Laboratory Study of Wave Attenuation by Mangrove Forest

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Abstract

Coastal vegetation can dissipate the energy of storm surge and tsunami, which serves a natural barrier for coastal protection. The experimental study of waves-mangroves interaction was carried out to evaluate the efficiency of wave attenuation by vegetation (WDV). In particular, the model mangrove consisted of a flexible canopy and a rigid stem to imitate natural Rhizophora better. It considered the effect of various wave conditions including incident wave height ($H_i$) and wave period ($T$) as well as plant characteristics including submergence ratio ($\alpha$) and stem density ($N$), respectively. Then, the exponential wave decay coefficient ($K_e$) was applied to determine the performance of WDV. It showed that larger $H_i$, $\alpha$ and smaller $T$ induced greater wave decay. To quantify WDV, a new analytical model was proposed considering the change of stem arrangement and wave parameters along the vegetation. Further, the drag coefficient, $C_D$ of mangrove forest was analytical calibrated by this model, and made a comparison with the previous model. Based on this model, the relationships between $C_D$ and some non-dimensional parameters, e.g. Reynolds number, $Re$, Keulegan-Carpenter number, $KC$ and Ursell number, $U_r$ were established to evaluate and predict the wave decay. Especially, it showed a better correlation relationship than the previous model, and the predicted results showed a good agreement with the experimental data.

Keywords: Wave attenuation; mangrove forest; energy dissipation; analytical model; drag coefficient

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1. Introduction

Wetland aquatic vegetation is ubiquitous in coastal regions and plays a significant role in marine hazard reduction. When facing natural disasters such as cyclones and tsunamis, vegetation can protect the lives and property of coastal residents, it also can ameliorate the coastal ecosystems (Koch et al., 2009; Marois et al., 2015). Due to the presence of vegetation, the wave energy can be effectively dissipated and the destroy on seashore was reduced (Dalrymple et al., 1984). Besides, coastal sediment transport can be changed to protect the shoreline from erosion (Horstman et al., 2014; Ros et al., 2014). Hence, vegetation can stabilize the seabed and improve the water quality to create favorable conditions for organisms (Koch et al., 2006; Luhar et al., 2010).

The interaction between wave and vegetation has been investigated through field study, experiment, and numerical simulation in the past decades. Knutson et al. (1982) showed that more than 90% mean wave height was attenuated by 30 meters vegetation and the leading reduction region occurred within the first 2.5 meters. Through long-term research, Möller et al. (1999) and Cooper (2005) pointed out that for the same water depth, the salt marsh vegetation is more than 50% effective than mudflats in wave attenuation performance. It was reported coastal mangroves acted as a barrier for wave and promoted the sediment deposition by field observations (Horstman et al., 2014). Vuik et al. (2018) revealed that wave attenuation by vegetation had strong seasonal differences by the datasets measured in two salt marshes in the Netherlands.

Numerous laboratory studies were conducted to evaluate the vegetation-induced wave dissipation by the features of an individual plant, stem configurations and hydrodynamic conditions. Some researches tend to generalize rigid vegetation to vertical cylinders and use the theory of interaction between oscillating flow and rigid cylinders to analyze and reveal the mechanism of WDV. Though generalize vegetation into an array of small-scale, rigid, vertical cylinders, Dalrymple et al. (1984) were the first to come out with an analytical model for wave damping by coastal vegetation.
based on energy conservation equation and linear wave theory. Kobayashi et al. (1993) showed exponential decay as waves propagating in the vegetation field based on the momentum conservation equation and continuity equation. Méndez et al. (1999) pointed out that the plant swaying can change with time series under the action of incoming waves, which lead to the unsteady interaction between vegetation and waves. Therefore, the swaying factor cannot be neglected in the establishment of an analytical wave attenuation model. Later, Mendez and Losada (2004) extended the model of Dalrymple et al. (1984) to the irregular waves. A new analytical model for wave dissipation by vegetation was derived by Losada et al. (2016) for combining wave and following or opposing current considering the Doppler Effect. Based on these analytical calibration approaches, the drag coefficient $C_D$ of vegetation can be obtained to evaluate and predict the wave decay along the vegetation. Augustin et al. (2009) studied experimentally and numerically on wave attenuation by the rigid and flexible vegetation models in near-emergent and emergent for diverse wave conditions. Ozeren et al. (2014) derived empirical equations of $C_D - KC$ for model and live vegetation under waves. It presented that $C_D$ values decreased with increased $KC$ especially for lower $KC$ values. Anderson and Smith (2014) analyzed the attenuation of irregular wave with a double-peaked spectrum by idealized flexible vegetation filed. The spectral attenuation was affected by frequency and was significant in the spectral peaks. Blackmar et al. (2013) presented the laboratory and numerical results in three configurations of artificial vegetation, it indicated that the damping factor could be a linear superposition for two kinds of plants for predicting the wave height decay. Wu et al. (2015) investigated experimentally the effect of the wave steepness and relative water depth on the drag coefficient of the vegetation field. Based on the study, the $C_D$ was fitted well with the $KC$ number and the $U_r$, while the $C_D - Re$ was worse considering the wave nonlinearity in a range of relative water depths. These studies were all aimed at completely rigid or flexible vegetation. Many previous studies used a rigid cylindrical model to generalize the simulation of rigid vegetation, and the wave attenuation of
mangroves is not only caused by the stems, but also by the interaction between the flexible canopies and the waves (He et al., 2019). Hence, the flexible canopies and rigid stems should be taken into account together to investigate the wave energy dissipation by natural mangroves in various hydraulic conditions well.

