Experimental study on wave attenuation by vegetation by means of particle imaging velocimetry

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Abstract

Coastal vegetation serves as an ecological defense and plays an important role when facing marine disaster such as storm surge. In this study, we investigated experimentally the wave attenuation, including wave height and wave force decay, and flow field within rigid vegetation by means of particle imaging velocimetry (PIV). Drag coefficient of vegetation is closely related the wave attenuation by vegetation. Based on Morison equation, a new modified direct measurement method to derive the drag coefficient of vegetation was proposed in this study. This method can eliminate the potential errors and obtain more accurate drag coefficient to have a well-fitted relationship with Reynolds number compared with the previous methods. More importantly, we showed the flow field including instantaneous velocity field in different wave phase within the vegetation and turbulent kinetic energy (TKE) field to describe the mechanisms of wave energy dissipation. In addition, a prediction model to reproduce the instantaneous TKE was proposed by the work input of vegetation. The results illustrated that all these characteristics of parameters can help us understand the effect of the coastal vegetation on wave attenuation better.

Keywords: wave attenuation; rigid vegetation; particle imaging velocimetry; modified direct measurement method; drag coefficient; turbulent kinetic energy; prediction model

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**1. Introduction**

Reducing marine disasters through ecological barriers is attracting more and more attention. Costal aquatic vegetation, such as mangroves and seagrasses are playing the extremely important role in terms of resisting various marine dynamic conditions (FitzGerald et al., 2008; Maza et al., 2015). They can not only protect the shoreline from erosion by attenuating the energy of waves and tidal currents, but also reduce sediment resuspension and promote siltation (Möller et al., 1999). What’s more, they are especially competitive with traditional breakwaters in coastal areas because vegetation can improve water quality and ecological environment.

Wave-vegetation interaction is a complex hydrodynamic process. Previous laboratory and field studies have indicated that flow resistance induced by vegetation can reduce water velocity and dissipate hydrodynamic energy when the flow penetrated into the vegetation field (Loder et al., 2009; Luhar and Nepf, 2016; Wamsley et al., 2010). This is mainly due to the drag force caused by vegetation, which induced the reduction of wave height and wave orbital velocity. The wave reflection by vegetation is also in existence especially for dense stem density, but the reflection coefficient is relatively small and considered negligible (Anderson and Smith, 2014). The performance of wave attenuation by vegetation is influenced by various conditions including plant characteristics and incident wave conditions (He et al., 2019). Previous studies point out that higher values including incident wave height, wave frequency, stiffness, stem density and the submergence ratio (the ratio of plant height to water depth) show better wave-damping effect (Anderson and Smith, 2014; Huang et al., 2011; Ozeren et al., 2014; Paul et al., 2012). The gesture of blades for flexible meadow is also important. Luhar and Nepf (2011) provided two dimensionless parameters: Cauchy number $Ca$ and buoyancy parameter $B$ to describe the blade motion and the effective blade length, which defined as the length of rigid plant generate same forces, was used to characterize the wave energy dissipation by flexible sea grasses.

Knowledge of wave energy dissipation by vegetation were required to provide a universally accepted methodology that can evaluate and predict the wave attenuation accurately. In most of past studies, the bulk drag coefficient ($C_D$) of rigid and flexible vegetation based on Morison equation (Morison et al., 1950) were used to make a prediction for wave damping. The $C_D$ can be obtained and fitted with various dimensionless parameters in order to establish empirical relations to predict the wave...
height, water velocity and wave force in vegetation areas. Hence, the selection of method for deriving the values of $C_D$ affects the accuracy of prediction results and the applications. Dalrymple et al. (1984) provided the analytical wave decay model assuming the plant as vertical rigid cylinder combined the linear wave theory with conservation of energy. Kobayashi et al. (1993) showed exponential decay as wave propagating in vegetation field based on the momentum conservation equation and continuity equation. Then Mendez and Losada (2004) made some extensions considering the bottom and random waves. Numerous existing studies have studied wave-vegetation through the above calibration method which the $C_D$ can be calculated by the wave height reduction along vegetation, and gave various relationships of $C_D$ and Reynolds number $Re$, Keuglan-Carpenter number $KC$, and Ursell number $Ur$ for pure waves (Anderson and Smith, 2014; Bradley and Houser, 2009; Lou et al., 2018; Ozeren et al., 2014). According to these functions, the wave parameters in vegetation field can be deduced back. The merit of this method is easy to implement and the required measurement wave height along the vegetation can be easily obtained. But it relied too much on the fitting results of measurements, and the actual wave nonlinearity and wave reflection can lead to inaccurate evaluation of $C_D$ and induce model loss. What’s more, this model can not be used to combined wave-current condition. Losada et al. (2016) put forward a new analytical formulation of wave decay under combined waves and both following and opposing currents considering the Doppler Effect. In addition to these analytical calibration methods, the direct measurement methods were proposed in recent years. Infantes et al. (2011) have measured the flow velocity and total force exerted on the sea grass and to derive the $C_D$. Husrin et al. (2012) experimentally investigated the $C_D$ of mangrove forests for various densities in the condition of solitary wave. Hu et al. (2014) carried out extensive experiments to derive the values of time-averaged $C_D$ by direct force measurement method considering the conditions combined wave-current. In previous studies, $C_D$ values deriving by direct measurement method depended on both the total force on single plant and flow velocity at a point in front of plant. Considering that Morison equation is a form of vertical integration along a cylinder, this method can lead to inaccurate evaluation of $C_D$ values of vegetation. Chen et al. (2018) indicated that determining and choosing $C_D$ was an important subject to fit and predict wave height reduction by either calibration or direct measurement approach.
To reveal the wave energy dissipation by canopies better, many studies have also been carried out on the flow characteristics in vegetation areas. Wang et al. (2016) employed 2D PIV technique to measure the velocity distributions inside the rigid canopy region effected by solitary wave. Lou et al. (2018) revealed the distributions of turbulent kinetic energy (TKE) within vertically varying vegetation in the condition of waves, currents and wave-current flow. The canopy can generate turbulence and the magnitude of turbulence depends on the stem density. Pujol et al. (2013) observed the vertical TKE profiles in different species of submerged vegetation under the oscillatory flow. Both the canopy morphology and wave condition influence the turbulence generation. Ros et al. (2014) investigated the TKE variation with and without vegetation for different wave frequencies by a set of experiments. The TKE varied with wave frequency and there are differences between rigid and flexible vegetation. A better understanding of TKE in vegetation area can help to know wave-vegetation interaction and prediction of sediment deposition within canopy (Tinoco and Coco, 2018). Zhang et al. (2018) experimentally measured the velocity profiles within model flexible vegetation and provided a method to predict TKE inside vegetation field. In previous studies on TKE within vegetation, none have proposed the whole TKE field around plant in various wave conditions. The turbulence within vegetation can be associated with the vegetation drag (Nepf, 1999). It’s significant to propose an instantaneous turbulent kinetic energy prediction model based the drag force induced by vegetation for better knowledge of wave energy dissipation and sediment mobilization within vegetation.

