-dominated. It is found that the similar rise-and-fall pattern of $C_D$-$KC$ relation occurs in this kind of combined flow. And the transition point of $KC$ locates at around $KC=10$, which is also the case found in pure wave conditions. But the peak value of $C_D$ would decrease a little bit.

However, for larger underlying current conditions, the combined flow is similar to pure current. Consequently, the peak values of $C_D$ would collapse. Thus, the values of $C_D$ obtained in these conditions are stable and close to 1.

The experimental results suggest the vegetation density as well as the water depths has limited effects on the values of $C_D$ and its variation trend with $KC$. It is recommended to carry further investigation concerning the influence on $C_D$ caused by vegetation density ($N$) and relative vegetation height ($\alpha$) in future studies.

The product of this thesis is a general description and explanation for the variation trend of $C_D$-$KC$ in pure wave and combined current-wave flow conditions. Physically, more insights have been gained about the evolution of vortex shedding in different flow conditions, say from pure wave to combined current-wave flow conditions. Moreover, both the calibration approach (used by Mendez and Losada, 2004, etc.) and direct measurement method have been utilised for data processing. The direct measurement method is recommended to apply in all the complicated flow conditions. As to the calibration approach, it should not be applied to obtain $C_D$ values in combined current-wave flow.

Key words: vegetation, drag, Keulegan-Carpenter number, wave, combined current-wave flow
Nomenclature

\(a\) amplitude of the oscillatory motion \([\text{m}]\)

\(2a\) stroke of oscillatory motion \([\text{m}]\)

\(b_v\) plant area per unit height of each vegetation stand normal to wave motion \([\text{m}]\)

\(C_D\) drag coefficient \([-\]\]

\(C_{D, \text{cali}}\) drag coefficient obtained from calibration approach \([-\]\]

\(C_M\) inertia coefficient \([-\]\]

\(c_g\) group velocity \([\text{ms}^{-1}]\)

\(d\) diameter of cylinder \([\text{m}]\)

\(E\) energy density \([\text{Nm}^{-1}]\)

\(f_w\) frequency of the oscillatory flow \([\text{s}^{-1}]\)

\(F\) total force \([\text{N}]\)

\(F_D\) drag force \([\text{N}]\)

\(F_{Di}\) instant drag force \([\text{N}]\)

\(F_i\) instant total force \([\text{N}]\)

\(F_I\) inertia force \([\text{N}]\)

\(F_{II}\) instant inertia force \([\text{N}]\)

\(g\) acceleration of gravity \([\text{ms}^{-2}]\)

\(h\) water depth \([\text{m}]\)

\(H\) wave height \([\text{m}]\)

\(H_0\) wave height at the entrance of the canopy \([\text{m}]\)

\(h\) water depth \([\text{m}]\)

\(h_v\) length of the stem immersed in the water \([\text{m}]\)

\(k\) wave number \([\text{m}^{-1}]\)

\(K_v\) relative wave height \([-\]\]

\(KC\) Keulegan-Carpenter number with actual flow velocity in definition \([-\]\]

\(L\) longitudinal spacing distance between vegetation cylinders \([\text{m}]\)

\(n_w\) number of periods \([-\]\]

\(N\) number of vegetation plants per unit horizontal area \([\text{m}^2]\)

\(Re\) Reynolds number \([-\]\]

\(S\) spacing distance between vegetation cylinders \([\text{m}]\)

\(T\) lateral spacing distance between vegetation cylinders \([\text{m}]\)

\(T_w\) period of oscillatory flow \([\text{s}]\)
\(T_p\)  
peak wave period  
[s]

\(t\)  
time series  
[s]

\(U_a\)  
averaged velocity along the cylinder height  
[ms^{-1}]

\(U_{1/2h}\)  
velocity at half water depth  
[ms^{-1}]

\(U_{1/2h_v}\)  
velocity at half height of cylinder  
[ms^{-1}]

\(U_c\)  
current velocity  
[ms^{-1}]

\(u_{max}\)  
maximum horizontal orbital velocity calculated based on linear wave theory  
[ms^{-1}]

\(U_{max}\)  
peak orbital velocities in positive direction  
[ms^{-1}]

\(U_{min}\)  
peak orbital velocities in negative direction  
[ms^{-1}]

\(U_w\)  
characteristic velocity in oscillatory flow  
[ms^{-1}]

\(U_{wi}\)  
instant characteristic velocity  
[ms^{-1}]

\(W_D\)  
work done by drag force over entire oscillatory flow periods  
[Nm]

\(W_I\)  
work done by inertia force over entire oscillatory flow periods  
[Nm]

\(x\)  
horizontal distance  
[m]

\(y\)  
vertical distance  
[m]

\(z\)  
top of vegetation canopy  
[m]

\(\alpha\)  
relative vegetation height  
[-]

\(\beta\)  
frequency parameter  
[-]

\(\beta_{cali}\)  
damping parameter  
[-]

\(\varepsilon_v\)  
time-averaged rate of energy dissipation per unit horizontal area  
[Nm^{-1}s^{-1}]

\(\sigma\)  
wave angular frequency  
[rad/s]

\(\omega\)  
angular frequency of oscillatory motion  
[rad/s]

\(\rho\)  
fluid density  
[kg/m^3]
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Chapter 1

Introduction

1.1 Role of vegetation in wave dissipation

Coastal protection is becoming increasingly important due to the sea-level rise phenomenon and more frequent storm events (e.g. Davis et al., 2004; ZHANG et al., 2000). Both are the threats to coastal areas with high economy values and large populations. The fight against coastline erosion has a long history and the protection of coastal area from flooding is an old and serious topic.

During last century, a great number of coastal structures have been built globally to provide such protection. Sea-dikes or sea-walls (Pilkey and Wright, 1988) and breakwaters are often the measures used to protect coastal area (Hur D-S and Mizutani N, 2003). These measures belong to hard measures in coastal protection. Many engineering projects have proved that this type of protection is effective (e.g. Bruun, 1985; Pilarczyk, 1998; Knudsen, 1984). However, some drawbacks of these hard measures can not be ignored (e.g. Temmerman et al., 2013; Borsje et al., 2011). For instance, strong reflection of incoming waves and currents actually increase the load to the structures and thus more investment in materials and construction are required. Such investment costs not only money but also working time as well as human labour. Furthermore, the existence of such hard measures could result in negative or unforeseen impacts on local environment. And it is even known to impact surrounding eco-systems on larger scales (Borsje et al., 2011).

Vegetation in coastal wetlands such as salt marshes and mangroves provides important habitats for unique plants and animal species. The upstanding vegetation can attenuate wave energy significantly (Anderson et al., 2011). Hence, such attenuation effect from vegetation can be used in coastal protection. Moreover, the reduced wave height due to the existence of vegetation benefits the coastal eco-system and natural habitats could be provided by vegetated area (Augustin et al., 2009). In addition, vegetation fields in coastal area could be important in coastal managements (S. Temmerman et al., 2013). Such importance is revealed not only in coastal protection but also in coastal eco-system conservation.

1.2 Statement of problem

However, our understanding on physical processes taking place in these vegetated areas is still limited because of the complex interactions between hydrodynamics and plants structures (reviewed by Nepf, 2012). One of the related issues is interpreting wave dissipation by vegetation in different conditions. Such dissipation may vary with plant density, wave condition, current velocity and drag coefficient. Wave dissipation is mainly induced by drag force on vegetation stems (Hu et al., 2014). The drag forces on vegetation due to waves and currents play an important role in energy dissipation process. To describe the drag force, a drag coefficient is introduced to characterize the flow conditions around the vegetation stems.

In pure wave, drag coefficient and its variation trend with Keulegan-Carpenter number have been studied in many studies (e.g. Mendez and Losada, 2004; Augustin et al., 2009; Sumer and Fredsoe, 2006; Sapkaya1976; Ni, 2014). However, in some studies the monotonous decrease of drag coefficient with KC number was reported (Mendez and Losada, 2004; Augustin et al., 2009). While in some other
studies (Sumer and Fredsoe, 2006; Ni, 2014), the rise-and-fall variation trend was found. The contradiction about the variation trend occurs at small $KC$ numbers. Hence in pure wave, it is important to investigate the variation trend of $C_D$ with $KC$ with small $KC$ numbers.

In coastal area, tidal currents can also play an important role together with the incoming waves in wave dissipation process (Hu et al., 2014). However, to our knowledge, no study has been done about the variation trend of $C_D$ with $KC$ number in combined current-wave flow condition. Thus, it is necessary to obtain insight of $C_D$ variation with $KC$ number in such flow condition.

1.3 Research objectives

The purpose of this study is to gain insight into the behaviour of $C_D$ with $KC$ number in pure wave and combined current-wave flow conditions. The research questions are summarized as follows:

1. What is the variation trend for $C_D$ with $KC$ number in $KC$ small numbers (say $KC$ smaller than 10) for multiple vegetation mimics in pure wave?

2. What is the behaviour of $C_D$ with $KC$ number for multiple vegetation mimics in combined current-wave flow conditions?

3. What is the possible influence of vegetation density in the relation between $C_D$ and $KC$ number?

1.4 Approach

In order to answer the research questions, an experimental approach was carried out. A patch of vegetation mimics was used in laboratory flume to simulate vegetated area. The calibration approach used by Mendez and Losada (2004) has been chosen in processing the data to obtain $C_D$. Based on the calibration approach, $C_D$ could be calculated from the reduced wave height which reflects the dissipation of wave energy. In addition, the results of $C_D$ obtained from the direct measurement method have also been presented. More insights could be gained about the difference in the application range of these two methods. Details of the experimental methods are described in Chapter 3.

The following chapters first give a detailed presentation of the results, and then provide discussions of the physical mechanisms which would influence $C_D$, and finally summarize the conclusions and give recommendations for future studies. Prior to introducing the experiments, an overview of theory on flows around cylinder provides background information relevant to this study.
Chapter 2

Theory background and literature review

As to the investigation on wave dissipation by vegetation, it has close connection with the background theory about flow around a cylinder (Sumer and Fredsøe (2006)). In this chapter, the related background theory of flow around a cylinder is introduced.

The contents in this chapter start from current condition since this kind of flow is unidirectional. After that, background theories about wave conditions are introduced to describe the condition for oscillatory flow around a cylinder.

2.1 Flow around a cylinder in pure current

To describe the flow around a cylinder in current condition, Reynolds number needs to be introduced.

\[ Re = \frac{U_c d}{\nu} \]  

(2-1)

Where \( d \) is the diameter of the cylinder, \( U_c \) is the current velocity and \( \nu \) is the kinematic viscosity. As the Reynolds number increases from zero, the flow would undergo tremendous change. Table 2.1 gives summarized flow regimes experienced with increasing Reynolds number.

From this figure, it is easy to follow the changes of flow regimes with the increase of Reynolds number. The description of Table 2.1 is given briefly as follows.

The separation of flow first happens when \( Re \) reaches 5. For the range of Reynolds number (hereafter referred as \( Re \)) \( 5<Re<40 \), one pair of vortices would be formed in the wake of the cylinder. After that with the increased Reynolds number, the unstable wake would give birth to vortex shedding. Consequently, the wake would appear to be a vortex street. As to the vortex street, it changes from laminar to turbulent with the increase of Reynolds number. For \( 300<Re<3*10^5 \), the wake becomes turbulent completely while the boundary layer separation still stays laminar. Further more, the laminar boundary layer separation turns to be partly laminar and partly turbulent for \( 3*10^5<Re<3.5*10^5 \). When \( 3.5*10^5<Re<1.5*10^6 \), the boundary layer separation is turbulent while the boundary layer is partly laminar and partly turbulent. After that, one side of boundary layer becomes completely turbulent for \( 1.5*10^6<Re<4*10^6 \). Eventually, both sides of boundary layer are completely turbulent when \( Re>4*10^6 \).
Table 2.1 Regimes of flow around a cylinder in current condition
(Adapted from the Figure 1.1 of the book *Hydrodynamics Around Cylindrical Structures* by B. Mutlu Sumer and Jørgen Fredsøe, Revised Edition, 2006, page 2)
Fig. 2.1 gives the appearance of vortex shedding behind the cylinder in a stream of oil with increasing $Re$. Compared to water, the oil liquid has higher viscosity which makes it possible for observers to record the appearance of vortex shedding in a stream of oil (Homann, 1936).

It should be noticed that in current conditions, as it is an unidirection flow around the cylinder, the wake and vortex shedding are generated at only one side of the cylinder. Thus for example the vortex shedding, it is generated after the cylinder and travelling away from the cylinder in the same direction of current.

Fig. 2.1 Vortex shedding behind a cylinder in a stream of oil (from Homann, 1936) with increasing $Re$ (Adapted from the Figure 1.3 of the book *Hydrodynamics Around Cylindrical Structures* by B. Mutlu Sumer and Jørgen Fredsøe, Revised Edition, 2006, page 4)
Due to flow separation on the surface of cylinder and vortex shedding at the rear side of it, the cylinder itself would thus experience pressure difference and the form drag force is generated. Fig. 2.2 gives the sketch of the drag force experienced by a cylinder.

![Sketch of drag force of single cylinder](image)

Fig. 2.2 Sketch of drag force of single cylinder
(Adapted from the Figure 2.1 of the book *Hydrodynamics Around Cylindrical Structures* by B. Mutlu Sumer and Jørgen Fredsøe, Revised Edition, 2006, page 37)

The expression for the drag force of a cylinder in current condition is given by Eq. (2-2):

$$ F_D = \frac{1}{2} \rho C_D d U_c^2 $$

(2-2)

Where $F_D$ is the drag force and $\rho$ is the density of the fluid and $d$ is the diameter of the cylinder while $U_c$ is the current velocity. The drag coefficient (hereafter referred as $C_D$) is a function of $Re$. Fig. 2.3 shows the variation of drag coefficient with Reynolds number. Both horizontal and vertical coordinates are logarithmic coordinates.