Wave energy dissipation in the coastal vegetation depends on various factors, e.g. incident wave height, wave period, and the ratio of submergence (Anderson and Smith, 2014), stem diameter (Feagin et al., 2011), stem density (Tang et al., 2015), configurations (Huang et al., 2011), stiffness of the vegetation (Luhar et al., 2017). Some non-dimensional characteristic parameters, i.e. Reynolds number (Re), Keulegan-Carpenter number (KC) and Ursell number (U,) are available to derive the $C_D$ to evaluate and predict the energy dissipation performance by vegetation. Here, the $C_D$ was mainly obtained by the aforementioned analytical models, which ignored the arrangement of vegetation and the change of work done along the vegetation. Importantly, the wave decay along the vegetation in varying density may not conform to the power function or exponential function.

This paper presents to explore the attenuation performance by mangroves under regular waves considering the coexistence of flexible canopies and rigid stems. The wave decay coefficient ($K_i$) was considered to evaluate the influences of wave conditions as well as the plant characteristics including incident wave height ($H_i$), wave period ($T$), the stem density ($N$) and a range of submergence ratios ($\alpha$), which spanned from the emergent to the submerged conditions. In addition, considering the arrangement of vegetation and the change of work done by plant along the vegetation, a new analytical model to describe WDV was proposed in this study based on the linear wave theory and Morison equation (Morison et al., 1950). Besides, the drag coefficient ($C_D$) was derived by the model of Dalrymple et al. (1984) and the new analytical model for comparison. The correlation relationships between $C_D$ and some non-dimensional parameters were fitted to assess and predict the wave height in an arbitrary region of mangrove forest.
2. Theory

In order to quantify the effect of vegetation for wave energy dissipation and explore how the plant properties, i.e. stem density \(N\), submergence ratio \(\alpha\), as well as the wave conditions, i.e. incident wave height \(H_i\), wave period \(T\) to determine the wave attenuation performance. We make use of the wave height exponential decay coefficient (Kobayashi et al., 1993) to assess the WDV in various conditions, which is given by

\[
\frac{H(x)}{H_i} = \exp(-K_i x)
\]  

(1)

where \(H_i\) is the incident wave height, \(H(x)\) is the local wave height, \(x\) is the distance from the front edge of the vegetation field in the wave propagating direction. \(K_i\) is the exponential decay coefficient.

As wave propagating in the vegetation field, it is mainly affected by two forces, i.e. inertia force \(F_M\) and drag force \(F_D\) due to the vegetation. However, the work done by \(F_M\) could be neglected compared with \(F_D\), so the horizontal force can be expressed by the Morison equation (Morison et al., 1950) per unit volume:

\[
F_D = \frac{1}{2} \rho C_D a U |U|
\]  

(2)

in which the \(\rho\) is the density of water, \(U\) is the wave orbital velocity component in the horizontal direction, \(C_D\) is the drag coefficient, \(a\) is the frontal plant area per unit volume.

Assuming the wave energy dissipation only due to the vegetation, according to the conservation of energy equation, the energy dissipation per wave period is equal to the gradient of the energy flux:

\[
\varepsilon_D = - \frac{\partial E c_g}{\partial x}
\]  

(3)

which the \(E\) is the wave energy density, \(c_g\) is the wave celerity, the \(\varepsilon_D\) is the vegetation-induced average energy dissipation rate per wave period, based on the wave attenuation model by (Dalrymple et al., 1984), the \(\varepsilon_D\) was shown as:
where the submergence ratio ($\alpha$) is defined as the ratio of plant height ($h_r$) to water depth ($h$).