In this study, the wave attenuation by vegetation under regular waves was investigated by means of PIV technique. Firstly, the wave height and force decay were analysed for different wave conditions. Combining the wave force exerted on a single plant with the vertical flow profile, a modified direct measurement method was proposed to derive more reasonable and accurate drag coefficients of vegetation. Then the $C_D$ was fitted with the characteristic Reynolds number. In addition, the velocity field in each phase and TKE field within vegetation were also shown to elucidate how the vegetation impact the incident waves and quantified to make a better understanding for wave attenuation by vegetation. Finally, based on the turbulent kinetic energy budget reduces to a balance between wake production and viscous dissipation (Nepf, 1999), we proposed an instantaneous turbulent kinetic energy prediction model to reproduce the variation of turbulence.
2. Theory

The interaction between waves and vegetation is a complicated hydrodynamic process due to the spatial and temporal variation of force and velocity in the vegetation area. To better describe and quantify the interaction between vegetation and waves, the drag coefficient can be derived and fitted with various dimensionless parameters in order to predict wave height reduction along the vegetation. In previous studies, various methods of calculating drag coefficient were put forward based on Morison equation (Morison et al., 1950), including analytical calibration method and direct force measurement. These methods were simplified by many theoretical assumptions, neglecting the nonlinearity under the actual wave conditions, and might not calculate the value of drag coefficient accurately. Combined the 2D PIV technique with force measurement, we proposed a modified direct measurement method for accurate measurement of drag coefficient.

2.1. Analytical calibration method

When waves propagating through the vegetation zone, assuming energy loss is entirely caused by vegetation. According to the conservation of energy, the wave energy dissipation induced by vegetation is equal to the gradient of the average energy flux along the vegetation, which can be given by:

$$
\varepsilon_D = -\frac{\partial E_c}{\partial x}
$$

where the $E$ is the wave energy density, $c_g$ is the group wave velocity, the $\varepsilon_D$ is the vegetation-induced average energy dissipation rate per wave length. Approximating the vegetation area as an array of rigid, vertical cylinders, based on the linear wave theory and Morison equation, ignoring the effect of vertical force and inertia force, Dalrymple et al. (1984) shown the $\varepsilon_D$ as:

$$
\varepsilon_D = \frac{1}{T} \int_{-h}^{+h} \rho C_D Du \|u\| dz dt
$$

where $T$ is wave period, $h$ is water depth, $\alpha$ is the ratio of submergence, which was defined as $h_r/h$, it represents the ratio of plant height ($h_r$) and water depth ($h$). The $\rho$ is the density of water, $C_D$ is the bulk drag coefficient of plant, $D$ is the stem diameter, $u$ is the wave orbital velocity in the horizontal direction, which can be derived by linear wave theory:
\[ u = \frac{H_i}{2} \frac{\omega \cosh(\alpha k h)}{\sinh(k h)} \cos(kx - \omega t) \]  

(3)

where \( H_i \) is the incident wave height, \( \omega \) is the angular frequency, \( k \) is wave number, \( kx - \omega t \) is phase angle.

By combining the above equations, Dalrymple et al. (1984) given a rational function attenuation trend of wave height in vegetation field:

\[ K_x = \frac{H(x)}{H_i} = \frac{1}{1 + \beta x} \]  

(4)

where \( K_x \) is the relative wave height at \( x \) from the beginning of vegetation, \( H(x) \) is wave height located at \( x \), the \( \beta \) is the wave damping factor, which can be derived from:

\[ \beta = \frac{4C_D}{9\pi} H_i NDk \frac{\sinh^3 kh_i + 3 \sinh kh_i}{\sinh kh (\sinh 2kh + 2kh)} \]  

(5)

Based on the Eq. (4) and Eq. (5), the bulk drag coefficient of vegetation can be worked out by means of calibration method.

For general waves, the instantaneous velocity \( u_i \) can be decomposed into three items as:

\[ u_i = u_c + u_w + u' \]  

(6)

the \( u_c \) is the time-averaged velocity which can be obtained as (Lowe et al., 2005):

\[ u_c = \frac{1}{2\pi} \int_0^{2\pi} u_i(\phi) d\phi \]  

(7)

here the \( u_i(\phi) \) denotes the instantaneous velocity as a function of wave phase, the \( u_w \) is the wave orbital velocity at each depth and predicted by second order wave theory in this study:

\[ u_w = \frac{H_i}{2} \frac{\omega \cosh(\alpha k h)}{\sinh(k h)} \cos(kx - \omega t) + \frac{3}{16} \frac{H_i^2 \omega k \cosh(2\alpha k h)}{\sinh^2 k h} \cos 2(kx - \omega t) \]  

(8)

The vertical turbulent velocity \( v' \) is obtained similarly, then the instantaneous two-dimensional turbulent kinetic energy \( TKE(\phi) \) was given by:

\[ TKE(\phi) = \frac{1}{2} [u(\phi)^2 + v(\phi)^2] \]  

(9)

the turbulent kinetic energy \( TKE \) is time-averaged \( TKE(\bar{\phi}) \) during a wave cycle.
2.2. Direct force measurement method

Hu et al. (2014) indicated that the accuracy of $C_D$ values derived by the model calibration were unreliable when the measurement results calibrated against wave decay model poorly, by measuring the total force impact on vegetation and velocity at mid water depth in its research, they given the direct force measurement method.