![Drag coefficient for a cylinder as a function of the Reynolds number](image)

Fig. 2.3 Drag coefficient for a cylinder as a function of the Reynolds number.
(Adapted from the Figure 2.7 of the book *Hydrodynamics Around Cylindrical Structures* by B. Mutlu Sumer and Jørgen Fredsøe, Revised Edition, 2006, at page 43)
As can be seen from Fig. 2.3, \( C_D \) decreases monotonously with increasing \( Re \) until \( Re \) reaches its value around 300. While through the range \( 300 < Re < 3 \times 10^5 \), it is possible to assume \( C_D \) as a constant value, namely 1.2. When \( Re \) attains the value of \( 3 \times 10^5 \), \( C_D \) decreases abruptly and could be assumed as a much lower value, about 0.25. Such drastic fall in \( C_D \) is because of the change of the pressure distributions over the cylinder. Due to the abrupt delay of the flow separation point when \( Re \) reaches \( 3 \times 10^5 \), the pressure difference experienced by the cylinder decreases suddenly and thus makes drastic fall in \( C_D \). But for most cases of Reynolds number, say, in the range from \( 1 \times 10^3 \) to \( 2 \times 10^5 \) for current conditions, the values of \( C_D \) are quite stable and close to 1.

### 2.2 Flow regimes around a cylinder in oscillatory flow

As shown in Chapter 2.1, the hydrodynamic quantities describing the flow around a cylinder in current conditions depend on Reynolds number \((Re)\). While in the case where the cylinder is exposed to an oscillatory flow, an additional parameter the so called Keulegan-Carpenter number appears (Sumer and Fredsøe (2006)). The Keulegan-Carpenter number, i.e. \( KC \) number is defined by

\[
KC = \frac{U_w T_w}{d}
\]  

(2-3)

Where \( U_w \) is the maximum orbital velocity and \( T_w \) is the period of oscillatory flow, \( d \) is the diameter of the cylinder. For regular waves which is a sinusoidal oscillatory flow, the velocity is given by

\[
U = U_w \sin(\omega t)
\]  

(2-4)

Then based on linear wave theory, the maximum orbital velocity can be obtained as

\[
U_w = a \omega = \frac{2\pi a}{T_w}
\]  

(2-5)

Where \( a \) is the amplitude of the oscillatory motion. So, for the sinusoidal case the \( KC \) number can also be expressed identically in this way

\[
KC = \frac{2\pi a}{d}
\]  

(2-6)

The quantity \( \omega \) in Eq. (2-5) is the angular frequency of the motion

\[
\omega = 2\pi f_w = \frac{2\pi}{T_w}
\]  

(2-7)

Where \( f_w \) is the frequency of the oscillatory flow.

Since the \( KC \) number is a newly introduced parameter, it is necessary to have an idea of the physical meaning of it. With the help of Fig. 2.4, explanation could be given in a clear way. By referring to Eq. (2-6), the stroke of the motion is \( 2a \) which is included in the numerator on the right-hand side of this equation. While the diameter of the cylinder is \( d \) and it is included in the denominator.

Hence, it is easy to imagine that for small \( KC \) numbers, the orbital motion of the fluid particles is relatively small if compared to the total width of the cylinder. On the other hand, for large \( KC \) numbers, the fluid particles travel relative large distance with respect to the total width of the cylinder. By doing the imagination one step further, for very large \( KC \) numbers, say \((KC \rightarrow \infty)\), it is reasonable to expect that the flow around the cylinder for every half period of the motion looks like the flow in current conditions.
In addition to the physical meaning explained previously about $KC$ number, there are more reasons why it is of great necessity to introduce this additional parameter in oscillatory flow conditions. Firstly, by referring to Eq. (2-3), it is obvious to find that the period of oscillatory flow $T_w$ is included in the definition of $KC$. Compared to the definition of $Re$ shown by Eq. (2-1), it would be better to include the oscillatory period $T_w$ in $KC$ number in describing the characteristics of oscillatory flow.

While it is true that by using $Re$, the flow regimes in current conditions could be described with the increased $Re$. However, fundamentally speaking, the increase of $Re$ usually means the increase of $U_c$ since the values of cylinder diameter $d$ and kinematic viscosity $v$ usually stay to be constant. As to the definition of $KC$ number in Eq. (2-3), velocity is also involved and that velocity is defined as the maximum orbital velocity $U_w$. Hence, $KC$ number could also be used in describing the flow regimes in wave conditions with the increasing of $KC$.

Based on the descriptions of $KC$ number above, it is a better choice to use $KC$ in describing oscillatory flow conditions.
2.3 Forces on a cylinder in oscillatory flow

The Morison equation (Morison et al., 1950) can be used to quantify the total force on cylinder in oscillatory flow.

\[
F = F_D + F_I = \frac{1}{2} \rho C_D d h_v U_w |U_w| + \frac{1}{4} \rho C_M \pi h_v d^2 \frac{\partial U_w}{\partial t}
\]  

(2-8)

Where \( F \) is the total force and \( F_D \) is the drag force and \( F_I \) is the inertia force. \( \rho \) is the density of the fluid, \( d \) is the diameter of cylinder, \( h_v \) is the length of the stem immersed in the water. And \( U_w \) is the characteristic velocity in oscillatory flow \( C_D \) is the drag coefficient and \( C_M \) is the inertia coefficient which is chosen to be 2 for circular cylinders in some previous studies (e.g. Dean and Dalrymple, 1984; Gudmestad, O. T. et al., 1990; Li and Yan, 2007).

As can be seen from Eq. (2-8), a new force term is introduced in oscillatory flow. The new force is called inertia force and the new coefficient is called the inertia coefficient. It is necessary to take into account the new term in quantifying the total force. It is because of the fact that for oscillatory flows, the flow around cylinder changes its direction periodically. This change in flow direction gives birth to local acceleration of the flow velocity and consequently provides inertia force to the cylinder. Fig. 2.5 gives the time variation of characteristic velocity and drag force as well as inertia force for three periods of time. More insights concerning the characteristics of these two forces could be obtained from this figure.

![Fig. 2.5 Time variation of the drag force and inertia force in oscillatory flow](Adapted from the Figure 4.5 of the book *Hydrodynamics Around Cylindrical Structures* by B. Mutlu Sumer and Jørgen Fredsøe, Revised Edition, 2006, page 132).

From Fig. 2.5, there is no phase difference between the instantaneous drag force and the instantaneous characteristic velocity. Based on Eq. (2-9), the work done by the drag force over entire oscillatory flow periods could be obtained by integrating the instantaneous drag force and the instantaneous characteristic velocity over time.
\[ W_D = \int_0^{n_w T_w} F_{Di} U_{Wi} \, dt \]  

(2-9)

Where \( W_D \) is the work done by drag force over entire oscillatory flow periods, \( F_{Di} \) is the drag force, \( U_{Wi} \) is the characteristic velocity, \( T_w \) is one oscillatory flow period and \( n_w \) is the number of periods. In this case, the value of \( n_w \) is equal to three.

However, there is a 90° phase difference between the instantaneous drag force and the instantaneous inertia force \( F_I \). Thus, makes the phase difference between them be 90°. From Eq. (2-10), the work done by the inertia force \( F_I \) could also be obtained by integrating over the entire oscillatory flow periods.

\[ W_I = \int_0^{n_w T_w} F_{II} U_{Wi} \, dt \]  

(2-10)

Where \( F_{II} \) is the inertia force, and due to the 90° phase difference between the integrated elements \( F_{II} \) and \( U_{Wi} \), the outcome of such integration is zero, i.e. \( W_I = 0 \). That is to say, the inertia force \( F_I \) does not contribute any work over the entire oscillatory flow periods.

Although the total force for cylinder in oscillatory flow is composed of drag force \( F_D \) and inertia force \( F_I \), only the drag force \( F_D \) contribute work. Consequently, in oscillatory flow conditions, it is necessary to keep focusing on the drag force \( F_D \) and the drag coefficient \( C_D \).

**2.4 Drag coefficient of cylinder in oscillatory flow**

As can be seen from Fig. 2.6, the instantaneous characteristic velocity \( U_{Wi} \) and instantaneous drag force \( F_{Di} \) could vary with time. So, it is possible to make the deduction that the instantaneous drag coefficient \( C_{Di} \) may have variations with time. Hu et al., (2014) did the laboratory investigation and obtained the variation over time and this is shown in Fig. 2.6. The author of this thesis was also involved in their work.

![Fig. 2.6 Variation of measured velocity, drag force and inferred \( C_D \) with time](image)

(Adapted from Hu et al., (2014) Laboratory study on wave dissipation by vegetation in combined current–wave flow, Coastal Engineering, 88, page 138, Fig. 5)
Based on the work done by Hu et al., (2014), it is true that the drag coefficient varies with time. Such finding would be used in time-dependent numerical models, e.g. SWASH in future numerical studies.

For this study, the time-dependent drag coefficient is not the focus but could be processed and further used in obtaining a time-averaged drag coefficient which could represent its behaviour over the entire oscillatory flow periods. It is noted that the inertia force does not contribute any work over entire oscillatory flow periods (Dalrymple et al., 1984) and this holds for both pure wave and combined current-wave flow conditions (Hu et al., 2014). Hence, the work done by drag force in a wave period is equal to that done by total force. By using Eq. (2-8) and Eq. (2-9) and Eq. (2-10), the time-averaged drag coefficient can be calculated as follows:

\[
\overline{C_D} = \frac{2 \int_0^{T_w} F_D |u| dt}{\int_0^{T_w} \rho h_c d |u| |w| dt} = \frac{2 \int_0^{T_w} F_i |u| dt}{\int_0^{T_w} \rho h_c d |u| |w| dt}
\]  

(2-11)

Where \(\overline{C_D}\) is the time-averaged drag coefficient while \(F_i\) is the instant total force. All the other variables in this equation were explained before.

As a matter of fact, the drag coefficient is very important in the predictions of the damping effect as well as in the calibration and verification of the measured data collected in the past. Actually, to select an appropriate value of \(C_D\) is quite a challenging task. In some analytical models (e.g. Asano et al., 1988; Asano et al., 1992) the values of \(C_D\) were chosen as a constant in describing the wave damping process. However, such constant-assuming approach is definitely not accurate enough and would limit the applicability of the model (Asano et al., 1992). Through calibration from measured data, \(C_D\) value can also be obtained and such method is called calibration approach which is based on linear wave theory (Dalrymple et al., 1984; Mendez and Losada, 2004). In fact, all these empirical models (e.g. Dean 1979; Knutson et al., 1982; Kobayashi et al., 1993; Mendez and Losada, 2004; Augustin et al., 2009) have their own model assumptions and simplifications which result in possible errors in the value of \(C_D\) by using calibration approach. Although this calibration approach proved to be useful in \(C_D\) estimation under pure wave conditions, the procedure may not be applicable in the presence of underlying current. It has not been proved that it would be a wise move to simply extend these models to describe the combined current-wave flow conditions. Because the damping effect can be different when current is accompanied with waves. Moreover, other dissipative processes such as bed friction as well as side-wall friction or wave breaking are not explicitly considered. If the possible effect of such processes has not been filtered out, but instead been lumped into the vegetation drag in the calibration approach, then inaccurate values of drag coefficient would be possibly obtained (Hu et al., 2014).

Previous research studies have demonstrated the effect of wave energy dissipation by vegetation (e.g. Jadhav et al., 2013; Suzuki et al., 2012; Bradley and Houser, 2009; Mendez and Losada, 2004; Mendez 1999; Huang et al., 2011). However, the potential effect of underlying current on wave dissipation by vegetation was not taken into account in most of the previous studies. In fact the existence of penetrating tide in coastal wetlands together with incoming waves could possibly affect the capability of vegetation in wave-damping. To our knowledge only two studies Li and Yan (2007), Paul et al., (2012) had been done by including underlying currents in their numerical model and flume experiment respectively. This means further studies should be done concerning this topic.

Generally speaking, three kinds of methods can be used in the studies of wave attenuation by vegetation. They are field measurements (e.g. Jadhav and Chen, 2012), laboratory experiments (e.g. Sánchez-González et al., 2011; Augustin et al., 2009) and numerical modelling (e.g. Suzuki et al., 2012). A number of models and model extensions for wave-vegetation interactions have been
proposed. Except for some models which simulate vegetation with higher bottom friction factors (e.g. Camfield 1977), most of the models implement an empirical $C_D$ to estimate the wave-induced drag forces along the plant stems (Darlymple et al., 1984). The presence of vegetation produces additional hydraulic resistance to the flow including waves in coastal area (James et al., 2004; Tanino and Nepf, 2008; Kim and Stoesser, 2011). A bulk $C_D$ was introduced in previous studies to describe the damping process (e.g. Darlymple et al., 1984; Li and Yan, 2007; Augustin et al., 2009).

2.5 Review on wave energy damping and calibration approach

Waves which propagate through vegetation mimics (e.g. salt marshes, mangroves) lose energy due to the work done by vegetation. It is assumed that linear wave theory is valid and no incident regular waves are considered on a coastline with straight and parallel contours (Mendez and Losada, 2004). Thus, the conservation of energy equation can be expressed as:

$$\frac{\partial E_g}{\partial x} = -\varepsilon_v$$

(2-12)

Where

$$E = \frac{1}{8} \rho g H^2$$

(2-13)

$$c_g = \frac{1}{2} \left[ 1 + \frac{2kh}{\sinh 2kh} \right] \sqrt{\frac{g}{k}} \tanh kh$$

(2-14)

Where $E$ is the energy density, $c_g$ is the group velocity, $x$ is the onshore coordinate and $\varepsilon_v$ is the time-averaged rate of energy dissipation per unit horizontal area because of vegetation, $\rho$ is the fluid density, $g$ is the acceleration of gravity, $H$ is the wave height, $h$ is the water depth and $k$ is the wave number.