Based on the linear wave theory and regard the plant as the rigid, vertical cylinder, Dalrymple et al. (1984) showed the wave decay equation as:

$$H(x) = \frac{1}{1+\beta x}$$  \hspace{1cm} (5)

where the $\beta$ is the wave damping factor, and it can be obtained by fitting the measured data and expressed as follow:

$$\beta = \frac{4C_D}{9\pi} \frac{H_Nak}{\sinh kh} \left( \frac{\sinh^3 kh + 3\sinh kh}{\sinh kh(\sinh 2kh + 2kh)} \right)$$  \hspace{1cm} (6)

where the $k$ is wave number, and the drag coefficient $C_D$ can be derived from the Eq. (6), and wave reflection induced by vegetation was not considered here.

The above analytical model of WDV was widely used by the previous studies (Bradley and Houser, 2009; Dalrymple et al., 1984; Ozeren et al., 2014), but there are also some limitations. Firstly, it only considers the stem density but ignores the arrangement of vegetation. In particular, for the vegetation with varying density along the wave direction, it may not conform to the law of the wave height decay which is given by Eq. (5). Besides, it ignores the change of wave, e.g. the wave orbital velocity, drag force, and work done by vegetation in wave propagation, which may not reflect the actual wave attenuation process of vegetation, and lead to a misestimate of the drag coefficient of vegetation. Hence, we proposed a new analytical model of WDV based on the linear wave theory and Morison equation (Morison et al., 1950).

When waves reach the vegetation, the initial wave energy flux was given as:

$$P_0 = Ec_B B$$  \hspace{1cm} (7)

here the $B$ is the width of the wave flume.

Considering the work done by the drag force, the work input by a row of plants per wave cycle was defined as:
\[ \Delta P = \frac{1}{T} \int_{-\pi}^{\pi} \int_{-h}^{h} F_D u(z,t) dz dt \times n = \frac{1}{T} \int_{-\pi}^{\pi} \int_{-h}^{h} \frac{1}{2} \rho C_D a \left| u(z,t) \right| dz dt \times n \] (8)

Here the \( n \) is the number of plants in a row, \( u(z,t) \) is the horizontal wave orbital velocity at position \( z \), time \( t \).

The transmitted wave energy flux after a row of plants was obtained as:

\[ P_i = Ec B = P_0 - \Delta P \] (9)

Specifically, the calculation process of this new analytical model of WDV is as follows: Firstly, the \( C_D \) of vegetation was set as an initial value based on the relationship of \( C_D - KC \) obtained by Keulegan and Carpenter (1958). Then, the work input of plants in the first row, \( \Delta P \) was obtained by Eq. (8), and the transmitted wave energy flux after the first row of plants, \( P_i \) was calculated. The local wave height and wave orbital velocity after the first row of plants can be derived by the Eq. (9). Then, substitute the velocity data into Eq. (8) and carry out cycle calculation from the first row, 1 to the last row, \( M \) combined the Eq. (8) and Eq. (9), the wave height reduction along the vegetation field can be reproduced. Through fitting with the measured wave decay by field or laboratory study, the drag coefficient of vegetation can be derived. In particular, the Python code of this analytical model was given in Appendix A.

Previous studies indicated that the \( C_D \) of vegetation fitted well with Keulegan-Carpenter number \( KC \) in low-energy wave conditions (Mendez and Losada, 2004; Ozeren et al., 2014). Representing the importance of the drag force to inertia force, the characteristic Keulegan-Carpenter number is defined by:

\[ KC = \frac{u_{\text{max}} T}{L_v} \] (10)

in which the \( L_v \) is the characteristic length of the plant as the canopy of model mangrove existed porosity. It was characterized by the ratio of submerged volume \( (V_m) \) to control water volume \( (V) \) (Mazda et al., 1997). Higher characteristic length represents lower plant canopy porosity, which was defined as:

\[ L_v = \frac{V - V_m}{A_f} \] (11)
here the $A_f$ is the averaged frontal area of model vegetation, which was measured through the pictures of the front area of the artificial plant (Husrin et al., 2012). The images were analyzed and calculated to obtain the $A_f$ by image recognition algorithm. As a characterization of wave intensity, the $u_{\text{max}}$ is the maximum wave orbital velocity, which can be predicted by linear wave theory:

$$u_{\text{max}} = \frac{H}{2} \omega \frac{\cosh(k\alpha h)}{\sinh(kh)}$$  \hspace{1cm} (12)

here $\omega$ is the wave angular frequency, it is important to note that the $u_{\text{max}}$ is on the top of the plant for vegetation in submerged, and on the water surface for emergent.