Because model vegetation was approximated to rigid cylinder, the total force can be expressed by Morison equation (Morison et al., 1950):

$$F = F_D + F_M = \frac{1}{2} \rho C_D h_s D u(t) |u(t)| + \frac{1}{4} \rho C_M \pi h_s D^2 \frac{\partial u(t)}{\partial t}$$ \hspace{1cm} (10)

where $F_D$ is the drag force, $F_M$ is the inertial force, $u(t)$ is the instantaneous velocity measured at the midpoint of water depth, $C_M$ is the inertial coefficient. It is noted that the work done by $F_M$ is zero during one wave period so that the wave energy dissipation induced by $F$ was attributed to $F_D$. Hence, the period-averaged drag coefficient can be obtained as:

$$C_D = \frac{2 \int_{-\pi/4}^{\pi/4} F_D u dt}{\int_{-\pi/4}^{\pi/4} \rho h_s D^2 |u| dt} = \frac{2 \int_{-\pi/4}^{\pi/4} F u dt}{\int_{-\pi/4}^{\pi/4} \rho h_s D^2 |u| dt}$$ \hspace{1cm} (11)

The space-averaged $C_D$ obtained by the average value of four measuring points in vegetation field was also given. Although this method reduces the model error compared with calibration method, Morison equation is a form of vertical integration along plant stem. It is not accurate enough to calculate the drag coefficient only by measuring the velocity at the midpoint of water depth and substituting into Morison equation because the velocity at mid depth can not represent the vertical velocity profile in practice.

2.3. Modified direct measurement method

Based on Morison equation, combing the results of horizontal velocity field in the vertical section with the total wave force acted on the front of mimic plant during a wave cycle, we proposed a novel method to calculate drag coefficient of vegetation under both wave-vegetation and wave-current-vegetation interactions. It can reduce the model error and increase the accuracy of direct measurement, and have a well fitted relationship between $C_D$ and other nondimensional parameters, so as to accurately evaluate and predict the effect of vegetation on wave attenuation.
According to the measured flow field in the front of rigid cylinder, the total force can be expressed by Morison equation (Morison et al., 1950):

\[
F = F_D + F_M = \int_{-h}^{h+ah} \frac{1}{2} \rho C_D u(z,t) \left| u(z,t) \right| + \frac{1}{4} \rho C_M \pi D^2 \frac{\partial u(z,t)}{\partial t} \, dz
\]  

(12)

where \( u(z,t) \) is the instantaneous horizontal velocity along the plant stem in the vertical direction, \( z \). Same as the direct force measurement method, the work by inertial force were zero per wave period and we assume that the work done by vegetation is entirely caused by drag force. Therefore, the period-average drag coefficient \( C_D \) can be expressed as:

\[
C_D = \frac{\int_{-\pi/a}^{\pi/a} \int_{-h}^{h+ah} \rho Du^2(z,t) \left| u(z,t) \right| \, dz \, dt}{\int_{-\pi/a}^{\pi/a} \int_{-h}^{h+ah} \rho Du(z,t) \left| u(z,t) \right| \, dz \, dt}
\]  

(13)

The space-averaged drag coefficient can be obtained by an average value of five measuring points in a quintile of vegetation region in this test (Fig. 1).

Many previous studies analysed the relationship between drag coefficient and Reynolds number (Anderson and Smith, 2014; Kobayashi et al., 1993; Ozeren et al., 2014). The Reynolds number was defined as:

\[
Re^* = \frac{u_{\text{max}}^* D}{\nu}
\]  

(14)

where \( u_{\text{max}}^* \) in most of analytical calibration method is the maximum velocity effect on the top of plant in the front of vegetation, and can be obtained by second order wave theory in this experimental study according to Eq. (8), the \( \nu \) is the kinematic viscosity of water (1.011×10\(^{-6}\) m\(^2\)/s). In order to consider the velocity inside the canopy, Hu et al. (2014) defined the Reynolds number by the spatially averaged velocity in canopy. Here, to make sure the Reynolds number is accessible for better prediction of \( C_D \) in practical application, we defined the Reynolds number as:

\[
Re = \frac{u_{\text{max}} D}{\nu}
\]  

(15)

here the \( u_{\text{max}} \) is the measured amplitude of the horizontal wave orbital velocity at midpoint of water depth in front of the plant.
3. Experimental setup and test procedures

3.1. Experimental setup

The experiments were conducted in a wave flume of Zhejiang University in Zhejiang province, China. The dimensions of the wave flume were 25-m long, 0.7-m wide and 0.7-m deep. Active absorption piston wave generator driven by servomotor which can absorb reflected waves is installed at the head of the flume, and a porous wave-absorbing beach with 1:6 slope was located at the end of wave flume to eliminate the wave reflection.

Fig. 1 shows a sketch of the experimental setup. Transparent PMMA rods were fixed on perforated false bottom and keep rigid with no deflection constructed the model vegetation field. The mimic plants were 0.29 m high and the diameter was 0.01 m. There was a 1:10, 1cm thick PMMA slope in front and back of the vegetation to ensure that the waves rise steadily to the vegetation elevation.