As to the vegetation plants-induced forces, a Morison-type equation is used according to several authors (Dalrymple et al., 1984; Kobayashi et al., 1993).

$$F_D = \frac{1}{2} \rho C_{D,\text{cali}} dN U_w |U_w|$$

(2-15)

Where $N$ is the number of vegetation plants per unit horizontal area. $C_{D,\text{cali}}$ is the drag coefficient calculated by using calibration approach (Mendez and Losada, 2004). The other variables in Eq. (2-15) have the same definitions as before. According to Eqs. (2-12) to (2-15), Dalrymple et al., (1984) expressed the energy dissipation for waves propagating through vegetation field as

$$\varepsilon_v = \frac{2\pi}{3} \rho C_{D,\text{cali}} dN \left( \frac{kg}{2\sigma} \right)^3 \frac{\sinh^3 kh_v + 3\sinh kh_v}{(\sinh 2kh + 2kh)\sinh kh} H^3$$

(2-16)

Where $\sigma$ is the wave angular frequency. The above equations give theoretical background about the calibration approach. In previous studies, the values for $C_{D,\text{cali}}$ in pure wave have been commonly obtained by calibrating numerical models against observed wave height damping (e.g. Mendez and Losada, 2004; Sanchez-Gonzalez et al., 2011; Augustin et al., 2009; Jadhav and Chen 2012; Bradley and Houser, 2009; Koftis et al., 2013). By using such calibration approach, it is not necessary to measure the actual force on plants to obtain the drag coefficient. Instead, $C_{D,\text{cali}}$ can be obtained by using the measured wave heights before and after vegetation mimic canopy.
Fig. 2.7 is an example which shows the definitions of the two wave heights used in calibration approach. In Fig. 2.7, $H$ is the wave height at horizontal distance $x$, $H_0$ is the wave height at the entrance of the canopy.

In calibration approach, the equations used to obtain the $C_{D,\text{cali}}$ are as follows:

$$K_v = \frac{H}{H_0} = \frac{1}{1 + \beta_{\text{cali}} x} \quad (2-17)$$
$$\beta_{\text{cali}} = \frac{4}{9\pi} C_{D,\text{cali}} b_v N H_0 k \frac{\sinh^2 kh_v + 3 \sinh kh_v}{(\sinh 2kh_v + 2kh_v) \sinh kh_v} \quad (2-18)$$

$K_v$ is the relative wave height. For wave conditions, $C_{D,\text{cali}}$ is derived commonly by inverting Eq. (2-17), provided that $\beta_{\text{cali}}$ has been obtained by fitting Eq. (2-18) to the measured wave height damping (e.g. Bradley and Houser, 2009; Augustin et al., 2009; Jadhav et al., 2013; Hu et al., 2014).

For previous studies used calibration approach, not only the values of $C_{D,\text{cali}}$ were obtained, but also the variation trends of $C_{D,\text{cali}}$ with $KC$ were found (e.g. Mendez and Losada, 2004; Augustin et al., 2009).

According to Mendez and Losada (2004), it is a suitable choice to relate $C_{D,\text{cali}}$ with $KC$ which was defined as

$$KC = \frac{u_c T_p}{b_v} \quad (2-19)$$

Where $T_p$ is the peak wave period, $b_v$ is the plant area per unit height of each vegetation stand normal to wave motion, $u_c$ is a characteristic velocity acting on the plant and defined as the maximum horizontal velocity at the middle of the vegetation width and $z = -h + \alpha h$ (i.e. the top of vegetation canopy), with $\alpha$ defined as relative vegetation height. That is to say, with different $\alpha$ values, different submerged conditions were tested in their study. The data points of $C_{D,\text{cali}}$ were obtained by using *Laminaria hyperborea* as vegetation material. In Fig. 2.8, the variation trends of $C_{D,\text{cali}}$ with $KC$ were obtained under different $\alpha$ values.
Fig. 2.8 $C_{D,cali}$ and $KC$ relation adapted from Mendez and Losada (2004) in pure wave conditions ($\alpha$ represents the relative vegetation height and $\alpha$ increases with the increase of vegetation height)

Different relative vegetation height ($\alpha$) had been tested, generally speaking, the variation trends of $C_{D,cali}$ and $KC$ are monotonous. For small $KC$ numbers, the values of $C_{D,cali}$ could soar to be around 0.5 which is as much as five times larger for the value corresponding to relatively large $KC$ numbers.

With the increasing of $\alpha$, the values of $C_{D,cali}$ became little bit larger. This is due to the fact that the increased relative vegetation height will lead to larger drag forces and consequently higher value of $C_{D,cali}$ (Anderson et al., 2011). Anyway, the monotonous variation trends have been found under different relative vegetation heights.

As mentioned before, the vegetation material used was *Laminaria hyperborea* as vegetation material. Fig. 2.9 shows the picture of such kind of flexible vegetation. The yellow lines indicate the width of single leaf. The red lines indicate the stem width.
Eq. (2-19) gives the definition of $KC$ number used by Mendez and Losada (2004). In the definition, the value of $b_v$ was chosen to be 0.25m. As can be seen from Fig. 2.9, $b_v$ corresponds to the total width of all the leaves. However, the width of a single leaf had been used in the definitions of their $KC$ number in some studies where flexible vegetation material was used. For example, the value of $b_v$ was 0.008m in the study done by Jadav and Chen (2012). And for Sanchez-Gonzalez et al., (2011), the value of $b_v$ was 0.003m.

Consequently, the value of $b_v$ chosen by Mendez and Losada (2004) would result in much smaller values of its $KC$ number.

In addition to Mendez and Losada (2004), Augustin et al., (2009) used the calibration approach to obtain the bulk $C_{D, cali}$ as well. It was also suggested by Augustin et al., (2009) that better correlation between $C_{D, cali}$ and $KC$ were found in their study. The definition of $KC$ was as follows:

$$KC \equiv \frac{u_{max} T_w}{d}$$

Where $u_{max}$ is the maximum horizontal orbital velocity calculated based on linear wave theory, $T_w$ is the wave period $d$ and is the diameter of cylinder. Two submerged water depths were used in their study. The height of the vegetation cylinder was called $l_v$, which was 0.30m. The two water depths were 0.30m and 0.40m respectively.

According to Augustin et al., (2009), two kinds of vegetation materials were used, one is the flexible polyethelene foam and the other is rigid wooden dowels. As to the diameter $d$ used in the definition of $KC$ in Eq. (2-20), it was 0.012m for rigid wooden dowels. The diameter of polyethelene foam was also
0.012m so as to be comparable. By having such choices of the diameter $d$ in $KC$ definition, the values of $KC$ number started from 40 in the study of Augustin et al., (2009).

It is a fact that calibration approach has been commonly used in obtaining $C_{D, cali}$ and variation trend of $C_{D, cali}$ and $KC$. The theoretical background is based on linear wave theory and energy damping reflected by the decreased wave heights. Since there are quite a number of studies (e.g. Dean 1979; Knutson et al., 1982; Kobayashi et al., 1993; Mendez and Losada, 2004; Augustin et al., 2009) where the data of measured wave heights were available, it is of course a proper choice to use calibration approach in obtaining $C_{D, cali}$.

However, this approach has its own limitation in application. One of the drawbacks is that the model assumptions and simplifications would result in possible errors in the value of $C_{D, cali}$ by calibration. Moreover according to Hu et al., (2014), the procedure may not be applicable for combined current-wave flow conditions. It is because of the concern that the damping effect can be possibly different when current is accompanied with waves. Hence, if the possible effect of such processes has been lumped into the vegetation drag in the calibration approach, then the values of $C_{D, cali}$ could be inaccurate (Hu et al., 2014).
2.6 Review on momentum force and direct measurement method

In addition to the constant-assumption approach and calibration approach, $C_D$ values can also be obtained via a direct measurement method. For current conditions, Ishikawa et al., (2000) and Kothyari U.C et al., (2009) measured total force and velocity directly in vegetation canopy in the flume.

For current conditions, the drag force is the only force component exerted on vegetation. The drag force exerted on the vegetation was directly measured by using a cantilever strain gauge. The current flow velocity is keeping constant by controlling the flow discharge and water level in the flume. Based on the original Morison equation (Morison et al., 1950), the value of $C_D$ can be directly calculated with the directly measured drag force and current flow velocity.

Besides, this kind of direct measurement method had also been applied in oscillatory flow as well (Sum and Fredsøe (2006)).

Actually, as to oscillatory flows, they are different compared to current conditions. Fig. 2.10 is an example which clearly demonstrates the oscillatory characteristic of wave motions. The arrows adjacent to the cylinder indicate the vertical velocity profiles in oscillatory flow.

![Wave direction](image.png)

Fig. 2.10 Sketch for oscillatory characteristic in wave motion

In oscillatory flows, since the flow changes its direction periodically, both drag force and inertia force are exerted on vegetation as a result. As stated before, Eq. (2-8) gives the expression in mathmatics. The inertia force $F_I$ can be calculated based on Eq. (2-8). The drag force $F_D$ could be obtained by subtracting the inertia force $F_I$ from the total force $F$. Furthermore, drag coefficient $C_D$ could be calculated with the defined characteristic velocity.

Not only did the values of $C_D$ can be obtained based on this method, but the variation trend of $C_D$ with $KC$ was obtained as well (Sarpkaya (1976), Bearman et al., (1985) and Anaturk (1991)). Fig. 2.14 shows the variation trend of $C_D$ with $KC$ where the data points were collected by their studies.

Actually, Fig. 2.11 shows a quite a different variation trend image. Such different trend is that $C_D$ first increased with $KC$ number and reached its peak value, after that it slightly decreased and became stable with further increase of $KC$. 

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Eq. (2-21) gives the definition of the $KC$ used in the study.

$$ KC = \frac{U_w T_w}{d} $$

Where $d$ is the diameter of the cylinder and other parameters having the same definitions as those given previously. Diameter of the cylinder was in the range of 0.0254m to 0.077m (Sarpkaya (1976)).

The dashed line which indicates asymptotic theory is shown in Fig. 2.11 and the dashed line starts at very small value of $KC$ ($KC=0.03$ in that case). For very small $KC$ numbers (such as $KC<<1$), asymptotic theory is applied in determining the drag coefficient (Bearman, Downie, Graham and Obasaju, 1985).

Asymptotic theory is valid for very small value of $KC$, during which the oscillatory flow remains to be laminar flow and there is no flow separation.

As to the value of $C_D$, the potential-flow theory is used in the calculation and Eq. (2-22) gave the analytical expression of $C_D$. Eq. (2-23) gave the definition of frequency parameter $\beta$ and it is a dimensionless parameter which is actually a ratio of $Re$ and $KC$. Fundamentally speaking, the frequency parameter $\beta$ is inversely proportional to the period of oscillatory flow $T_w$ since the diameter of the cylinder $d$ is usually a constant value.

$$ C_D = \frac{3}{2} \pi^3 (KC)^{-1} (\pi \beta)^{-1/2} \text{ for } 0.03 < KC < 1 $$

$$ \beta = \frac{Re}{KC} = \frac{U_w d}{v U_w T_w} = \frac{d^2}{v T_w} $$

Stokes (1851) was the first to give an analytical solution of the value of $C_D$ for cylindrical body in laminar oscillating flow (B. Mutlu Sumer and Jørgen Fredsøe, 2006). Stokes’ solution was given in the form of a series expansion in powers of $(Re/KC)^{-1/2}$. Eq. (2-22) is the same as the Stokes’s result if the infinitesimal of higher order is negelected, i.e. $O[(Re/KC)^{-1/2}]$. 

Fig. 2.11 $C_D$ and $KC$ relation adapted from Sumer and Fredsøe (2006) in pure wave (Data points collected from Sarpkaya (1976), Bearman et al., (1985) and Anaturk (1991))
It should be noticed that, usually, the asymptotic theory can not be applied if $KC$ is larger than 1 since the separation effects would appear afterwards so that the oscillatory flow is not laminar flow any more (Bearman, Downie, Graham and Obasaju, 1985). In Fig. 2.12, four pictures are shown to describe the development of flow separation and vortex shedding regimes of the oscillatory flow around a single cylinder.

With the increase of the sequence number of individual picture, the related value of $KC$ also increases. Table 2.2 gives the corresponding relations concerning individual picture and its vortex motion and shedding regime as well as corresponding $KC$ range.

### Table 2.2 Relations between vortex motion and shedding regimes with $KC$ range

<table>
<thead>
<tr>
<th>Sequence number of the picture</th>
<th>Pair of vortex</th>
<th>Vortex motion and shedding regimes</th>
<th>$KC$ range (Sumer and Fredsøe (2006))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Single</td>
<td>Transverse vortex</td>
<td>1.4 $&lt; KC &lt;$ 4</td>
</tr>
<tr>
<td>2</td>
<td>Single</td>
<td>Oblique vortex</td>
<td>4 $&lt; KC &lt;$ 15</td>
</tr>
<tr>
<td>3</td>
<td>Double</td>
<td>Oblique vortex</td>
<td>15 $&lt; KC &lt;$ 24</td>
</tr>
<tr>
<td>4</td>
<td>Three</td>
<td>Parallel vortex</td>
<td>24 $&lt; KC &lt;$ 32</td>
</tr>
</tbody>
</table>

Fig. 2.12 Vortex motion and shedding regimes for single cylinder in pure wave (Adapted from the Figures 3.5 and 3.6 and 3.8 of the book *Hydrodynamics Around Cylindrical Structures* by B. Mutlu Sumer and Jørgen Fredsøe, Revised Edition, 2006, pages 78 and 79 and 81).
The $KC$ ranges shown in Table 2.2 are only based on the the definition of $KC$ from Sumer and Fredsøe (2006). In different studies previously (e.g. Mendez and Losada, 2004; Augustin et al., 2009; Ni, 2014) it is possible to have different values of $KC$ but correspond to the same vortex motion or shedding regimes. This is due to the fact that different choices of characteristic velocity or other coefficients involved in the calculation of $KC$ were made.

In Fig. 2.12, four circles with hatched lines inside represent the single cylinder while each arrow shows the instantaneous oscillatory flow direction around this cylinder. The letters such as M and N and etc. are the given names of the formed vortexes in oscillatory flow around single cylinder. The dashed lines with arrows represent the vortex motion and shedding directions. While the solid lines with arrows represent the oscillatory flow direction around the single cylinder.

The velocity of oscillatory flow in pure wave starts from zero which corresponds to the value of $KC$ starts from zero as well. Vortex motion would happen with the increase of oscillatory flow velocity and the value of $KC$ increases as well. The first picture shows that this single-pair vortex (M and N) motion belongs to transverse vortex regime. It means the single-pair vortex travels in the direction perpendicular to the oscillatory flow direction. When the value of $KC$ keeps increasing, single-pair vortex (M and N) travels in oblique direction which is shown in the second picture. Afterwards, with further increasing of the value of $KC$, the double-pair vortex shedding regimes is reached. In this regime two vortexes (M and N, P and Q) also travel in oblique way shown in the third picture. After that, in the last picture, three pairs of vortexes (M and N, P and Q, R and S) are formed and travelling in the parallel direction with the oscillatory flow direction, and this is called parallel vortex shedding regime.