Representing the importance of inertia force to viscous force, the drag coefficient, $C_D$ tend to perform better in fitting with Reynolds number ($Re$) in the larger energy flows (Bradley and Houser, 2009). The expression of characteristic Reynolds number was given by:

$$Re = \frac{u_{\text{max}} L_e}{\nu}$$  \hspace{1cm} (13)

where $\nu$ is the kinematic viscosity of water ($1.011 \times 10^{-6} \text{m}^2/\text{s}$). Kobayashi et al. (1993) showed an empirical relationship of $C_D - Re$ and $C_D - KC$:

$$C_D = B + (\frac{\kappa}{Re})^c \hspace{1cm} \text{and} \hspace{1cm} C_D = B + (\frac{\kappa}{KC})^c$$  \hspace{1cm} (14)

where the $B$, $\kappa$, $c$ are the empirical parameters based on the experimental results. Various investigations derived different values (Anderson and Smith, 2014; Méndez et al., 1999; Ozeren et al., 2014).

As a characterization to wave nonlinearity, Ursell number ($U_r$) is also an available parameter to estimate the $C_D$ (Lou et al., 2018).

$$U_r = 8\pi^3 \frac{H}{L(h)^3}$$  \hspace{1cm} (15)
3. Experimental design

3.1. Experimental setup

The experiments were carried out in wave flume of the Port Engineering Hall in Zhejiang University, Zhejiang province, China. The wave flume is 25.0 m long, 0.7 m wide, 0.7 m deep. Active-absorption typed wave generator driven by a servo motor can absorb reflected waves. The wave generator can adjust the wave-generating signal through wave height information measured by the wave gauge at the front end of the wave paddle. Therefore, it can eliminate the influence of wave reflection by wave paddle.

To make sure shoal waves raise to the elevation of the vegetation field slightly, a 1:10 Perspex slope was conducted 9.70 m from the wave paddle. Four 0.96 m long, 0.695 m wide, 1 cm thick Perspex perforated sheets were installed after the slope to place plants. It can make the vegetation keep in a staggered pattern. The synthetic mangrove forest covered the flume bottom 10 m to 13.84 m from the wave paddle. A wave-absorbing porous slope of 1:6 was installed at the end of the tank to eliminate wave reflection, and the wave reflection coefficient was less than 5% without models in this test. The physical model experiment setup is shown in Fig. 1.

![Fig. 1. Sketch of the wave flume and the mangrove forest setup (not drawn in scale), the hollow rectangles represent wave gauges and the adjacent distances have been shown above.](image-url)
3.2. Vegetation models

Considering the dynamic and geometric similarity to *Rhizophora*, the mangrove model in this study was composed of a flexible canopy section and a rigid stem section with a geometric scale of 1:20. For more details, as shown in the following Fig. 3, the canopy section consists of many flexible branches and leaves which made by polyethylene. The averaged width and length of leaves were 2 mm and 6 mm, respectively. Each mimic unit of branches and leaves was nearly 4.6 cm long, which can sway under waves. The stem section consists of a PVC dowel with 20 cm in height, 0.8 cm in diameter, which can keep rigid under waves. Consequently, the mimic units of branches and leaves were attached around the stem to form the mangrove model. Once attached, the stem scale of mangrove was 7 cm above the bed and the canopy scale ranged from \( z = 7 \) cm to 21 cm in diameter of 10 cm. Hence, the total plant height \( h_s = 21 \) cm.

Previous studies mostly focus on three arrangements of vegetation, i.e. staggered configuration (Ozeren et al., 2014), alignment configuration (Augustin et al., 2009) and random configuration (Pujol et al., 2012). The staggered configuration was applied in our study, the varying plants’ number \( n \) in a row is a cycle of four and three stems, which was shown in Fig. 2.