The vegetation stems were arranged as alignment configuration and the stem density was 200 stems/m². The stem configuration was shown as Fig. 2, and the stem density can be calculated by the spacing of each adjacent plant S. The vegetation field was 5m long, 0.7m wide, and 7m from the wave-making paddle, the installed model vegetation bed was shown in Fig. 3.
3.2. Test conditions and instrumentation

Eight HR Wallingford wave gauges (WG) were used to measure the surface elevations. WG1 and WG2 were placed in front of the vegetation field for separation of the incident waves and the reflected waves induced by vegetation. WG3-WG6 were located in the canopy with an interval of 1m for measurement of waves propagating in vegetation areas. WG7-WG8 were arranged behind the vegetation to separate the transmitted waves and reflected waves induced by the wave absorbing beach. The accuracy of the wave gauges is 0.001 cm, and the sample frequency is 200 Hz. The two-point method, proposed initially by Goda and Suzuki (1977), was employed to separate the incident and reflected waves.
Five Kistler Load Cells 9317C were installed on the corresponding mimic plants of the quintiles of vegetation field which were at the same cross sections of WG3-WG6. These Load Cells were not in contact with water when measuring to avoid disturbing the flow field. The accuracy was 0.001 N and measurement range was from -5 N to 5 N, so it can meet the measurement requirements of all wave conditions in this test. Data was sampled at 2000 Hz to make sure capture the variation of wave force.

In the present study, the particle imaging velocimetry technique were conducted by Phantom high speed camera of 1280×1024 pixel resolution and 200 frames per second. The light sheet was generated by continuous laser and orthogonal to the direction of wave propagation. The frames were filtered by Laplacian 5×5 smoothing filter to remove any outliers and the particle displacements were obtained based cross-correlation algorithm. The field of views (FOV) were located in the position corresponding to the Load Cells in order to obtain the flow field of vegetation areas.

As list in Table 1, sixteen wave conditions were conducted in this test including various incident wave height and wave period, the still water level is 0.25 m, so the vegetation was in emergent and the ratio of submergence was 1.16. Each wave gauge was calibrated before test and data of every case was collected more than 400 s. Each case was repeated for three times.

| Water depth(\( h \)) | Wave height(\( H_i \)) | Wave period(\( T \)) | Wave length(\( L \)) | \( h_i / h \) | Density(\( N \)) |
|----------------------|------------------------|----------------------|----------------------|--------------|----------------|
| 0.25 m               | 0.04 m                 | 0.8-1.4 s            |                      |              |                |
|                      | 0.05 m                 | 0.8-1.4 s            | 0.932-2.003 m        | 1.16         | 200 stems/m²   |
|                      | 0.06 m                 | 0.8-1.4 s            |                      |              |                |
|                      | 0.07 m                 | 0.8-1.4 s            |                      |              |                |

4. Results

4.1. Wave attenuation by vegetation

4.1.1. Wave height decay

The measured relative wave height \( K_i \) in vegetation field and wave damping factor \( \beta \) fitted by Eq. (4) are shown in Fig. 4 and the fitted relationships were well and the corresponding coefficient of determination \( R^2 \) were more than 0.98. It
indicated that wave height decay along the canopy was in accordance with power function proposed by Dalrymple et al. (1984). The $\beta$ fell in the range from 0.077 to 0.163, and it is obvious that the dominating wave attenuation occurred in the front area of vegetation. Fig. 4a presented that in the same wave period, a higher incoming wave height $H_i$ induced higher wave energy dissipation, the $\beta$ rose from 0.093 to 0.158 when $H_i$ increased from 0.04 m to 0.07 m. The decay trend was similar to that of Anderson and Smith (2014). In Fig. 4b, for the case with same incident wave height, the test results showed that higher wave frequency lead to higher wave decay when wave period range from 0.8 s to 1.4 s, the corresponding $\beta$ decreased from 0.163 to 0.125, respectively. It means that the wave height reduction caused by vegetation varied from 47.2% to 38.8%. Bradley and Houser (2009) and Lowe et al. (2007) also pointed out that wave of higher frequencies induced more wave attenuated, However, contrary to this study, Manca et al. (2012) found that longer waves lead to more wave energy dissipation. The influence of wave conditions on attenuation can be explained by the flow field within vegetation, and the analysis was given in the later part.

Fig. 4. Relative wave height ($K_x$) and wave damping factor ($\beta$) in canopies. (a) The incident wave height effects on wave attenuation by vegetation ($T$=0.8 s); (b) The wave period effects on wave attenuation by vegetation ($H_i$=0.07 m). The fitted curves were also shown.

4.1.2. Acting force on the plant decay

The measured maximum horizontal acting force ($F_{\text{max}}$) on the plant along the vegetation field is shown in Fig. 5 and the values of $F_{\text{max}}$ ranged from 0.02 N to 0.09N. Fig. 5a indicated that higher incoming wave height induced larger wave force. In the condition of $H_i$=0.07 m, when the waves propagated to the vegetation, the $F_{\text{max}}$ reached to 0.074 N, and the $F_{\text{max}}$ was only 0.034 N when $H_i$=0.04 m. What’s
more, similar to the trend of wave height reduction, the dominant area of force decay was concentrated in the front part of vegetation. The reduction rate of $F_{\text{max}}$ decreased gradually with the propagation of waves. For more details, the gradient of $H_i=0.07$ m changed from -0.015 to -0.004 between the $x=1$ m and $x=4$ m. Hence, it is noted that as the waves propagated in the vegetation field, the influence of incident wave height on $F_{\text{max}}$ decreased gradually. The effect of the wave period on force decay is given in Fig. 5b, it is clear that longer waves lead to larger forces acting on the vegetation, but the magnitude of the difference is relatively small and the difference in $F_{\text{max}}$ value caused by wave period seemed to remain unchanged along the vegetation field.

**Fig. 5.** The variation of maximum horizontal acting force ($F_{\text{max}}$) on plant during a wave cycle along vegetation area. (a) The incident wave height effects on $F_{\text{max}}$ ($T=0.8$ s); (b) The wave period effects on $F_{\text{max}}$ ($H_i=0.07$ m).