Nevertheless, with the increase of the value of $KC$, the vortex motion and shedding regimes develop from single-pair transverse vortex motion to single-pair oblique vortex shedding regime and then double-pair oblique vortex shedding regime and finally three-pair parallel vortex shedding regime. For $KC$ with even larger value, for example if the value of $KC$ is larger than 32 according to Sumer and Fredsøe (2006), the vortex shedding regime stays the same as parallel vortex shedding regime but with possibly more pairs of vortex.

Due to such development of vortex motion and shedding regime together with the increasing value of $KC$, the value of $C_D$ is therefore connected and also changes in a synchronized way. That is to say, when the vortex motion travels from transverse direction to oblique direction, the pressure difference before and after the cylinder increases which corresponds to the increased value of $C_D$. After that, it reaches parallel vortex shedding regime and stays at the same regime with further increase of $KC$ value. The only difference in this vortex shedding regime is that more pairs of vortex will be shed for larger $KC$ value. However, since the vortexes shed previously, e.g. vortexes M and N in the last picture in Fig. 2.12 were already been carried away from the cylinder, the pressure difference caused by the vortexes M and N has little effect on the cylinder itself.

For oscillatory flow conditions which is experienced by single cylinder, when $C_D$ reaches its peak value, it goes down slowly afterwards. The rise-and-fall variation trend of $C_D$-$KC$ happens in small $KC$ numbers.

As to that part of $C_D$ where it goes down with $KC$, it could be explained in this way. For that $KC$ range, the oscillatory flow velocity at large value of $KC$ could be compared to that in current conditions (Schlichting, 1979). It is reasonable to expect that the value of $C_D$ would go down slowly with the increased oscillatory flow velocity, i.e. increased value of $KC$.

Ni (2014) also used the direct measurement method in his laboratory investigation in pure wave. The experiment was implemented in the Fluid Mechanics Laboratory in Hydraulic Engineering
Department, TU Delft. In that study, the drag force of single wooden cylinder and oscillatory flow velocity had been both directly measured in wave conditions. $C_D$ was derived by using Morison equation (Morison et al., 1950) and the relation between $C_D$ and $KC$ was found. The rise-and-fall variation trend of $C_D$ with $KC$ was also found in that study, shown by Fig. 2.13. As to the definition of $KC$, it was kept the same as that used by Sarpkaya (1976), Bearman et al., (1985) and Anaturk (1991). The value of $d$ was 0.01 m in the laboratory study done Ni (2014) for single cylinder in pure wave.

![Graph showing $C_D$ and $KC$ relation](image)

Fig. 2.13 $C_D$ and $KC$ relation from Ni (2014) in pure wave

2.7 Review on density influence on vegetation drag coefficient

The value of vegetation drag coefficient $C_D$ could be influenced by vegetation densities (e.g. Nepf (1999), Augustin et al., (2009), Suzuki (2012)). Based on the results from the laboratory experiment done by Nepf (1999), the obtained conclusion was that the value of drag coefficient would decrease with the increased vegetation density. That is to say the wake of an upstream cylinder can suppress the drag coefficient $C_D$ for downstream cylinder. To be specific, two reasons were stated as follows as explanation. First, the downstream cylinder would experience a lower impact velocity due to the reduced velocity in the wake generated by upstream element. Second, the flow separation point on the downstream cylinder would delay due to the turbulence contributed by the wake from upstream element, resulting in a lower pressure difference around the cylinder and thus a lower drag (Zukauska, 1987; Luo et al., 1996). According to Nepf (1999), both of these wake characteristics contribute to the “sheltering effect” described by Raupach (1992) and diminishes the drag on downstream elements.

In addition, such drag reduction is related to the layout of the vegetation and such layout reflects the boundary of the wake generated by upstream cylinder. Fig. 2.14 is adapted based on the figure from Nepf (1999) and gives the description of the relation between drag reduction and spacing distance.
Fig. 2.14 Contours of drag coefficient, \( C_D \), on trailing cylinder, B, show the suppression of \( C_D \) due to wake interaction. Contours are based on data measured with two cylinders (black dots (Bokaian and Geoola, 1984)) and on the observed decay of wake interference with separation distance (Blevins, 1994, pp. 177-181), which was used to set the longitudinal trend for the above contours between \( L/d = 6 \) and 20. \( Re = 2600 \), and \( C_D = 1.17 \) at \( T/d, L/d \rightarrow \infty \). \( C_D \) is based on upstream velocity (Adapted from Figure 1 of Nepf (1999)).

As can be seen from Fig. 2.14, the lateral spacing distance \( T \) plays an important role in the density influence on \( C_D \). That means as long as the ratio of \( T/d \) is larger than 2, almost no drag reduction would be observed for all of the range of \( L/d \). While as to the longitudinal spacing distance \( L \), the trend for the above contours does not show significant drag reduction until \( L/d \) equals 6 (Nepf, 1999).

It is necessary to notice that the theory of drag reduction from Nepf (1999) was only found for vegetation cylinders in pure current conditions. Hence if the actual flow behaves in a unidirectional way, then the observed drag reduction could be explained based on the \( C_D \) contours showed by Fig. 2.14. However, for pure wave which is oscillatory flow, the flow direction changes during the wave period and the fluid particle would reverse its travelling direction during the wave period. For multiple vegetation cylinders, as to the trajectory of the fluid particle in pure wave is concerned, it could possibly cover the spacing distance of two adjacent cylinders. It is also possible for the trajectory to be smaller than the spacing distance.

Imagine there is one fluid particle which locates closes to one vegetation cylinder, a theory about the influence of vegetation density on \( C_D \) had been proposed by Suzuki (2012). \( S \) represents the spacing distance while \( 2a \) stands for the stroke of oscillatory motion. If the stroke of oscillatory motion \( 2a \) is larger than \( S \), i.e., \( 2a/S > 1 \), the trajectory would cover the spacing distance, meaning the fluid particle would feel the existence of adjacent cylinder. While if the stroke of oscillatory motion \( 2a \) is smaller than \( S \), i.e., \( 2a/S < 1 \), the fluid particle would not feel the existence of adjacent cylinder, thus there is no drag reduction at all. Fig. 2.15 is the sketch which gives the descriptions stated above. This sketch gives the top view of the relation between the stroke of oscillatory motion \( 2a \) and spacing distance \( S \). Both of the red ellipses represent the trajectories of fluid particles. For the top view here, the trajectories are drawn as ellipses in order to be demonstrated in a more clear way. In fact, in this case the trajectories of fluid particles in oscillatory flows should be straight lines from the top view.
The stroke of oscillatory motion $2a$ could be calculated based on Eq. (2.24). Also, there is a connection between the stroke of oscillatory motion with $KC$ and such connection is shown by Eq. (2.25) and Eq. (2.26).

$$2a = H \frac{\cosh k(h + y)}{\sinh kh}$$  \hspace{1cm} (2-24)

$$KC = \frac{\pi H \cosh (h + y)}{d} \frac{\sinh kh}{d}$$  \hspace{1cm} (2-25)

$$2a = \frac{KC}{\pi} d$$  \hspace{1cm} (2-26)

$$KC = \frac{U_w T_w}{d}$$  \hspace{1cm} (2-27)

Where $H$ is the wave height, $k$ is the wave number, $h$ is the water depth, $y$ represents the vertical distance and $d$ is the cylinder diameter. $U_w$ is the orbital velocity of oscillatory flow, $T_w$ is the oscillatory flow period. $KC$ is the Keulegan-Carpenter number which takes the oscillatory flow velocity $U_w$ in the definition. A non-dimensional parameter $2a/S$ was proposed by Suzuki (2012) to describe the possible influence on $C_D$ due to vegetation density. Based on that theory, the drag reduction would start as long as the stroke of motion is larger than one cylinder spacing, i.e. $2a/S > 1$. With the increase of $2a/S$, the reduction would become more obvious. However, the results obtained from both numerical modeling and laboratory experiment did not fit the theory that perfectly. According to the data points, the drag reduction had not been obviously shown even when $2a/S=2$. There is almost no drag reduction until $2a/S=4$. In addition, the data points are very limited and they were collected only on two constant $KC$ values, i.e. $KC=5$ and $KC=66$. Hence, further investigation should be done concerning more values of $2a/S$ and the data points should be collected under more $KC$ numbers in pure wave conditions.

Last but not least, according to our knowledge there is no study about the vegetation density influence on $C_D$ in combined current-wave flow conditions.
2.8 Summary

Based on the literature study, the vegetation drag forces contribute work and damp the wave energy. According to Morison (1950), the drag coefficient $C_D$ plays an important role in the calculation of the drag forces. And some relations between $C_D$ and $KC$ had been proposed in previous studies. However, contradictory conclusions about the variation trend of $C_D$ with $KC$ in pure wave conditions had been reported. For the studies done by Mendez and Losada (2004) as well as Augustin et al., (2009), the monotonous variation trend of $C_D$ with $KC$ had been found. However, as were shown by Sumer and Fredsøe (2006) and Ni (2014), the rise-and-fall variation trend of $C_D$ with $KC$ had been found. For the rise-and-fall variation trend, the transition point of $C_D$ happened at small $KC$ number, around 10. Especially, more attention should be paid for the behaviour of $C_D$ in small $KC$ numbers.

According to our knowledge, such rise-and-fall variation trend had only been found for single cylinder in pure wave conditions for the range of small $KC$ numbers (Sumer and Fredsøe, 2006; Ni, 2014). Hence, it is of great necessity to extend the research of the behaviour of $C_D$ with $KC$ to multiple vegetation mimics and for small $KC$ numbers as well.

Moreover, no conclusion about the variation trend of $C_D$ with $KC$ under combined current-wave flow condition has been reported in the past. However, the effect of current such as the tidal current, plays an important role together with the incoming waves in the energy damping by vegetation mimics (Li and Yan, 2007; Paul et al., 2012). Thus, it is of great importance to have some idea about what happens about $C_D$ with $KC$ number in such kind of hydrodynamic conditions.

By having better understanding about the behaviour of $C_D$ with $KC$ in pure wave conditions and combined current-wave flow conditions especially for small $KC$ numbers, more insights in physics could be obtained. Furthermore, it is possible to apply such physical understanding in numerical studies and model predictions for future studies.

Some research studies had been done concerning the influence of vegetation density on $C_D$ in multiple vegetation mimics. However, the theory proposed by Nepf (1999) which explained the drag reduction was only for pure current, i.e., unidirectional flow. As to pure wave, Suzuki (2012) used the non-dimensional parameter $2a/S$ to describe possible density influence but the theory did not explain some of the data points. In addition, the vegetation density influence remains unknown for combined current-wave flow conditions. Thus, it is necessary to have better understanding about the density influence in both pure wave and combined current-wave flow conditions.

Since the data points from previous studies were mostly collected from laboratory tests, it is necessary to carry out laboratory test in doing this study. Chapter 3 gives detailed description of the methodology.
Chapter 3
Methodology

Laboratory experiment method is chosen in this study to achieve the objectives mentioned previously. Wooden cylinders are used as vegetation mimics within a six-meter long patch in the flume. These cylinders experience forces and such forces do the work to dissipate wave energy in combined current-wave flow as well as in wave conditions. Among the vegetation mimics several force sensors are used in measuring the force experienced by vegetation and these force sensors are connected to wooden cylinders so as to record the instantaneous outcome voltages[V]. The voltages collected can be transferred later to force[N] and such kind of signal transformation makes it possible to record instantaneous force directly.

In addition, velocity transducers are used to record the simultaneous velocity which is experienced by individual wooden cylinder. Instantaneous outcome voltages[V] have also been collected and transformed to velocity[m/s]. Each velocity transducer is employed strictly parallel to its corresponding force sensor so there is no geographical phase difference between force signal and velocity signal. However, actually there is phase difference and this is due to the different response time of these two apparatus, intrinsically. Such phase difference between force signal and velocity signal has already been taken care of during data process through the singal one-to-one correspondence technique.

By obtaining the data in this way, some methods can be used to process the derived instantaneous drag coefficient and to see the possible relation between the processed drag $C_D$ with $KC$.

3.1 Flume set-up

Fig. 3.1 Sketch of the flume set up

Laboratory experiments were carried out in Fluid Mechanics Laboratory in Hydraulic Engineering Department, Delft University of Technology, the Netherlands. The flume is 40m long and 0.8m wide. Fig. 3.1 shows the experiment set up. With such flume set up it is possible to creat experimental conditions. Waves can be generated by the wave generator which locates at the beginning spot of the flume. Besides, current can be generated by using water circulation with pumping system. After the generation of steady current, combined current-wave flow can be obtained with the movement of wave
maker paddle. Fig. 3.2 gives top view of the locations of all the measuring apparatus. From left to right is the logitudinal direction of the flume.

![Diagram of instruments deployment](image)

**Fig. 3.2 Top view of instruments deployment**

As to the vegetation mimics, they were fixed on patches in certain patterns along the logitudinal direction of the flume. Fig. 3.3 shows one patch which was used in this study to provide such possibility in placing vegetation mimics. Regular holes were drilled in each patch and the diameter of each hole is 0.01m. The hole spacing is 0.03m both in longitudinal direction and in lateral direction. Six patches were used in the experiment and each of them is 1m long and 0.8m wide. The width of each patch almost exactly matches the width of the flume and this is shown by Fig. 3.4. By using such design in the width of patches, any potential disturbance in flow regimes due to the gaps between patches and side walls can be limited as small as possible.

![Diagram of individual patch](image)

![Diagram of six patches](image)

**Fig. 3.3 Front view of individual patch**

**Fig. 3.4 Top view of six patches**

In this study, three different vegetation densities (VD) are used and they are named as VD1 VD2 and VD3, respectively. The number of wooden cylinders per square meter for each density is 62 and 139 and 556, respectively. Fig. 3.5 and Fig. 3.6 and Fig. 3.7 show the layout of the three different densities of vegetation mimics. The space distance of adjacent cylinders in both longitudinal direction and lateral direction of the flume is 0.18m, 0.12m and 0.06m, respectively.
Fig. 3.5 VD1 (62 stems/m²) vegetation mimics layout

Fig. 3.6 VD2 (139 stems/m²) vegetation mimics layout

Fig. 3.7 VD3 (556 stems/m²) vegetation mimics layout
Fig. 3.8 is a sketch of the layout of vegetation mimics for three densities in this study. In this sketch, $d$ stands for the cylinder diameter and $T$ represents the lateral spacing distance between vegetation cylinders and $L$ means the longitudinal spacing distance. Vegetation mimics were planted in staggered pattern.