Based on the criteria determining the level of density of mangroves reported by Mursalim et al. (2020), we arranged the vegetation in sparse and dense densities. The sparse stem density was 40 stems/m\(^2\), the dense stem density is 80 stems/m\(^2\). The method adopted for control of the density was to change the spacing of each adjacent plant stem, \( s \), the stem density can be calculated as:

\[
N = \frac{2}{s^2} \quad \text{(16)}
\]

Individual synthesis mangrove was built on the perforated sheets firmly and the deflection was negligible. The overall vegetation layout as shown in Fig. 3.
Fig. 2. Configuration of artificial vegetation stem (not drawn in scale). The $d$ is average crown diameter, and the $s$ is the space between the stem and adjacent stem.

Fig. 3. Installed artificial vegetation bed ($N=80$ stems/m$^2$).

3.3. Test conditions and instrumentation

Two hundred and eighty-eight regular wave conditions were designed in this laboratory study as is shown in Table 1, which considered the combinations of various incident wave heights, wave periods, and water depths for each vegetation arrangement. The situation of mangrove forest was classified by the submergence ratio, i.e. submerged conditions ($\alpha<1$), near-emergent conditions ($\alpha=1$), and emergent conditions ($\alpha>1$). Each wave case was carried out at least three times and
generated 450s to make sure the accuracy and stability of the experiments.

The wave height and period were determined by the zero up-crossing method. Eight HR Wallingford resistance-type wave gauges (WG) sampling at 100 Hz were used for free water surface measurement. For more details, WG1 and WG2 were set up at 6.0 m and 6.4 m from the wave paddle, so the incident wave height and reflected wave height were separated by the two-point method (Goda and Suzuki, 1977). Then the reflection coefficient by both flume and vegetation can be obtained to evaluate the influence on vegetation-induced wave dissipation. In addition, the separation results suggest that the wave reflection induced by the vegetation is less than 5%, which can be neglected. As shown in Fig. 1, the front edge of the vegetation was defined as \( x=0 \) m. WG3 is as a control gauge that located at \( x=0 \) m, and WG4-WG6 were arranged at equal intervals 0.96 m for wave decay measurement. WG7 was set 1.5 m behind the vegetation field and can be combined with WG8 to separate the transmitted wave height to eliminate the influence of the flume end. The accuracy of each wave gauge is 0.001 cm to ensure the quality of measurement.

**Table 1**

Hydrodynamic conditions with regular waves and vegetation conditions

| Water depth \( (h) \) | Wave height \( (H_i) \) | Wave period \( (T) \) | Wave length \( (L) \) | \( h_i / h \) | Density \( (N) \) |
|-------------------------|------------------------|----------------------|----------------------|-------------|-------------|
| 0.15 m                  |                        |                      |                      |             |             |
| 0.17 m                  | 0.02-0.05 m \* (interval of 0.01 m) | 0.8-1.8 s \* \( (\text{interval of 0.2 s}) \) | 0.849-2.241 m | 1.26 | 40/80 stems \( \cdot \text{m}^2 \) |
| 0.19 m                  |                        |                      |                      |             |             |
| 0.21 m                  |                        |                      |                      |             |             |

\( h_i \) and \( h \) are the incident wave height and reflected wave height, respectively.
4. Results and discussions

4.1. Characteristics of wave decay coefficient

The exponential wave decay coefficient, $K_i$, which fitted by the wave height reduction along the $x$-direction represents the wave energy dissipation performance induced by vegetation. Some wave decay results were shown in Fig. 4, the measured data presented a satisfactory agreement with the fitted curve obtained by Eq. (1), and the corresponding coefficient of determination, $R^2$ was more than 0.980. Higher $K_i$ means more wave energy loss, the $K_i$ value was larger in the dense stem density ($N = 80$ stems/m$^2$) than sparse stem density ($N = 40$ stems/m$^2$). Besides, the trend lines also revealed that the wave attenuation mainly occurred in the front area of mangroves.
Fig. 4. Relative wave height, $H(x)/H_i$, along the vegetation field. (a) $H_i=0.04$ m, $T=1.4$ s; (b) $H_i=0.02$ m, $T=1.4$ s; (c) $H_i=0.03$ m, $T=1.6$ s; (d) $H_i=0.05$ m, $T=1.0$ s.