### 4.2. Drag coefficient of vegetation

#### 4.2.1. Time dependent drag coefficients

In this study, the time dependent drag coefficient of vegetation can be derived from a modified direct measurement method which use direct measurement combined the total force $F$ with vertical velocity profile $u(z, t)$ exerted on plant during a wave cycle. According to Eq. (12), the drag force $F_D$ is proportional to the vertical integration of $u^2(z,t)$ and is in phase with $u(z,t)$. The measured drag force and velocity at midpoint of water depth in the FOV1 are shown in Fig. 6. Compared with the results of Hu et al. (2014), the trend of $C_D$ values was similar. Due to the variation of both $F_D$ and $u(z, t)$, the $C_D$ values are not constant and unreal when $u(z, t)$ are small to near zero, but when the horizontal velocity arrives near its crest or trough, the $F_D$ and $u(z, t)$ are large enough so that the values of $C_D$ tend to be stable. This is mainly due to the existence of phase difference. It is worth mentioning that drag coefficient of vegetation derived by the direct force measurement method of Hu et al. (2014) which by means of velocity data at mid depth was not appropriate
particularly in the conditions of larger water depths or higher wave frequencies. However, the modified method proposed in this study takes into account the vertical velocity profile, so that a more accurate and reasonable $C_D$ value can be obtained.

![Diagram](image)

**Fig. 6.** Time dependent parameters when $H_i=0.04$ m, $T=0.8$ s during a wave cycle at the position of FOV1. (a) Velocity at midpoint of water depth chosen in vertical section, (b) drag force in the same section with velocity, (c) drag coefficient derived by modified direct measurement method.

### 4.2.2. Period-averaged drag coefficients

In previous studies, both calibration method and direct measurement method have investigated the relationship of period-averaged $C_D$ and the Reynolds number. $\text{Re}^*$ and $\text{Re}$ were defined in Eq. (14) and Eq. (15), respectively. Various experimental fitting formulas were provided to describe the wave decay by vegetation and predict the wave height reduction through Reynolds number. As shown as Fig. 7, the $C_D$ values derived by different methods and corresponding fitting curve were presented.
Fig. 7a showed the drag coefficient of vegetation obtained by the calibration method that combined Eq. (4) with Eq. (5) against the Reynolds number which ranged from 1400 to 3000. Compared with the experimental $C_D$–Re$^*$ relationship of Ozeren et al. (2014) in regular waves, which was given by:

$$C_D = 2.1 + \left( \frac{793}{Re^*} \right)^{2.39}$$

the data in this study fitted well with it, but the data points were dispersed. The coefficient of determination $R^2$ was less than 0.25 so that the $C_D$–Re$^*$ empirical formula derived by calibration method might not be used to predict the wave attenuation by vegetation in this study. However, the trend of $C_D$ with Re$^*$ was evident. $C_D$ declined with increase of Re$^*$.

As shown in Fig. 7b, the $C_D$ values of vegetation obtained by the direct force measurement (Eq. (11)) were plotted against Reynolds number Re$^*$ which defined by in-canopy velocity. In order to consider the variation along the vegetation, the spatial averaged $C_D$ was obtained by the five locations in this experiment. The variation pattern of $C_D$ with Re$^*$ was clearer. For more details, the $C_D$ dropped rapidly from 5.5 to 3.2 when $600 < \text{Re}^* < 1200$. Compared with the method of calibration, the correlation was better, whose $R^2$ was more than 0.69 and can be used to revisit and derive the acting force exert on the plants. However, the acting force reproduced by the fitting formula in this study was not accurate because the degree of correlation was not high enough. It’s noted that although the $C_D$ values derived by direct force measurement in this study were higher than the fitting line of Hu et al. (2014), it’s consistent with their data points of measurement results when vegetation in emergent and the velocities in the front part of canopy were not considered which made the Re$^*$ lower in their experiment.

In Fig. 7c, the values of $C_D$ derived from the modified direct measurement approach were closely related to Reynolds number Re and corresponding $R^2$ reached to 0.91. The test data points almost coincide with the fitting curve, the $C_D$–Re relation can be expressed as:

$$C_D = 3.07 + \left( \frac{905}{Re} \right)^{4.58}$$

It is clear that $C_D$ values decreased quickly with the increase of Re particularly when Re < 1200 and the rate of reduction decreased gradually and approached zero when Re was greater than 1200. Due to the high correlation
between the measured results and fit formula, the new approach can be well applied to accurately evaluate the $C_D$ values of vegetation. Hence, the exact acting force on the plant and wave energy dissipation by vegetation can be better reproduced.

![Graphs showing the relationship between drag coefficient $C_D$ and Reynolds number $Re$.](image)

**Fig. 7.** Period-averaged drag coefficient $C_D$ as a function of Reynolds number. (a) The relationship between $C_D$ derived by the calibration method and $Re^*$ defined in Eq. (14); (b) The relationship between $C_D$ derived by the direct force measurement method and $Re^*$; (c) The relationship between $C_D$ derived by the modified direct measurement approach and $Re$. The solid lines represent the fitted results of experimental data in this study, and the dash lines represent the empirical relationship in previous studies.
4.3. Flow field

4.3.1. Velocity field

This study not only described the wave attenuation from the wave height and force exerted on plant decay along the vegetation area mentioned above, it further illustrated the dissipation effect by vegetation on wave energy through the local flow field. In order to indicate the whole hydrodynamic behavior variation within the vegetation, the flow fields from the bottom of tank to near free water surface ($z/h=0.04$~0.86) were analysed for different phases in a wave period. Figs. 8-9 showed the phase-averaged velocity field in vegetation corresponding to each phase (a to d) under the wave condition ($H=0.05$ m and $T=1.0$ s), respectively. The top graph indicated the timing from the wave trough to wave crest, and again to wave trough covering the entire wave period (phase=$-180^\circ$, $-90^\circ$, $0^\circ$, $90^\circ$ and $180^\circ$).