![Sketch for the layout of vegetation mimics in three densities](image)

According to Nepf (1999), ratios $T/d$ and $L/d$ are important parameters in analyzing possible density influence on $C_d$. Table 3.1 gives the summary of all the ratios applied in this study.

<table>
<thead>
<tr>
<th>Vegetation Density</th>
<th>$T$[m]</th>
<th>$L$[m]</th>
<th>$d$[m]</th>
<th>$T/d$</th>
<th>$L/d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>VD1</td>
<td>0.09</td>
<td>0.18</td>
<td>0.01</td>
<td>9</td>
<td>18</td>
</tr>
<tr>
<td>VD2</td>
<td>0.06</td>
<td>0.12</td>
<td></td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>VD3</td>
<td>0.03</td>
<td>0.06</td>
<td></td>
<td>3</td>
<td>6</td>
</tr>
</tbody>
</table>

### 3.2 Laboratory test conditions

All the tested cases in the present study are listed in Table 3.2. Three different vegetation densities were tested in present study. For each individual vegetation density, incident wave height and wave period varied from case to case. The designed wave height ranges from 0.04m to 0.20m. The designed wave periods ranged from 1.0s to 2.5s which can be representative for shore wind wave periods. By having such combination choice of small wave height (e.g. 0.04m) and small wave periods (e.g. 1.0s), small $KC$ number could be achieved in this study for wave conditions as well as for combined current-wave flow conditions. For combined wave-current conditions, the designed underlying current was first created and then different wave cases were respectively generated by the wave generator. Hence it is possible for the generated waves to propagate together with the designed underlying currents. For VD1, three currents, i.e. 5cm/s, 15cm/s and 20cm/s, have been tested as designed currents. While for VD2 and VD3, one more current 30cm/s has been added as the designed current.
Table 3.2 Test conditions with different combinations of hydrodynamic conditions and mimic canopy configurations

<table>
<thead>
<tr>
<th>Source</th>
<th>Plant mimic type</th>
<th>$\alpha$ (plant height/water depth)</th>
<th>Mimic stem density ($N$) [stems/m$^2$]</th>
<th>Wave height ($H$) [m]</th>
<th>Wave period ($T_w$) [s]</th>
<th>Wave case name</th>
<th>Current velocity ($U_c$) [cm/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present study</td>
<td>Stiff wooden rods</td>
<td>0.73</td>
<td>62</td>
<td>0.04</td>
<td>1.0</td>
<td>wave0410</td>
<td>0/5/15/20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.06</td>
<td>1.2</td>
<td>wave0612</td>
<td>0/5/15/20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.08</td>
<td>1.4</td>
<td>wave0814</td>
<td>0/5/15/20</td>
</tr>
<tr>
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<td></td>
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<td></td>
<td>0.10</td>
<td>1.6</td>
<td>wave1016</td>
<td>0/5/15/20</td>
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<td>1.6</td>
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<td>1.8</td>
<td>wave1218</td>
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<tr>
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<td></td>
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<td>1.8</td>
<td>wave1518</td>
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<td></td>
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<td>0.20</td>
<td>2.5</td>
<td>wave2025</td>
<td>0/5/15/20/30</td>
</tr>
<tr>
<td>Augustin et al., 2009</td>
<td>Rigid wooden cylinders/ Flexible polyethylene tubes</td>
<td>0.75</td>
<td>97/194</td>
<td>0.085</td>
<td>1.5-2.0</td>
<td>_</td>
<td>0</td>
</tr>
<tr>
<td>Mendez and Losada, 2004</td>
<td>Laminaria hyperborea</td>
<td>0.20</td>
<td>1200</td>
<td>0.045-0.17</td>
<td>1.26-4.42</td>
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<td>0.50</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

a The case name is created using a combination of incident wave height 0.04 m and wave period 1.0 s, namely wave0410.
b Mimic stem diameter of rigid wooden cylinders tested in Augustin et al., (2009) is 1.2 cm which is comparable to that of the present study during which the stem diameter of rigid wooden cylinder is 1.0 cm.
The relative vegetation height $\propto = 0.75$ tested in Augustin et al., (2009) and $\propto = 0.50$ tested in Mendez and Losada (2004) are comparable to that of present study during which the relative vegetation height $\propto = 0.73$.

The range of wave height and wave period tested in both Augustin et al., (2009) and Mendez and Losada (2004) are comparable to those of present study.

### 3.3 Data process method

#### 3.3.1 $C_D$ quantification by calibration approach

In present study, wave gauges were used in the vegetation mimic canopy. In order to have an idea about the reliability of the wave gauges in its measurement, the calibration work of the wave gauges had been done before doing laboratory experiment tests. Appendix A gives the calibration results of the wave gauges as well as the working principles. Moreover, measurement errors are also given in Appendix A.

Since the wave height data are available both in wave conditions and combined current-wave flow conditions, the calibration approach can be used to process the data and obtain $C_D$ values. Eq. (2-17) and Eq. (2-18) were used in obtaining the bulk $C_D$ in present study.

#### 3.3.2 $C_D$ quantification by direct measurement method

In present study, the direct measurement method was also used. Based on Eq. (2-8) and Eq. (2-11), the time-averaged drag coefficients $C_\alpha$ were obtained in wave conditions as well as combined current-wave flow conditions.

#### 3.3.3 Keulegan-Carpenter number ($KC$) definition

In present study, the definition of $KC$ stays almost the same as that shown by Eq. (2-21). But there needs more description as to the characteristic velocity used in this study.

The characteristic velocity $U_w$ is the amplitude of the measured horizontal wave orbital velocity [m/s], defined as

$$ U_w = \frac{1}{2}(U_{max} - U_{min}) \quad (3-1) $$

Where $U_{max}$ and $U_{min}$ are the values of peak orbital velocities [m/s] at half of the water depth in positive and negative directions respectively during a wave period.

For combined current-wave flow conditions, although there are several alternatives with regard to the definition of $KC$ number, the definition of $KC$ adopted in the case of pure wave conditions may be maintained (Sumer and Fredsøe (2006)). The definition adopted in combined current-wave flow conditions is shown by Eq. (3-2).

$$ KC = \frac{U_w \cdot T_w}{d} \quad (3-2) $$

For the direct measurement of $C_D$, one has to choose a position to place the wave velocity transducers. Based on Eq. (3-1), the derived values of drag coefficient could be affected by the choice of characteristic velocity used in the equation. That means if the characteristic velocity is not chosen in a reasonable way, the obtained $C_D$ value would possibly be overestimated or underestimated.
In previous studies (e.g. Mendez and Losada, 2004; Augustin et al., 2009; Sanchez-Gonzalez et al., 2011) calibration approach had been used to obtain the value of drag coefficient. For their studies, there is no need to use the characteristic velocity in obtaining $C_{D,\text{cali}}$. However, it is necessary to use characteristic velocity in the calculation of $KC$ and find the variation trend of $C_{D,\text{cali}}$-$KC$. For example, the maximum orbital velocity over the blades was chosen by Sanchez-Gonzalez et al. (2011) in their calculation of $KC$. While for Mendez and Losada (2004) and Augustin et al., (2009), their characteristic velocities were derived by using linear wave theory in processing the measured wave height and wave period.

As to our knowledge, for direct measurement method, no previous studies concerning the choice of characteristic velocity could be used for reference in pure wave conditions and combined current-wave flow either. In this study, for the sake of simplicity in carrying out the measurement work of velocity, the velocity at half of the water depth, i.e. $U_{1/2h}$, had been defined as characteristic velocity in obtaining the value of $C_D$ for direct measurement method.

That is to say, the defined $U_v$ is the amplitude of the measured horizontal wave orbital velocity which was measured at half water depth equals to $U_{1/2h}$. For emergent vegetation with the water depth as 0.25m, three EMS were placed at 0.125m above the false bottom. While for submerged vegetation with the water depth as 0.50m the velocities were measured at 0.25m deep, which is the 72.8% vertical position of the full cylinder height of 0.364m.

Fig. 3.9 gives the sketch of the position of measured characteristic velocity in submerged conditions. In this figure, the wave propagates from left to right. The two vertical rectangular thin boxes represent the vegetation mimics and the EMS is placed among the vegetation cylinders. The electronic signal obtained from EMS can be transported and collected by the computer. Based on the EMS menu which describes the relation between the electronic voltage signal and corresponding velocity, the measured velocity data could be obtained.

![Fig. 3.9 Vertical position of the velocity transducer EMS](image)

The velocities at half of the water depth were measured for all the test conditions in this study. During the tests, the velocity profiles for some conditions were measured. It is possible to use the measured velocity profile data to calculate the averaged velocity, i.e. $U_a$, along the total height of the vegetation cylinder. It is necessary and meaningful to compare the values between $U_{1/2}$ and $U_a$ so as to know if the chosen characteristic velocity can represent the average velocity along the total height of the
vegetation cylinder or not. It will also be meaningful to know if any improvement about the choice of characteristic velocity would be made in future studies.

Table 3.3 gives the test conditions where velocity profiles were measured.

Table 3.3 Test conditions for measured velocity profiles

<table>
<thead>
<tr>
<th>Name of vegetation mimic density</th>
<th>Density of vegetation mimics (stems/m²)</th>
<th>Underlying current velocity (cm/s)</th>
<th>wave case name</th>
</tr>
</thead>
<tbody>
<tr>
<td>VD1</td>
<td>62</td>
<td>0</td>
<td>wave1016 - 15 wave1016 -</td>
</tr>
<tr>
<td>VD2</td>
<td>139</td>
<td>0</td>
<td>wave1016 wave1518</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>wave1016 wave1518</td>
</tr>
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<td>wave1016 wave1518</td>
</tr>
</tbody>
</table>

Since waves and the combined current-wave flow are oscillatory flows, the measured orbital velocity changes within a wave period. In this study, the velocities from two moments of the whole period of the oscillatory flow were used to construct velocity profiles. That is to say, for one wave case, the wave peak velocities measured at different vertical positions were used to construct a wave-peak velocity profile. Also, the wave trough velocities measured at different vertical positions were used to construct a wave-trough velocity profile. By combining the wave-peak velocity profile together with wave-trough velocity profile, for one wave case, the envelop lines of velocity profiles could be obtained. In order to have more data and avoid possibly biased measurement, for one wave case, the velocity profiles were usually measured at least twice. For most of the wave cases, nine vertical positions were applied to obtain the velocity profile. Table 3.4 gives detailed information.
Table 3.4 Vertical positions applied in the measurement of velocity profiles

<table>
<thead>
<tr>
<th>Height of the wooden cylinder [m]</th>
<th>Half water depth [m]</th>
<th>Height of vertical position in velocity profile measurement [m]</th>
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Chapter 4

Results

In this chapter, results concerning the relations between $C_D$ and $KC$ are presented. These results not only show the $C_D$-$KC$ relation in wave conditions (referred to as C00W hereafter) for three vegetation densities, but also show such relation under combined current-wave flow conditions under three vegetation densities. The combined current-wave flow conditions are as follows: waves with underlying current velocity 5cm/s (referred to as C05W hereafter), waves with underlying current velocity 15cm/s (referred to as C15W hereafter), waves with underlying current velocity 20cm/s (referred to as C20W hereafter) and waves with underlying current velocity 30cm/s (referred to as C30W hereafter) for all three mimic densities except the underlying current of 30cm/s was not applied to the waves under VD1.

Two different abbreviations for drag coefficients are used in this chapter. For the drag coefficients obtained from calibration approach, they are named as $C_{D,cal}$. While for the drag coefficients obtained from direct measurement approach, strictly speaking, they are time-averaged values, i.e. $\overline{C_D}$ which were calculated based on Eq. (2-11). But for the sake of simplicity in presentation, they are named as $C_D$ in this chapter.

4.1 Results based on calibration approach

In calibration approach the measured wave heights which are before and after the vegetation mimic patches need to be used in its model. Fig. 4.1 shows one test case (wave1516 for C00W under VD3) about the wave height damping process along the vegetation mimic patch. $H_o$ represents the incident wave height and $H$ represents the outgoing wave height. So, the relative wave height $K_v$ could be obtained by using Eq. (2-17) and $C_{D,cal}$ could be obtained by applying the calculated $K_v$ in Eq. (2-18).

![Fig. 4.1 Wave height damping along the vegetation mimic patch](image)

In this study the calibration approach has been used not only in wave conditions but also under combined current-wave flow conditions since the wave height data are available for all the tests.
As to the wave height data, they are measured by using wave gauges and the absolute measurement error for the wave gauges used in this study is 0.002m. Such kind of measurement error needs to be taken into account in the obtained $C_{D,cali}$ value. Error bars are applied in presenting the value of $C_{D,cali}$ in all the figures shown in Section 4.1.

Since different wave heights were tested in this study, the relative measurement error is different from one wave case to another. The relative measurement error of wave heights has an effect on the relative error of the $C_{D,cali}$ value obtained. That is to say for smaller wave heights, although the absolute measurement error is 0.002m, the relative error is larger not only in the measured wave height but also in its corresponding $C_{D,cali}$ value. While for larger wave heights, the relative error is smaller. Five figures shown in Appendix B give the calculation method of the absolute measurement errors of the obtained $C_{D,cali}$ values for all the test conditions.

4.1.1 $C_D$ and $KC$ relation in pure wave

![Fig. 4.2 $C_{D,cali}$ and $KC$ relation under submerged VD2 in pure wave (C00W)](image)

From Fig. 4.2, it is obvious to find the rise-and-fall variation trend of $C_D$-$KC$. The transition happened at small $KC$ number, say around 9. Similar variation trend has also been found in other densities. Fig. 4.3 shows the relevant results.