4.1.1. Incident wave period

As shown in the following Fig. 5a, the influence of the incident wave period, $T$ on the wave decay coefficient indicated that $K_i$ decreased with increasing $T$ for all stem densities ($N=40$ stems/m$^2$ and 80 stems/m$^2$). In particular, for the case of $T=0.8$ s, the $K_i$ was 0.524 when $\alpha=1.26$ in dense configuration, which means the wave height reduction was more than 82.8% caused by mangrove forest. It can be explained that the short-period waves pass through the canopy easier (Lowe et al., 2007). Bradley and Houser (2009) revealed that the canopies serve as a low-pass filter and the wave with high frequency can be attenuated more. For more details, the decreasing rate of $K_i$ reduced gradually from -0.610 to -0.078 as $T$ increased in the range of this test. It shows that $T$ has the most significant effect on WDV when $T$ was small. However, with the increase of $T$, its influence on WDV becomes
weaker. The $K_i$ of dense configuration was in the range of 0.290 to 0.524 and approximately twice as the sparse density in the scenario ($H_i=0.04$ m, $\alpha=1.26$), but the wave amplitude reduction was not linearly correlated with stem density. The results showed that the greater horizontal distribution density induced the better effect of WDV in the scope of this study. Because more plants in per unit area causes a larger frontal area of the vegetation interacted with waves. Hence, the more work done by vegetation leads to more wave energy dissipated by vegetation. However, when the distribution density is large enough, there will be a shelter effect between plants (Augustin et al., 2009). If the stem density continues to increase, the effect of WDV will not change significantly. Also, it is clear that the effect of the stem density on WDV is small for waves with large $T$.

The relationship between wave decay and wave period can also be taken use of the relative depth defined as the ratio of the water depth to wavelength, $h/L$. According to the value of $h/L$, the wave is divided into shallow-water wave ($h/L<0.05$) and deep-water wave ($h/L>0.5$). As is shown in Fig. 5b, the results revealed that $K_i$ increased with $h/L$ for both the submerged condition and emerged condition. The slope of $K_i$ is not uniform, but increased gradually with $h/L$. This trend was different from the results of Anderson and Smith (2014) which studied with a limited range of $h/L$. 

![Diagram](image_url)
**Fig. 5.** Effect of wave and vegetation conditions on the wave exponential decay coefficient, $K_i$. (a) The relationships between $K_i$ and wave period, $T$ for $H_i=0.04$ m. (b) The relationships between $K_i$ and relative depth, $h/L$. (c) The relationships between the $K_i$ and incident wave height, $H_i$ for $T=1.0$ s. (d) The relationships between $K_i$ and submergence ratio, $\alpha$ for $H_i=0.04$ m.

### 4.1.2. Incident wave height

The effect of incident wave height, $H_i$, on the WDV is discussed in this section. The wave decay coefficient, $K_i$, against incident wave height, $H_i$ was shown in Fig. 5c. It can be observed that $K_i$ increased slightly with $H_i$ and the slope of the trend lines was almost monotonous. Besides, the increased rate of $K_i$ enhanced mildly as the $\alpha$ improved. For more details, $K_i$ increased from 0.143 to 0.205 and the slope is 2.06 which was relatively smaller for $\alpha=0.84$ in dense vegetation. However, the slope has a significant growth as $\alpha$ increased, it increased to 5.27 for $\alpha=1.40$ in dense, which was almost twice than the former. It indicated that the influence induced by incident wave height for WDV was promoted by the submergence ratio. Because the increasing incident wave height means increasing wave orbital velocity worked on the surface of vegetation accordingly. It induced more work done by the mangrove forest, which leads to larger wave energy dissipation. The results revealed that wave energy dissipation was positively correlated with incident wave height particularly for emergent vegetation scenarios.

### 4.1.3. Submergence ratio

Submergence ratio, $\alpha$ was a very significant parameter for assessing wave height reduction. A large range of $\alpha$ spanned from submerged to emergent mangroves was investigated in this study. Fig. 5d shows the trend of wave decay coefficient, $K_i$ against the $\alpha$, which ranged from 0.84 to 1.40 due to the varying water depth. The $K_i$ values were between 0.076 and 0.431. Obviously, the increased $K_i$ with the ratio of plant height to water depth in all experimental tests. It presents
that the $K_i$ increased rapidly with the increasing value of $\alpha$ especially for vegetation in submerged. For the case of $\alpha=0.91$, $T=1.0$ s and $H_i=0.04$ m, the growth slope of $K_i$ was more than 0.89. It induced the $K_i$ increased from 0.231 to 0.302, which represented the nearly 10% more wave height reduction. One possible explanation for this difference is that higher values of $\alpha$ in a certain range, cause more part of the canopy area to interact with the intensive energy region of the incident wave and promote the effect of vegetation, so that the wave energy dissipation becomes stronger. Compared the sparse with dense stem density conditions, the trends of $K_i$ are similar, but more clear in dense. It shows that the influence of the $\alpha$ on wave attenuation can be affected by stem density.