The Fig. 8 showed the velocity vectors within the emergent vegetation in FOV1 where incident wave first encounter vegetation and the measured maximum instantaneous wave velocity occurred. At wave trough (Fig. 8a), the lowest position of the water surface induced the maximum negative horizontal phase-averaged velocity, $u=-10.27$ cm/s in the mid of depth, and the vertical phase-averaged velocity was near zero. From the elevation near free water surface to the bottom boundary structure ($z/h=0.86$~0.04), the values of flow velocity began to decrease gradually. What’s more, it’s worth to note that the reduction of wave orbital velocity was observed under the influence of mimic vegetation. Compared with incoming wave, the two-dimensional velocity near the plant declined to $-7.05$ cm/s at the mid of water depth. As waves propagated, Fig. 8b-d showed the variation of phase-averaged velocity distributions in the vegetation zone. The horizontal velocity became positive from negative and finally tend to zero. It also revealed that the variation of drag force exerted on plant. The vertical velocity reached to maximum when at the phase (b), then decline to zero at (c), and increased in the opposite direction until the maximum was reached at (d). The trends of velocity variation can be explained by second order wave theory. Whatever at any phase, the vectors of velocity near the bottom boundary and mimic plant were affected and decreased. Considering the stem density is not high enough and the stem diameter is small, so that only a cross-section of vegetation can not lead to larger influence on waves. Hence, as shown in Fig. 9, the flow field in FOV5 at the location of $x=4$ m in vegetation field was presented to compared with
FOV1. The velocity pattern in each phase was similar to corresponding frame of FOV1, but the value of velocity in the same position were generally decreased because of the existence of vegetation. For example, the phase-averaged velocity of the mid water depth declined from $-10.27$ cm/s to $-6.88$ cm/s in the front of plant at wave trough. The proportion of velocity reduction was 33% and agreed well the wave height reduction.

Fig. 8. Phase-averaged velocity fields in the front of vegetation of FOV1 during a wave cycle when $H_i=0.05$ m and $T=1.0$ s. The top graph shows the corresponding moments of the PIV measurement (phases a to d) with stand for the free surface
elevation in the front of plant. The rectangle geometry filled with gray represents the mimic plant.

Fig. 9. Phase-averaged velocity fields in the front of vegetation of FOV5 during a wave cycle when $H_i=0.05$ m and $T=1.0$ s. The top graph shows the corresponding moments of the PIV measurement (phases a to d) with stand for the free surface elevation in the front of plant. The rectangle geometry filled with gray represents the mimic plant.
4.3.2. Turbulent kinetic energy

In this section, in order to reveal the distributions of turbulent kinetic energy \( TKE \) in vegetation field, the values of 2D \( TKE \) were obtained by Eq. (9) and showed in Fig. 10. It is clear that the \( TKE \) profile had three regions in vertical direction at FOV1 (Fig. 10a). For more details, the values of \( TKE \) near bed and upper layer were observed to be much larger than middle part and the gradient of variation was higher. The \( TKE \) decreased from the bottom boundary to the middle part gradually and then it was close to vertically uniform. The \( TKE \) increased from the middle part to the water surface generally and the rate increased. The tendency at this location was nearly same as that at the observations of Pujol et al. (2013), but it did not increase monotonically from the bed to the surface of water, it’s a process of first decreasing and then increasing caused by the influence of bottom boundary layer. What’s more, due to the existence of rigid vegetation, the stems can make the largest relative motion with waves and generate strong wakes and turbulence (Zhang et al., 2018). In the \( x \) direction of wave propagating, the \( TKE \) increased gradually near the plant and the growth rate increased. It was obvious that the \( TKE \) was large around the plant especially in the upper position where the relative velocity was higher. In addition, the \( TKE \) was just 1.15 cm\(^2\)/s\(^2\) in the mid of water depth at \( x=-2\) cm in the frame, and reached to more than 15 cm\(^2\)/s\(^2\) near the plant.

To analyse the turbulence intensity along the vegetation, Fig. 10b showed the turbulent kinetic energy field in the FOV4 at the location of \( x=3\) m from the beginning of vegetation area. As the incident waves propagating, the local wave height decayed to 3.78cm by vegetation. Compared with the FOV1, the trend of \( TKE \) values was similar. However, unlike the vegetation in FOV1 where the incoming wave only interacted with the first row of plants, the waves in FOV4 were affected by both anterior and posterior plants. So the turbulence can be generated by both anterior and posterior plants. Moreover, the \( TKE \) values reduced obviously near the plants because of the decrease of wave amplitude.

The experimental results also indicated that wave period can influence the whole \( TKE \) distribution around the plants. Fig. 10c showed the \( TKE \) field in the FOV1 when \( H_c=0.05\) m and \( T=1.2\) s. The trend of \( TKE \) was similar to the forementioned results, but it is obvious that the \( TKE \) in whole flow field was larger in higher wave period especially near the plant.
Fig. 10. Turbulent kinetic energy field in the front of vegetation during a wave cycle. (a) $H_i=0.05$ m and $T=1.0$ s in FOV1, (b) $H_i=0.05$ m and $T=1.0$ s in FOV4, (c) $H_i=0.05$ m and $T=1.2$ s in FOV1, (d) $H_i=0.04$ m and $T=1.0$ s in FOV1.

The larger values of $TKE$ occurred near the water surface, plant and bottom boundary as disturbed by the vegetation and bed. When $0.06h<z<0.5h$, the $TKE$ values nearly keep constant away from the plant. To investigate the effects of incident wave height on turbulence, Fig. 10d showed the $TKE$ field in the FOV1 in the condition of $H_i=0.04$ m and $T=1.0$ s, it’s clear that the $TKE$ decreased generally as the wave height down, when $z<0.74h$, the $TKE$ remained nearly unchanged.