![Fig. 4.3 $C_{D,cali}$ and $KC$ relation under submerged three densities in pure wave (C00W)](image)
Data points shown in Fig. 4.3 represent the relations between $C_{D, cali}$ and $KC$ in pure wave conditions (C00W) for three densities. In these cases, by using the calibration approach, the obtained $C_{D, cali}$ does not monotonously increase with the decrease of $KC$ number. Instead, for VD2 and VD3 under C00W conditions, the rise-and-fall variation trends are found and the transition happened at small $KC$ numbers, say around 10–15. While for VD1 under C00W conditions, the rise-and-fall variation trend is not obviously found. The $C_{D, cali}$ value does not decline for small $KC$ numbers in this density case, however, it does not soar rapidly either, which would be the case if the monotonous variation trend was expected. If the error bars of $C_D$ value are taken into consideration, then it is reasonable to expect the rise-and-fall variation trend is also valid in VD1 conditions.

### 4.1.2 $C_D$ and $KC$ relation in combined current-wave flow

The calibrated drag coefficients with $KC$ number in combined current-wave flow are shown in Figs. 4.4 and 4.5 and 4.6 for the three mimic densities respectively. Fig. 4.4 gives the comparion between the results collected in wave conditions and small current veolocity in combined current-wave flow condition under VD2.

![Calibration $C_{D, cali}$-$KC$](image)

**Fig. 4.4 $C_{D, cali}$ and $KC$ relation under submerged VD2 in C00W and C05W**

Based on what was suggested in Hu et al., (2014), it would not be a proper choice to apply calibration approach in combined current-wave flow conditions. Well, this opinion may not sound that perfect. From Fig. 4.5, it is interesting to have found that the rise-and-fall variation trend of $C_D$-$KC$ in both flow conditions. Such phenomenon indicates that, the combined current-wave flow conditions are closer to wave conditions in physics for underlying current with relatively small flow velocity. It can also be put in this way, the movement of the fluid particles as orbital circulations still dominates.

Now, it is necessary to see if the calibration approach could be applied in combined current-wave flow conditions for large flow velocities. Fig. 4.6 shows relevant results for C15W and C20W as well as C30W under VD2.
However, as can be seen from Fig. 4.5, for the combined current-wave flow conditions the monotonous variation trends of $C_{D, cali}$-$KC$ are quite obvious. For example as to the data representing VD2-C20W, the largest value of $C_{D, cali}$ soared to be around 10 and such kind of similar phenomenon is also shown for the data representing VD2-C30W. In addition, it is also obvious to see that with the increase of the underlying current velocity, larger values have been found for small $KC$ numbers.

In fact, the underlying current also plays a role in wave energy damping process for combined current-wave flow conditions (Li and Yan, 2007). According to Hu et al., (2014), the ratio of current velocity ($U_c$) with orbital velocity ($U_w$) plays an important role in describing the damping effect caused by current. Especially when the flow velocity of underlying current is large, much more energy would have been damped (Hu et al., (2014)). However, such damping effect caused by underlying currents should not be lumped into the value of $C_D$. Hence, it is not a wise move to extend the application of calibration approach in obtaining the $C_D$ value for the combined current-wave flow conditions with large current flow velocities.

It can also be stated as follows, for wave conditions as well as the combined current-wave flow with only relatively small underlying current velocity conditions, the drag coefficients obtained from calibration approach also have rise-and-fall variation trend with $KC$ number. The transition of $C_{D, cali}$ values happens at small $KC$ number. As to the combined current-wave flow conditions, the variation trend of $C_{D, cali}$-$KC$ is monotonous since the energy damping effect from current is also lumped into drag coefficient. Thus making the calibrated $C_{D, cali}$ overestimated.

Due to such shortcomings of calibration approach, the direct measurement method should be applied to obtain the drag coefficient directly. Since the forces on vegetation mimics as well as simultaneous velocities are both measured in this study, the value of $C_D$ could be derived not only in wave conditions (C00W) but also under the combined current-wave flow conditions.
4.2 Results based on direct measurement approach

In this study, three EMS were used in measuring velocities. The velocity measured for individual EMS is named as \( E1 \) and \( E3 \) and \( E4 \). By using force signals and velocity signals, the instantaneous drag coefficient can be derived by these two directly-measured variables. Two old force sensors were used in this laboratory study and the forces measured by them are named as \( F1 \) and \( F3 \). The drag coefficients based on the measured force are named \( C_{D1} \) and \( C_{D3} \), respectively. Two new sensors were used and the forces measured by them are named as \( F2 \) and \( F4 \), corresponding to drag coefficients \( C_{D2} \) and \( C_{D4} \). Unfortunately, immediately after the setting up of the experiment, the force sensor \( F2 \) was broken and no signal could be collected from it. Hence, only the forces measured by \( F1 \) and \( F3 \) and \( F4 \) were recorded. As to the results present in Section 4.2, the values of \( C_d \) are the averaged values of \( C_{D1} \) and \( C_{D3} \) and \( C_{D4} \).

4.2.1 Results of characteristic velocity

As stated in Section 3.3.3, a number of velocity profiles have been measured. As examples, Figs. 4.6 and Fig. 4.7 show the measured velocity profile which came from the same case of wave1016 under the same wave conditions in submerged VD3 (556 stem/m²). Appendix C presents all the measured velocity profiles measured in this study.

As stated before, by repeating the measurement of the velocity profile, more data as well as less biased data would be obtained. Figs. 4.6 and 4.7 show that for the same vertical positions, the measured velocity data were considerably close to each other. That is to say, the experiment test conditions have very good repeatability. In addition, the operation state for \( E1 \) and \( E3 \) and \( E4 \) are stable. Thus, the velocity profiles data are reliable. Further more, these data could be used in the calculation of the averaged velocities experienced by the vegetation cylinders.

![Fig. 4.6 Velocity profile for wave1016_1_C00W_VD3](image-url)
However, there is one small flaw in the measured velocity data. It is easy to find that for higher vertical positions, say 0.45m height position, the velocities measured at the wave trough can be scattered. This is because of the fact that the magnetic field at the bottom of EMS is actually quite close to the water surface when the EMS is lifted up to higher positions. Since EMS measured the velocity of conductive liquid motion, the measured velocity data could possibly be unstable when the magnetic field is not being submerged enough in higher vertical positions. Especially, when the wave trough went over the magnetic field, it is reasonable to expect that some scatters about the velocity data for wave trough. But fortunately, this flaw does not affect the calculation of average velocity (i.e. $U_a$) at all. Since the wooden cylinder height is 0.364m and $U_a$ is the averaged velocity along the wooden cylinder height rather than the whole water depth.

The averaged velocity $U_a$ could be calculated based on the velocity profile and the characteristic velocity ($U_{1/2h}$) is direct measured at half of the water depth. It is necessary to compare their values so as to see if the characteristic velocity ($U_{1/2h}$) was chosen in a reasonable way.

Fig. 4.8 shows the correlation of these two velocities, i.e. $U_{1/2h}$ and $U_a$ for all the profiles listed in Table 3.1. The correlation coefficient R-squared reaches up to 0.985. So it can be concluded that the characteristic velocity (i.e. $U_{1/2h}$) can represent the average velocity in this study. However, such kind of choice in characteristic velocity has its own risk. That is to say, if the water depth is increased and the velocity at half water depth $U_{1/2h}$ could have less correlation with the average velocity $U_a$ which is experienced by the mimic cylinder. So, it is worthwhile to find another choice of characteristic velocity which could possibly have better correlation with $U_a$ and such choice could be used in a more general way for future studies. The velocity which corresponds to the half height of cylinder is used and has its name as $U_{1/2h}$ in Fig. 4.9. The correlation between $U_{1/2h}$ and $U_a$ is shown by this figure.
Fig. 4.8 Correlation between $U_{1/2h}$ and $U_a$

Fig. 4.9 Correlation between $U_{1/2hv}$ and $U_a$
If $U_{1/2h}$ were chosen as the characteristic velocity in this study, then the correlation coefficient R-squared between $U_{1/2h}$ and $U_a$ would have been up to 0.993, which has a little bit better behaviour if compared to the correlation shown in Fig. 4.8. Hence, it is recommended that the velocity at half cylinder height should be chosen as the characteristic velocity, especially with the deeply submerged vegetation for future studies.

In this study, the velocity at half water depth has been decided as the characteristic velocity in data presentation and discussion afterwards. This choice may not be perfect, but it has been determined not only based on the above analysis but also due to actual circumstances. Since a large number of experimental test conditions shown by Table 3.1 need to be carried out in this study, it is time-saving and financially economical to choose the half water depth as the position in measuring the characteristic velocity. Moreover, the correlation coefficient R-squared between $U_{1/2h}$ and $U_a$ is up to 0.985 and it is reasonable to have the statement that the velocity at half water depth can be regarded as the representative velocity for the averaged velocity.
4.2.2 $C_D$ and $KC$ relation in pure wave

In direct measurement method, the value of $C_D$ is obtained from the measured force and velocity by using Eq. (2-11). For wave conditions in submerged vegetation, the relation between $C_D$ and $KC$ in VD2 is shown as example by Fig. 4.10.

![Fig. 4.10 $C_D$ and $KC$ relation in pure wave for submerged conditions VD2](image1)

In Fig 4.10, the value of $KC$ has the range from 4 to 67. It is obvious to find that the rise-and-fall variation trend of $C_D$–$KC$ within this range of $KC$ number. The values of $C_D$ increase with the increased $KC$ number and the transition point happened around $KC$ equals 8. After that, decreased values of $C_D$ are found. For larger part of $KC$ number, the values of $C_D$ are getting closer to be 1.2. Rise-and-fall variation trend has also been found for emergent conditions. This is shown by Fig. 4.11.

![Fig. 4.11 $C_D$ and $KC$ relation in pure wave for emergent conditions VD2](image2)
While for emergent conditions, it is also clear to find the rise-and-fall variation trend of $C_D$–$KC$ in the range of $KC$ number from 5 to 16. Seen from Fig. 4.11, the rising part of the value of $C_D$ happened for $KC$ being smaller than 10 and decreasing of $C_D$ happened afterwards.

As to the rising part of $C_D$ shown by Figs. 4.10 and 4.11, they are both found for $KC$ number up to 10. While for this range of $KC$ number, the flow separation in oscillatory flows actually experience different flow regimes and they are shown in the first four subplot pictures in Fig. 4.12. As to the last subplot, it indicates that for larger $KC$ number, the oscillatory flow would behave like a unidirectional flow.

![KC increasing](image.png)

**Fig. 4.12 Flow separation regimes and vortex motion in pure wave conditions**

In Fig. 4.12, five subploted pictures are shown to demonstrate individual regime with the increase of $KC$. The black arrows in these pictures represent the instantaneous oscillatory flow direction. While the red arrows inside the pictures represent the corresponding drag force $F_D$. The open circles stand for vortexes and the dashed lines with arrows indicate the direction of shedding vortex motion.

For oscillatory flow, first consider the velocity starts from zero to be larger gradually. After passing the laminar oscillatory flow regimes (the oscillatoiy flow remains attached to the cylinder), the flow separation would occur and vortexes are generated naturally. Seen from the first subplot above, one single-pair vortex (M and N) has been generated and it is going to move away. The single-pair vortex travels in the direction perpendicular to the oscillatory flow and they are named as transverse vortex. Since the pair of vortex travels in the lateral direction, the pressure difference experienced by the cylinder is very limited.

As for the second subplot, the value of $KC$ increases a little bit and the single-pair vortex would travel in oblique direction as a result. The pressure difference, i.e. the drag force experienced by the cylinder would thus increase. After that, double-pair oblique vortexes are generated. This means the pair of vortex M and N have been carried away obliquely while the newly-generated pair of vortex P and Q is about to move away from the cylinder. The drag force shown in the third subplot is larger than that shown previously. From the physics point of view, the drag coefficient $C_D$ is a coefficient which represents the flow resistance experienced by the cylinder. Consequently, $C_D$ would rise with the increased $KC$ in the second and the third subplots.

For the fourth subplot, multiple pairs of vortexes have been generated and they are traveling in parallel direction with the oscillatory flow. So the drag force would become even larger. For the parallel vortex regime, the pairs of vortexes would keep increasing with the increased value of $KC$. The drag force would follow the pace and get larger. However, $C_D$ would not keep rising but instead will reach a peak value. That is because of the fact that the vortexes which had been shed previously, e.g. vortexes M and N were already been carried away from the cylinder, the corresponding pressure difference caused by the carried-away vortexes has little effect on the cylinder itself. After that, see the the last subplot, when $KC$ is increased beyond $KC$~10, the transverse and oblique vortex street will disappear, and the
shed vortices form a vortex street lying parallel to the direction of the oscillatory motion, in much the same way as in steady current. Therefore the drag coefficient in this regime will not change very extensively with $KC$. Or it can also be put in this way. For $KC$ number larger than around 10, for the first half period of the oscillatory flow, the cylinder would experience a downstream flow and the vortexes are generated and be carried away downstream. For the second period of the oscillatory flow on the other hand, the cylinder would experience an upstream flow and the vortexes are generated and be carried away upstream.

From Figs. 4.10 and 4.11, for $KC$ within the range of 4 to 10, the values of $C_D$ would give a rise variation trend and reach a peak value. After that the values of $C_D$ would decrease and converge to 1.

4.2.3 $C_D$ and $KC$ relation in combined current-wave flow

As an example, Fig. 4.13 gives the comparison between the results collected in pure wave conditions and small current velocity in combined current-wave flow condition under VD2.

![Graph showing $C_D$ and $KC$ relation under VD2 in C00W and C05W submerged conditions](image)

In Fig. 4.13, such rise-and-fall variation trend of $C_D$ with $KC$ has been found in C05W condition which is actually the combined current-wave flow with 5cm/s as underlying current velocity. The peak value of $C_D$ happens at around $KC=10$. The transition point of $KC$ number in C05W is close to that in C00W. This finding indicates that the movement of fluid particles as orbital circulations can still be dominating in small underlying current flow. The underlying current only plays a role as a carrier which carries the dominating oscillatory flow and propagates together.

However, for combined current-wave flow conditions with larger underlying current velocities, things could be different. The underlying current would rather not be regarded as a carrier but instead, it can change the flow conditions from oscillatory flow to unidirectional flow around the cylinder. Hence, the relation between $C_D$-$KC$ changes accordingly.
Fig. 4.14 shows relevant results for C15W and C20W as well as C30W under VD2 as an example. Obviously, the values of $C_D$ are quite stable and converge to 1 with the increased values of $KC$.