However, the increased gradient of $K_i$ tended to mild for the emergent conditions when the plant height was greater than the water depth. When $H_i=0.04$ m, $T=1.0$ s in dense density, the slope of $K_i$ was 0.89 for $\alpha=0.91$ and 0.05 for the case of $\alpha=1.33$. As the still water depth exceeded the vegetation height by nearly twice wave amplitude, the growth rate of $K_i$ tended to extremely little, which suggests that the performance of WDV can not grow indefinitely with $\alpha$. It is worth dimensioning that wave energy dissipation induced by vegetation in the emergent scenarios was larger than the submerged scenarios. It’s mainly due to the reason that the whole water volume was occupied by the plant in emergent condition but the maximum wave orbital velocity was not influenced by vegetation in the submerged conditions (Augustin et al., 2009). Luhar et al. (2017) suggested the consistent reason that vegetation with larger $\alpha$ lead to a larger fraction of plants in the water column. In particular, when the plant is in an emergent state, the plant body resistance for the wave in the dissipation effect was dominant. When the plants turn to the submerged from the emergent, the shear layers begin to appear on the top of the canopy, which can produce a certain degree of dissipation caused by shear turbulence. When the plant is fully submerged, the shear turbulence dissipation of the plant canopy is dominant. As the results showed, the $\alpha$ is a very important parameter for the WDV and varying frequently in coastal wetlands.
4.2. Behavior of drag coefficient

The drag coefficient, $C_D$, is a significant factor that can evaluate and predict the wave decay efficiency in various hydrodynamic conditions and plant profiles. Rigid vegetation shows a higher value of $C_D$ compared with flexible vegetation (Houser et al., 2015). This is because a flexible plant can deflect when interacted with incident wave action, and the effective length will decrease (Luhar et al., 2010). It is worth mentioning that the $C_D$ for wave-vegetation interaction or wave-current-vegetation interaction has been studied in many previous investigations through the calibration method (Kobayashi et al., 1993; Losada et al., 2016; Mendez and Losada, 2004). Besides, some studies made use of direct measurement to obtain the $C_D$ of model vegetation precisely (Hu et al., 2014; Husrin et al., 2012). Although the direct measurement method can reduce mistakes for evaluating $C_D$, it’s not effective enough in practical applications because it requires measurement data of the instantaneous velocity and wave force.

In this section, the $C_D$ of model mangrove forest was obtained by both the model derived by Dalrymple et al. (1984) and the new analytical model proposed in this study. The comparison of wave height decay by this model and experimental results was shown following Fig. 7 including vegetation in submerged or emergent, dense or sparse. It is clear that the predicted wave height has a very satisfactory agreement with the measured results, and the corresponding coefficient of determination $R^2$ was more than 0.990. Compared with the previous power or exponential function (Dalrymple et al., 1984; Kobayashi et al., 1993), the trend lines of wave height decay were not smooth because of the varying number of plants in each row along the mangrove forest. In this study, the analytical model also reflects that the main wave height reduction occurred at the front part of the vegetation field, where the work input by vegetation is more significant. Considering the stem arrangement, this new analytical model also can be applied for WDV in the field study, which has complex and random stem arrangements. For instance, if the vegetation density is smaller at the front and larger at the back, it may be not consistent with the
The decay law proposed by Dalrymple et al. (1984), but the new analytical model proposed in this study is unaffected.

![Graphs showing wave height decay](image)

**Fig. 6.** Comparison of wave height predicted by the new analytical model and experimental data. (a) $N=40$ stems/m$^2$, $\alpha=1.00$, $T=1.4$ s and $H_i=0.04$ m; (b) $N=40$ stems/m$^2$, $\alpha=0.84$, $T=1.4$ s and $H_i=0.02$ m; (c) $N=80$ stems/m$^2$, $\alpha=1.26$, $T=1.6$ s and $H_i=0.03$ m; (d) $N=80$ stems/m$^2$, $\alpha=0.91$, $T=1.0$ s and $H_i=0.05$ m.