4.4. Wave energy dissipation and turbulent kinetic energy

Wave energy dissipation in vegetation field is caused by the drag of plants (Dalrymple et al., 1984), assuming the turbulent kinetic energy budget is reduced to a balance between the wake production and the viscous dissipation (Nepf, 1999), we proposed a prediction model of instantaneous turbulent kinetic energy values. The production of turbulence within stem wakes $P_w$ is obtained by the work input by
the wave, which was defined as:

\[ P_w = F_D u(z,t) = \frac{1}{2} C_D N D u^2(z,t) |u(z,t)| \]  

(18)

it assumes that all of the energy extracted from the incident wave through plant drag converts to the turbulent kinetic energy.

Considering that the characteristic length scale of the turbulence is determined by the stem geometry, the stem diameter \( D \), the dissipation rate \( \varepsilon \) can be scale as (Tennekes and Lumley, 1972):

\[ \varepsilon \sim k_i^{3/2} D^{-1} \]  

(19)

where \( k_i \) is the instantaneous turbulent kinetic energy. On the basis of the balance between \( P_w \) and \( \varepsilon \), the \( k_i \) can be derived as:

\[ k_i = \delta \left( \frac{1}{2} C_D N D^2 u^2(z,t) |u(z,t)| \right)^{2/3} \]  

(20)

here the \( \delta \) is the scale factor.

Fig. 11 showed the comparison between the measured and predicted instantaneous turbulent kinetic energy values in the condition of \( H_i = 0.04 \) m, \( T=1.0 \) s at the location of \( x=2.0 \) cm, \( y=12.5 \) cm in FOV4. Here, the drag coefficient was obtained by the above results. The scale factor was determined to be 0.152 to reach the best fit of the results. The measured scattered points fall on the prediction curve and it presented a well agreement. It can be inferred that the turbulent kinetic energy was related to the drag force and proportional to \( u^4(z,t) \). There were some differences of measured \( k_i \) which showed a double-peak pattern in different phases. Under the wave crest and wave trough, the horizontal relative velocity between the plant and water had reached its maximum, so that the stem can generate more turbulence. However, when the wave phase was at \(-90^\circ\) and \(90^\circ\), the relative velocity between the plant and water was close to zero which can lead to the decrease of \( k_i \) values in the region near plant. It indicated that the turbulence generation within vegetation was more active at wave crest and though in a wave cycle. Based on this TKE prediction model, both the instantaneous turbulent kinetic energy variation and the time-averaged TKE values can be obtained.
5. Discussion

5.1. Wave attenuation by vegetation

The performance of wave attenuation by vegetation was showed in present study, including wave height and wave force exerted on single plant along the vegetation field for various wave conditions. Our study indicated that the main wave height attenuation occurred in the front part of vegetation (Figs. 4-5), which was consistent with the previous studies (Knutson et al., 1982; Lou et al., 2018), but the main reasons for this phenomenon were often not fully explained. Apart from wave height reduction, the trend of wave force decay within the canopy analysed in this study was more distinct. The leading area of the vegetation between WG2 and WG4 where the incident waves are larger led to larger relative velocities and wave forces to interact with the canopy to form more work done by vegetation and cause more wave energy dissipation. Nepf (1999) investigated that the vegetation drag was associated with the turbulence generation within canopy, Zhang et al. (2018) pointed out that the wave energy dissipation can be predicted by the rate of turbulence generation within the canopy. Combined with the above results in this paper, higher wave height can induce more turbulence especially near the plant and bed. In conclusion, the mostly wave decay happened in the front part of vegetation and the condition of higher incident waves lead to more wave attenuation.

The trend of wave height reduction along the vegetation showed in Fig. 4 also indicated that higher wave frequency induce more significant wave energy dissipation, which was consistent with previous investigations (Lowe et al., 2007; Stratigaki et al.,...
2011). This is mainly due to the steeper waves can generate higher wave nonlinearity. In addition, Fig. 5 showed that long waves lead to high values of horizontal force exerted on plant as longer waves has larger values of integration of horizontal velocity in vertical section. What’s more, large incident wave height also can induce large wave force which was caused by the higher incident wave velocity.

5.2. Drag coefficient obtained by modified direct measurement method

Based on the energy flux conservation, the analytical calibration method was applied in previous studies for the condition of pure wave and flow combined wave with current (Dalrymple et al., 1984; Losada et al., 2016; Mendez and Losada, 2004). It was a common way to derive the drag coefficient of vegetation by experimental results and obtain the relationship between the drag coefficient and various parameters for application (He et al., 2019; Lei and Nepf, 2019; Ozeren et al., 2014). However, there are some limitations existing in the analytical calibration approach. Firstly, it largely depends on the fitting results of the test data of wave height along the vegetation. What’s more, there are some differences between the theoretical hypothesis and the actual condition of wave or wave-current. This is mainly because of wave nonlinearity induced by structures and wave steepness. Hu et al. (2014) pointed out that the density of vegetation can induce scattered $C_D$ against $Re$. These factors might lead to a certain model error and inaccurate prediction of wave height reduction.

Hu et al. (2014) provided a direct force measurement method to derive the $C_D$ of vegetation using the measured total force exerted on the plant and measured flow velocity at mid water depth in combined wave-current flow and defined the characteristic Reynolds number using the in-canopy velocity. It effectively avoids the influence of model error on the evaluation of $C_D$ value and obtains a well relationship of $C_D – Re$. However, a single point velocity at mid depth can not reflect the complex vertical section flow velocity especially in the condition of deeper water depth because the wave energy is concentrated in the upper water column.

Hence, the new approach was proposed in this study to derive more accurate $C_D$ values of vegetation based on Morison equation. This method measured the total force $F$ and the vertical section velocity $u(z,t)$ acting on the plant in canopy. It can eliminate the influence of modeling miscalculations and can be applied for any conditions of water depths, pure waves and combined wave-current. What’s more, the
PIV technique was applied to reveal the flow field in vegetation field. Considering the accessible of $C_D$ for applications, the PIV technique can be replaced by multiple velocity measuring points in front of plant. In our experiment, we carried out the tests of regular wave attenuation by rigid mimic vegetation. Consistent with the results of Hu et al. (2014), there is a little phase difference between the force data and velocity data which lead to error estimation of time dependent drag coefficient when $F$ or $u(z,t)$ is near to zero (Fig. 6). Then the period-averaged drag coefficient were showed in Fig. 7 by integrating the work done of $F$ during a wave cycle, it can efficiently eliminate the misestimates due to the time lag.