For underlying current with large velocities in combined current-wave flow conditions, the rise-and-fall variation trend of $C_D$-$KC$ is not found any more. The peak values of $C_D$ collapse. This is due to the fact that the combined current-wave here around the cylinder behaves more like unidirectional flow, i.e. steady current and thus would lead to a gradual decrease of the value of $C_D$ and converge to 1 with further increased $KC$.

In order to have better description about the flow around cylinder in combined current-wave flow conditions, it is necessary to give distinctions between small underlying current velocity and large underlying current velocity in this study. The ratio between the underlying current velocity $U_c$ and orbital velocity $U_w$, meaning $U_c/U_w$, can be used in this distinction. A theory is proposed here. The combined current-wave flow would keep being oscillatory flow if the ratio $U_c/U_w<1$ and therefore, the combined flow would keep being oscillatory flow dominated. While if the ratio $U_c/U_w>1$, it is easy to have the image that the trough velocity of the oscillatory flow would be carried up to be positive value and thus the combined flow has been turned into unidirectional. While for unidirectional flow, then the values of $C_D$ could be close to 1 which is the case found in current conditions.

In addition, the rise-and-fall variation trend of $C_D$-$KC$ has been found also in emergent conditions. Fig. 4.15 presents the experimental data in emergent conditions under VD2 as an example.
For emergent vegetation, the rise-and-fall variation trend of $C_D-KC$ could also be found for C00W and C05W. Similarly, the transition point of the peak value of $C_D$ occurs around $KC=10$. For C05W, the combined current-wave flow still behaves like wave which is oscillatory flow. Due to the existence of underlying current, the peak values of $C_D$ collapse in C05W. With the further increase of current velocity, say in C15W and C20W in this figure, the combined current-wave flow behaves more like unidirectional flow. In these cases, the peak values of $C_D$ collapse much more and the rise-and-fall variation flattens to be close to 1.

4.2.4 $C_D$ and $KC$ relation comparison in different densities

In this study, three different densities of vegetation mimics have been studied and they are named VD1 (62 stems/m²), VD2 (139 stems/m²) and VD3 (556 stems/m²). In order to better demonstrate the experimental data and focus on the variation trend of $C_D-KC$ relation in complicated flow conditions, the experimental data concerning VD2 has been chosen as an example to show in the previous section. But here in this section, the experimental data concerning other densities are presented so as to see if there is any influence on $C_D$ due to the density variation.

Fig. 4.16 shows the data collected in the emergent conditions with C00W and C05W for all densities. It includes the data from pure wave as well as the data from combined current-wave flow with small underlying current. As analysed before, the flow of C00W and C05W is oscillatory dominated. The rise-and-fall variation trend of $C_D-KC$ could be found and the transition point occurs at around $KC=10$. In addition, such variation trend has been found in all three densities. In this figure, the data points from VD1 and VD2 and VD3 are close to each other and the density influence could not be seen.

Fig. 4.17 also shows the data collected in the emergent conditions for all densities for waves combined with large currents C15W and C20W. In these cases, the combined current-wave flow behaves similar to current. The values of $C_D$ collapse and are found flattened to be close to 1. Such collapse of peak value and flattening phenomena could be found in all the three densities.
For submerged conditions, two figures are presented here to show the possible density influence. Fig. 4.18 gives the view of the data collected in C00W and C05W for all densities in submerged conditions. As expected, the rise-and-fall variation trend of $C_D$-$KC$ is found. In addition, this kind of variation has been found in all the three densities.
As to Fig. 4.19, the data collected in submerged conditions for all densities have been presented, for C15W and C20W and C30W. In these cases with large underlying current in the combined current-wave flow conditions, the flows behave comparable to that in current. Thus, collapse of the peak values of $C_D$ and flattening behaviour of $C_D$ with $KC$ could be found.

Fig. 4.18 $C_D$ and $KC$ relation in submerged conditions with C00W and C05W for all densities

Fig. 4.19 $C_D$ and $KC$ relation in submerged conditions with C15W C20W C30W for all densities
In this study, three vegetation densities have been used to study the possible density influence of $C_D$ in multiple cylinders. The sparse vegetation density is 62 stems/m$^2$ and the middle density is 139 stems/m$^2$ while the highest density is 556 stems/m$^2$. Although the density has been increased for nine times, it is still difficult to see any remarkable density influence on $C_D$ in this study. Thus, the theory stated in previous section should be used to give possible explanations.

As stated in Section 2.8, the non-dimensional parameter $2a/S$ could be used to find out the possible influence of vegetation density on $C_D$. Fig. 4.20 shows the behaviour of $C_D$ in different densities for emergent vegetation. The data collected in pure wave (C00W) together with C05W are shown in Fig. 4.20. The horizontal coordinate is $2a/S$. Since there is a connection between $KC$ and $2a/S$ shown by Eq. (2-26), the rise-and-fall variation trend in oscillatory-dominated flow are also shown in this figure. For different vegetation densities, the spacing distance $S$ could be related to the cylinder diameter $d$. $S=18d$ for VD1 and for VD2 and VD3, $S=12d$ and $S=6d$ respectively.

In addition, for the same wave case, the value of $2a/S$ would increase with the increased vegetation density due to the fact that the spacing distance $S$ is becoming smaller for larger density vegetation.

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![Diagram](image.png)

Fig. 4.20 $C_D$ and $2a/S$ relation in C00W and C05W for emergent vegetation

It is found that the values of $C_D$ have not been influenced by the changed vegetation density for emergent vegetation. As is shown by the purple arrows in this figure, there is almost no change of the range of the values of $C_D$ in three different densities. In fact all the data points are located for $2a/S<1$. According to the theory stated by Suzuki (2012), no drag reduction would be observed if $2a/S<1$. It is reasonable not to observe any drag reduction in this range in this study.

As to the results for submerged vegetation, they are shown in Fig. 4.21. For the other data points which are located for $2a/S>1$, however, the values of $C_D$ are not significantly reduced. This phenomenon does not agree with the theory proposed by Suzuki (2012).
In order to explain this phenomenon, it is necessary to know the flow conditions around the cylinder by checking the value of $KC$ when $2a/S=1$. For VD1 the spacing distance is 0.18m and based on Eq. (2-6), i.e., $KC=2\pi a/d$, the corresponding value of $KC$ can be calculated and $KC$ is 57. For VD2, $2a/S=1$ makes the value of $KC$ is 38 while for VD3, the value of $KC$ is 19. As stated in Section 4.2.2, the vegetation cylinder would experience the oscillatory flow much the same way as unidirectional flow if the value of $KC$ is larger than 10. Hence in this study, for pure wave C00W and combined flow C05W with $2a/S>1$, the flow behaves similar to unidirectional flow and could be possibly regarded as current. While for current condition, it is only possible to have drag reduction as long as the layout of vegetation mimics is comparable to the layout shown by Nepf (1999). Based on Fig. 2.14 the drag reduction would be found only if $T/d<2$, however, it is not the case for this study.

![Graph showing $C_D$ and $2a/S$ relation in C00W and C05W for submerged vegetation](image)

Fig. 4.21 $C_D$ and $2a/S$ relation in C00W and C05W for submerged vegetation

As can be seen from Table 3.1, in all the test conditions of this study, the minimum value of $T/d$ is 3. However, according to Nepf (1999), the drag reduction is only possible to be observed only if $T/d \leq 2$. Hence for pure wave (C00W) and C05W with $2a/S$ larger than 1, the flow would behave much the same way as the unidirectional flow. It is reasonable to have found out that there is almost no drag reduction. Because the layout of vegetation mimics in this study does not meet the requirement.

For the combined current-wave flow conditions with larger underlying current velocities, the flow would keep behaving similar to unidirectional flow. Since the minimum value of $T/d$ is 3 which is still larger than the range of possible density influence which requires $T/d<2$, there is almost no drag reduction in combined current-wave flow with larger underlying current velocities, e.g., C15W, C20W, C30W. Figs. 4.22 and 4.23 show the data points collected in these test conditions. Although the data points of $C_D$ were collected from different densities, they are close to each other. That is to say, the density influence is not obvious based on the results in this study.
Fig. 4.22 $C_D$ and $2a/S$ relation in combined current-wave flow for emergent vegetation

Fig. 4.23 $C_D$ and $2a/S$ relation in combined current-wave flow for submerged vegetation
Chapter 5

Discussion

5.1 $C_D$–KC relation in pure wave conditions

In this study, the rise-and-fall variation trends of $C_D$ with $KC$ in pure wave have been found for multiple vegetation mimics. Such findings have been observed based on the results from both the calibration approach and direct measurement method. As to previous studies, monotonous variation trends of $C_D$ with $KC$ were found (Mendez and Losada (2004), Augustin et al., (2009)). Hence, it is necessary to have discussion about such contradictory phenomena and get more insights.

Since quite a large value of $b_v$ was used in calculating its $KC$ number by Mendez and Losada (2004), the corresponding value of $KC$ was greatly underestimated. Although small $KC$ numbers were there, as a matter of fact, they should have been larger if proper choice of the value of $b_v$ had been made. That means if the value of $b_v$ had been chosen as the width of single leaf or the stem width which is at least 15 times narrower compared to the total width of all the leaves, then the obtained value of $KC$ number would have been 15 times larger.

Based on this deduction, it can be concluded that range of $KC$ number studies in Mendez and Losada (2004) had not truly included small $KC$ numbers. The transition point of the variation trend could happen at small $KC$ numbers (around 10), however in fact, it had not been included. Naturally, it was a matter of certain to have monotonous variation trend of $C_D$ with $KC$ by Mendez and Losada (2004).

Also as mentioned before, according to Augustin et al., (2009), the diameter of vegetation mimics was 0.012m and it was actually very close to 0.01m of the wooden cylinder diameter used in this study. However, the values of $KC$ number only started from 40 in Augustin et al., (2009) and that means small $KC$ numbers (around 10) had not been included either. Consequently, it was reasonable to also get monotonous trend of $C_D$ with $KC$ by Augustin et al., (2009).

Therefore the previous studies both from Mendez and Losada (2004) and by Augustin et al., (2009) had not covered the range of small $KC$ numbers, say smaller than 10. As a result, the transition point of the rise-and-fall variation trend had not been included in previous studies. Due to such shortage about the experimental data, they did not see the whole picture of $C_D$-$KC$ and hence it was impossible for them to have a general conclusion.
5.2 $C_D$–$KC$ relation in combined current-wave flow conditions

As stated in Section 1.2, no previous study concerning the variation trend of $C_D$ with $KC$ has been obtained in combined current-wave flow conditions.

In this study, different underlying current velocities have been generated in the combined current-wave flow. For small underlying current, say C05W, the combined flow is still dominated by the oscillatory flow. Thus the increase of $KC$ would lead to similar vortexes motion and similar evolution of the pressure difference experienced by the cylinder in this kind of combined current-wave flow conditions. Consequently, the rise-and-fall variation trend of $C_D$–$KC$ could be found. In addition, the peak value of $C_D$ usually occurs at around $KC=10$, which is also the case found in C00W. But due to the existence of underlying current, the peak value of $C_D$ would decrease a little bit, as is shown by Fig. 4.15. After reaching the peak value, $C_D$ would slightly decrease with further increase of $KC$ and converge to 1.

However, for underlying current with large flow velocities, say C15W, C20W and C30W, the oscillatory flow could not be dominant any more.

Due to the large underlying current velocity, the flow field around the cylinder looks more likely that in current conditions and the vortexes are shed unidirectionally. This is easy to understand since the negative direction of the oscillatory flow has been ‘compensated’ by the underlying current. During the entire period of the combined current-wave flow, the velocity keeps to be unidirectional which is quite similar to current conditions.

As for current conditions in vortex shedding regimes, the value of $C_D$ would for sure collapse and being close to 1.

5.3 Influence of vegetation density and relative vegetation height

As shown from Fig. 4.16 to Fig. 4.23, in this study three vegetation densities and two relative vegetation heights have relatively small effect on the variation trend of $C_D$–$KC$. For all densities the value of $C_D$ would converge to 1 and these phenomena have been found in both relative vegetation heights.

Moreover, the values of $C_D$ have not been significantly affected even with $2a/S>1$. The reason is that for the test condition with $2a/S>1$, the corresponding value of $KC$ is also large enough for the oscillatory flow to behave like a unidirectional flow. Then it is necessary to use the theory stated by Nepf (1999) to see if $C_D$ would be influenced due to “sheltering effect”. That is to say, the ratio of $T/ld$ which indicates the vegetation layout becomes more important. If $T/ld$ is larger than 2, no matter how large the value of $2a/S$ is, the downstream cylinder is not affected by the wake generated from upstream cylinder. Hence, almost no drag reduction would happen.

As to the variation of relative vegetation heights in this study, for a given value of $KC$, the change of relative vegetation height does not influence the flow regimes around the cylinder.

For submerged vegetation with the relative vegetation height $\alpha=0.73$, the velocities within the vegetation canopy has limited variation under different designed current velocities. According to the figures shown in Appendix C the flow velocities above the canopy are usually much influenced by the variation of current velocity, however, the velocities within the vegetation canopy do not have enough change to affect the flow regimes around the cylinder. That may be due to the rigidity of the wooden rods vegetation mimics which restricts the penetration of the flow above the canopy into the canopy.
5.4 Different methods to derived $C_D$

In this study, two methods were used in processing the measured data, including the data collected in waves as well as those collected in combined current-wave flow conditions. One of the methods is the calibration approach which had been commonly used in previous studies (e.g. Mendez and Losada, 2004; Sanchez-Gonzalez et al., 2011; Augustin et al., 2009; Jadhav and Chen, 2012; Bradley and Houser, 2009; Koftis et al., 2013; Hu et al., 2014). While the other is the direct measurement method which had only been used by Hu et al. (2014) in such complicated hydrodynamics. In this work, the author was also participated and involved.

The results concerning the variation trend of $C_D$-$KC$ in different hydrodynamics and vegetation mimic densities were shown in Chapter 4. For the same measured data, the results obtained from the two methods have something in common and also something different. It is necessary to have discussion about the applicability of these two methods in this chapter.

For the results obtained by these two methods in wave conditions (C00W), the same variation trend of $C_D$-$KC$ has been found. Such variation trend is rise-and-fall of the value of $C_D$ with the increase of $KC$ for small $KC$ numbers.

For the results obtained by the two methods in combined current-wave flow conditions (CW), they are more complicated. For example, as to calibration approach, the results shown in Fig. 4.5 are obvious that the values of $C_D$ could be much larger with the increase of underlying current velocity. The damping effect of current was wrongly lumped into the calibrated drag coefficient and that is why it is not recommended to use the calibration approach to obtain $C_D$ in combined current-wave flow conditions.

It should be noticed that for relatively small underlying current velocity conditions (say, C05W), the calibration approach could also possibly obtain the rise-and-fall variation trend of $C_D$-$KC$, see Fig. 4.4. Because for underlying current with relatively small velocity, the movement of the fluid particles as orbital circulations still dominates. Hence, the physical regimes for pure wave conditions and combined current-wave flow with small underlying current velocity are similar to each other. For the sake of safety in data process, calibration approach should not be used in combined current-wave flow conditions.

Hence in this study, the results obtained from the two methods have common in presenting the variation trend of $C_D$-$KC$ in pure wave. For the combined current-wave flow conditions, however, the direct measurement method should be used while the calibration approach is not recommended. As to the application of the direct measurement method, the average velocity which is actually experienced by the vegetation mimics should be used.
Chapter 6
Conclusions

1. In this study, the rise-and-fall variation trends of $C_D$ with $KC$ in pure wave conditions have been found for multiple vegetation mimics for small $KC$ values, which is consistent with $C_D$-$KC$ for single vegetation mimic. The rise part of $C_D$ corresponds to the values of $KC$ from around $KC$=3 to 10. Typically transition points occur at about $KC$=10. Beyond this point, the values of $C_D$ would decrease and converge to be 1.

2. For the combined current-wave flow conditions, the $C_D$-$KC$ relations have different characteristics depending on the relative importance of wave and current flow. For small underlying current in this study, the combined flow behaves similar to oscillatory-dominated flow and the rise-and-fall variation trend could also be observed. The transition points also occur at about $KC$=10. But the peak value of $C_D$ would drop. While for other current-wave conditions, the peak value of $C_D$ would collapse even more so that no rise-and-fall variation trend could be shown any more. Instead, the values of $C_D$ are flattened and close to 1 for the combined current-wave flow with large underlying current velocity.

3. According to the experimental data from this study, the possible influence on $C_D$ caused by vegetation density ($N$) and relative vegetation height ($\alpha$) have not been observed.

4. Direct measurement method is applicable in both pure wave and combined current-wave flow conditions. In this method, it is important to use the averaged velocity actually experienced by vegetation in the $C_D$ quantification. As to the calibration approach which has been used in previous studies, e.g. Mendez and Losada (2004), it is not recommended to be applied in the combined current-wave flow conditions.
Chapter 7

Recommendations

1. In this study, the range of $KC$ from 3 to 10 made it possible to observe the rise-and-fall variation trend of $\frac{KC}{\text{fr}}$. In this study, a linear relation between $C_D$ and $KC$ has been derived so as to be handy in application for future studies. However as far as the quantity of the data points within this range of $KC$, more data points should be collected so as to derive a better-correlated function to describe the rise-part of $C_D$ with $KC$.

2. According to Sarpkaya (1976) and Sumer and Fredsøe (2006), for $KC$ smaller than 2 in pure wave, the oscillatory flow would remain attached to the cylinder and the flow is a kind of oscillatory laminar flow. Since the flow regime is laminar, $C_D$ should decrease with increase $KC$ which is similar due to classic relation between $C_D-\text{Re}$ found in laminar flow. It should be noticed that it is extremely difficult to directly measure the force experienced by the cylinder in laminar oscillatory flow regime in this study and the relevant data were not able to be collected. For future studies it would be possible to collect the data if the drag force sensors are more precise and sensitive so as to measure the force and the oscillatory flow velocities are extremely small around the cylinder and make the flow remain attached. Maybe such extreme small velocities could be possibly generated in the oil liquid which has higher viscosity. If the data concerning the relation between $C_D$ and $KC$ are collected in oscillatory flows, then the picture about the relation would be more general and more convincing as well.

3. According to this study, the direct measurement method better reflected the force and velocity experienced by the cylinder in oscillatory flows and $C_D$ could be derived from Morison equation. However, the value of $C_D$ is very sensitive to the characteristic velocity used in the definition since $C_D$ is inversely proportional to the square of the characteristic velocity. That is to say, the choice of characteristic velocity should be very careful so as to prevent the values of $C_D$ from being contaminated and biased. In fact, the average velocity experienced by the cylinder should be chosen as the characteristic velocity. Luckily in this study the velocity at half water depth is highly correlated with the averaged velocity experienced by the cylinder. Consequently, the errors of $C_D$ obtained from direct measurement have been limited as much as possible. To be honest, that choice is a compromised choice. The three EMS are designed to measure the velocity at one vertical position and consequently not able to provide the data for vertical velocity profile. So for future studies, it is recommended to use ADV (Acoustic Doppler Velocimetry) or ADCP (Acoustic Doppler Current Profiler) to obtain the instantaneous velocity profile data. The averaged velocity experienced by the vegetation mimics could be calculated afterwards. It is handy and time-saving in collecting the data in laboratory experiments by using ADV or ADCP as long as they are properly installed and do not strongly affect the propagation of pure wave or combined current-wave flow in the flume.

4. As to the density influence of the vegetation drag, it is recommended to design the layout of the vegetation mimics for higher density with $T/d<2$ for future studies. With such design of the layout, it is possible to observe drag reduction in multiple vegetation mimics. However, it is desired to have greater wave damping capacity in engineering application in coastal protection. Thus, any kind of drag reduction in coastal protection should be avoided. That is to say, $T/d=2$ may be a critical value to have possible drag reduction. It is recommended to do further studies concerning this topic about the vegetation density influence on $C_D$. As to the influence of relative vegetation height ($\alpha$) on $C_D$, only two values of were applied in this study. Based on the results collected in
this laboratory study, there is little effect for the values of $C_D$ by changing the relative vegetation height $\alpha$. Hence, it is recommended to cover larger range of $\alpha$ for future studies.

5. In this study, the rigid wooden rods cylinders had been used as vegetation mimics. Generally speaking, it is always good to start from simple substitutes for vegetation in order to understand the physical process. But afterwards for future studies, it would be better if real vegetation plants could be used in the laboratory study so as to obtain the data and conclusions which are more practical in engineering application.
Reference


Yan Ni (2014). Laboratory investigations on the drag coefficient of cylinder subjected to wave motion. Additional master thesis from Delft University of Technology.


Appendix A—Calibration of wave gauges

Six wave gauges were used in doing the measurement of wave height before and along as well as after the vegetation mimics. The names of the six wave gauges in the longitudinal directions are as follows: G18 G22 G20 G21 G23 G27. Each wave gauge consists of two parallel stainless steel rods and these rods act as the electrodes of an electric resistance meter. By measuring the electrical resistance of the ‘dry’ part of the wire the water surface elevation can be obtained.

Calibration of six wave gauges:

- **Calibration of G18 wave gauge**
  - \( y = 2.363x - 0.075 \)
  - \( R^2 = 0.999 \)

- **Calibration of G22 wave gauge**
  - \( y = 2.518x + 0.013 \)
  - \( R^2 = 1 \)

- **Calibration of G20 wave gauge**
  - \( y = 2.467x - 0.040 \)
  - \( R^2 = 0.999 \)

- **Calibration of G21 wave gauge**
  - \( y = 2.349x - 0.063 \)
  - \( R^2 = 1 \)

- **Calibration of G23 wave gauge**
  - \( y = 2.297x - 0.12 \)
  - \( R^2 = 0.999 \)

- **Calibration of G27 wave gauge**
  - \( y = 2.210x - 0.117 \)
  - \( R^2 = 0.999 \)
## Appendix B—Error analysis of $C_{\text{drag}}$ in calibration approach

### Error analysis of drag coefficient obtained from calibration approach under pure wave conditions (C00W)

<table>
<thead>
<tr>
<th></th>
<th>Absolute measurement error in wave height (m)</th>
<th>Relative error in the value of $C_{\text{drag}}$ (%)</th>
<th>Value of $C_{\text{drag}}$ in VD1 (C00W)</th>
<th>Absolute measurement error in $C_{\text{drag}}$ in VD1 (C00W)</th>
<th>Value of $C_{\text{drag}}$ in VD2 (C00W)</th>
<th>Absolute measurement error in $C_{\text{drag}}$ in VD2 (C00W)</th>
<th>Value of $C_{\text{drag}}$ in VD3 (C00W)</th>
<th>Absolute measurement error in $C_{\text{drag}}$ in VD3 (C00W)</th>
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Fig. B.1 Error analysis of drag coefficient obtained from calibration approach in C00W
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<td>Absolute measurement error in wave height (m)</td>
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<td>Wave height in each wave case (m)</td>
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<td>Relative error in the value of $C_{d,cal}$ (%)</td>
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<td>Value of $C_{d,cal}$ in VD1 (C0SW)</td>
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<td>Absolute measurement error in $C_{d,cal}$-VD1 (C0SW)</td>
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<td>Value of $C_{d,cal}$ in VD2 (C0SW)</td>
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Fig. B.3 Error analysis of drag coefficient obtained from calibration approach in C15W

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<td>Absolute measurement error in $C_{2, cal}$-VD2 (C20W)</td>
<td>0.506</td>
<td>0.265</td>
<td>0.115</td>
<td>0.085</td>
<td>0.043</td>
<td>0.043</td>
<td>0.028</td>
<td>0.031</td>
<td>0.021</td>
<td>0.013</td>
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<tr>
<td>Value of $C_{2, cal}$ in VD3 (C20W)</td>
<td>5.711</td>
<td>2.808</td>
<td>1.867</td>
<td>1.245</td>
<td>0.937</td>
<td>0.987</td>
<td>0.613</td>
<td>0.808</td>
<td>0.634</td>
<td>0.449</td>
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<tr>
<td>Absolute measurement error in $C_{2, cal}$-VD3 (C20W)</td>
<td>0.286</td>
<td>0.096</td>
<td>0.047</td>
<td>0.025</td>
<td>0.016</td>
<td>0.016</td>
<td>0.008</td>
<td>0.011</td>
<td>0.008</td>
<td>0.003</td>
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## Error analysis of drag coefficient obtained from calibration approach under combined current-wave flow conditions (C30W)

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<tr>
<td>Absolute measurement error in wave height (m)</td>
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<tr>
<td>Wave height in each case (m)</td>
<td>0.04</td>
<td>0.06</td>
<td>0.08</td>
<td>0.1</td>
<td>0.12</td>
<td>0.12</td>
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<td>0.18</td>
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<td>Relative error in the value of $C_{D,cw}$ (%)</td>
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<td>Value of $C_{D,cw}$ in VD1 (C30W)</td>
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<tr>
<td>Absolute measurement error in $C_{D,cw}$-VD1 (C30W)</td>
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<tr>
<td>Absolute measurement error in $C_{D,cw}$-VD2 (C30W)</td>
<td>0.713</td>
<td>0.322</td>
<td>0.137</td>
<td>0.08</td>
<td>0.057</td>
<td>0.026</td>
<td>0.022</td>
<td>0.021</td>
<td>0.031</td>
<td>0.026</td>
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<tr>
<td>Value of $C_{D,cw}$ in VD3 (C30W)</td>
<td>6.493</td>
<td>4.807</td>
<td>3.25</td>
<td>1.631</td>
<td>1.256</td>
<td>1.237</td>
<td>0.933</td>
<td>0.886</td>
<td>0.973</td>
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<td>Absolute measurement error in $C_{D,cw}$-VD3 (C30W)</td>
<td>0.325</td>
<td>0.16</td>
<td>0.081</td>
<td>0.053</td>
<td>0.021</td>
<td>0.021</td>
<td>0.012</td>
<td>0.012</td>
<td>0.013</td>
<td>0.007</td>
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</table>
Appendix C—Measured velocity profiles

Fig. C1 Velocity profile for wave1016_1_C00W_VD1

Fig. C2 Velocity profile for wave1016_2_C00W_VD1
Fig. C3 Velocity profile for wave1016_1_C15W_VD1

Fig. C4 Velocity profile for wave1016_2_C15W_VD1
Fig. C5 Velocity profile for wave1016_1_C00W_VD2

Fig. C6 Velocity profile for wave1016_2_C00W_VD2
Fig. C7 Velocity profile for wave1518_1_C00W_VD2

Fig. C8 Velocity profile for wave1518_2_C00W_VD2
Fig. C9 Velocity profile for wave1016_1_C05W_VD2

Fig. C10 Velocity profile for wave1518_1_C05W_VD2
Fig. C11 Velocity profile for wave1016_1_C15W_VD2

Fig. C12 Velocity profile for wave1518_1_C15W_VD2
Fig. C13 Velocity profile for wave1016_1_C20W_VD2

Fig. C14 Velocity profile for wave1518_1_C20W_VD2
Fig. C15 Velocity profile for wave1016_1_C30W_VD2

Fig. C16 Velocity profile for wave1518_1_C30W_VD2
Fig. C17 Velocity profile for wave1016_1_C00W_VD3

Fig. C18 Velocity profile for wave1016_2_C00W_VD3
Fig. C19 Velocity profile for wave1518_1_C00W_VD3

Fig. C20 Velocity profile for wave1518_2_C00W_VD3
Fig. C21 Velocity profile for wave1016_1_C05W_VD3

Fig. C22 Velocity profile for wave1016_2_C05W_VD3
Fig. C23 Velocity profile for wave1518_1_C05W_VD3

Fig. C24 Velocity profile for wave1518_2_C05W_VD3
Fig. C25 Velocity profile for wave1016_1_C15W_VD3

Fig. C26 Velocity profile for wave1016_2_C15W_VD3
Fig. C27 Velocity profile for wave1518_1_C15W_VD3

Fig. C28 Velocity profile for wave1518_2_C15W_VD3
Fig. C29 Velocity profile for wave1016_1_C20W_VD3

Fig. C30 Velocity profile for wave1016_2_C20W_VD3
Fig. C31 Velocity profile for wave1518_1_C20W_VD3

Fig. C32 Velocity profile for wave1518_2_C20W_VD3