The relationship of $C_D - \text{Re}$ plays an important role in prediction of wave height reduction. Fig. 7 indicates that the values of $C_D$ decrease with the increasing $\text{Re}$ in all three methods. Although the fitted results of Eq. (4) was fine, the calibration method showed scattered $C_D$ values. The relationship between $C_D$ obtained by direct force measurement approach and $\text{Re}$ defined by spatial averaged velocity inside canopy improved and can be applied to practice as a preliminary empirical prediction formula. Fig. 7c gives the plot of the more accurate $C_D$ derived by the new approach proposed in this study against the $\text{Re}$ ranged from 700 to 1700. It is worth noticing that the correlation of $C_D - \text{Re}$ is very well and the Reynolds number is easy to access. This provides a better supplement for the assessment of the wave attenuation characteristics of coastal vegetation.

5.3. Velocity and turbulent kinetic energy field within vegetation

The velocity field within canopy of different phases in a wave cycle were obtained by PIV technique (Figs. 8-9). It indicated that the velocity decreased gradually from the water surface to the bottom, particularly near the plants and bed. Higher incident wave height induced larger values of velocity which can be explained by the second stokes wave theory. As the horizontal force exerted on vegetation is proportional to $\int_{-h}^{-h+ah} u(z,t) |u(z,t)|$, the velocity field also can reflect the variation of the drag force. Due to work done by the existence of vegetation, the velocity field decreased generally at each wave phase by comparing the results of FOV1 and FOV5 ($H_i=0.05$ m, $T=1.0$ s). This is also an internal manifestation of wave energy dissipation.
Figs. 10 showed the whole 2D $TKE$ fields within canopy along the vegetation field in a wave cycle. It is obvious that $TKE$ values near the water surface, plants and bottom boundary were large especially when the wave period was high because high wave energy is concentrated near the water surface and the interaction between wave and vegetation promoted the turbulence generation. Pujol et al. (2013) revealed that the effects of wave period was due to the different wave attenuation performances. Higher wave period induced lower wave energy dissipation and caused difference of local wave height in same position. By comparing Fig. 10a and Fig. 10c, although the incident wave height was same, the higher wave period led to higher turbulence. This is mainly due to the difference of work input by vegetation. As discussed in the section 4.1.2, wave with higher period have larger wave force acted in plant. Considering the balance between work input and turbulence generation, higher wave period induced larger $TKE$ values. What’s more, combined the Fig. 10a with Fig. 10d, the higher incident wave height can lead to larger $TKE$ values as high energy waves intensify the wave-vegetation interaction and more wave energy convert to the turbulent kinetic energy. Higher wave amplitude induced more intense vortex shedding (Zhang et al., 2018). Fig. 10b showed that the $TKE$ values within canopy decreased as waves propagating along the vegetation. The decreasing wave energy make the turbulence generation become low.

Previous studies revealed that the wave decay can be associated with the turbulence generation within vegetation (Nepf, 1999; Zhang et al., 2018). As shown in Fig. 11, this study indicated that different wave phase induced different instantaneous turbulent kinetic energy patterns. For more details, the instantaneous horizontal velocity reached to maximum and vertical velocity was close to zero at crest and trough. It made $k_i$ reach to the peak. When waves at $-90^\circ$ or $90^\circ$, the horizontal velocity became to the minimum which resulted in the decrease of $TKE$. Only the drag force is considered in energy dissipation and the turbulent kinetic energy budget is reduced to a balance between the wake production and the viscous dissipation. The instantaneous turbulent kinetic energy prediction model was proposed in this study which led to a very well agreement between measured and predicted $k_i$ within canopy. It can effectively make us understand and predict wave turbulence generation in vegetation field.
6. Conclusions

Experimental study were conducted to evaluate the wave dissipation on rigid idealized vegetation by means of particle imaging velocimetry (PIV). It is indicated that waves with higher wave frequency or incident wave height lead to more wave height reduction by rigid vegetation and the main decay occurred at the front part of vegetation field as well as the maximum wave force acting on the plant, $F_{\text{max}}$. Higher incident wave height and wave period induced larger values of $F_{\text{max}}$. Then, based on the velocity profile and force exerted on the plant, a modified direct measurement method was proposed to derive more accurate and reasonable $C_D$ of vegetation. Compared with the previous analytical calibration method and direct force measurement method, it considered the actual velocity distribution in front of plant from bottom to near water surface and can reduce model error more. The method provided a better fitting relation with the Reynolds number and can be applied for prediction. It also can be used for the condition of wave-current flow. The PIV technique can be replaced by multiple velocity measurement points near the plant in this method.

Importantly, we investigated the variation of velocity field in different wave phases within the vegetation to understand the mechanism of energy dissipation better. The wave orbital velocity decreased in whole field of views especially near the plants and bed. The change of wave orbital velocity also can reflect the trend of wave force during a wave cycle. The whole turbulent kinetic energy $TKE$ fields within vegetation in various wave conditions were showed. Compared with the vertical $TKE$ distributions in the previous studies, the $TKE$ trend was not just growing from the bottom to the water surface, but increased near the bed particularly in wave crest and trough. In addition, higher incident wave height and period induced higher $TKE$ values. The $TKE$ decreased gradually especially near the plants and bed as the wave propagated and the $TKE$ field can explain the wave attenuation by vegetation well. Based on the work input caused by the vegetation, the turbulent kinetic energy prediction model was proposed and presented a well agreement between the measured and predicted instantaneous turbulent kinetic energy values.

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