There are many significant non-dimensional parameters for predicting the $C_D$ of vegetation, e.g. Reynolds number ($Re$), Keulegan-Carpenter number ($KC$) and Ursell number ($U_r$). Previous studies indicated that $C_D$ is a function of these parameters, and the relationships can be derived utilizing the empirical results, then revisit to predict the wave decay by vegetation. As shown in Fig. 7, the relationship of $C_D$ against $Re$ were plotted for the mangrove forest in all submergence ratios, in the dense and sparse configuration. The drag coefficient of vegetation in Fig. 7a-b were derived from the model of Dalrymple et al. (1984) and Fig. 7c-d were obtained by the new analytical model proposed in this study. The semi-empirical formula of $C_D - Re$ has been derived for various model vegetation from many previous studies.
(Bradley and Houser, 2009; Ozeren et al., 2014), which given various values of parameters \((B, \kappa, c)\) in the Eq. (14).

The \(Re\) in this test ranged from 5000 to 25000. The experimental data of \(C_D – Re\) had a not good fit, which performed a relatively higher scatter in Fig. 7a-b, and especially for vegetation in dense stem density. Besides, the submerged model vegetation conditions fitted slightly well than the emergent. It is clear that the \(C_D\) decreased nearly 50% with the increasing \(Re\) and the reduction rate was greater when \(Re<15000\) and smaller when \(Re>15000\). For the case of low \(Re\) in dense stem density, the value of \(C_D\) was more than 4, but was less than 2 in the case of large \(Re\). It is observed that the plant had a greater drag coefficient in the lower \(Re\). However, the stem density of vegetation seems to have little effect on the \(C_D\) of plant, the vegetation in the denser configuration presented slightly smaller \(C_D\), this is mainly because of the sheltering effect among the vegetation. The wave decay coefficient increased with the increase of stem density, while the drag coefficient decreased mildly with the increase of stem density, this is because Eq. (6) has taken account to stem density.

A clearer trend of \(C_D – Re\) was shown in the Fig.7 c-d, because the new analytical model has considered the change of wave force along the vegetation, the obtained \(C_D\) were smaller compared with the values derived by the model of Dalrymple et al. (1984). A good fit between \(C_D\) and \(Re\) can be observed including various submergence ratios especially for sparse stem density, and the coefficient of determination, \(R^2=0.935\), the correlation coefficients \(B, \kappa, c\) for the formula of drag coefficient versus the \(Re\) was given as follows:

\[
C_D = 0.369 + \left( \frac{7447}{Re} \right)^{0.914}
\]  

(17)
Fig. 7. The relationships between the drag coefficient, $C_D$, of mangrove forest, and the Reynolds number, Re. (a) $C_D$ derived by Dalrymple et al. (1984) in dense conditions; (b) $C_D$ derived by Dalrymple et al. (1984) in sparse conditions; (c) $C_D$ derived by the new analytical model in dense conditions; (d) $C_D$ derived by the new analytical model in sparse conditions.

The derived drag coefficient though the new analytical model was revisited to calculate and predict the transmitted wave height along the mangrove forest. For more details, the predicted drag coefficient was obtained by Eq. (21) and combined the Eq. (7), Eq. (8) and Eq. (9), the predicted values of local wave height at any position in the vegetation field can be obtained. Fig. 8 showed the comparison between the predicted transmitted wave height, $H_p$, and measured transmitted wave height, $H_m$. It showed a very satisfactory agreement, which indicated that the new model can be a good predictor for WDV in practical applications.
The compassion between the predicted transmitted wave height, $H_p$, and measured transmitted wave height, $H_m$, in the vegetation field.

Fig. 8. The compassion between the predicted transmitted wave height, $H_p$, and measured transmitted wave height, $H_m$, in the vegetation field.

Fig. 9a and Fig. 9b showed the relationship between the drag coefficient, $C_D$, derived by the new analytical model and Keulegan-Carpenter number ($KC$), and performed a good correlation for all submergence ratios. According to the Eq. (13), the fitted lines and the regression functions were also exhibited, and the correlation coefficients were listed in Table 2. The $KC$ number represents the relationship between drag force and inertia force affected by vegetation in the wave fields. The $C_D$ deceased with the increased $KC$ number similar to the profile of the $C_D - Re$, and the decreasing slope of $C_D$ was very high when $KC<0.80$, but the reduction rate became mild as the value of $KC$ increasing. Some studies suggested that the relationship of $C_D - KC$ was more suitable for wave-vegetation interaction exploration than $C_D - Re$ (Mendez and Losada, 2004; Sánchez-González et al., 2011). Compared with the previous experiments, the values of $KC$ are relatively small in this study, because the effective length of plant, $L_e$, of the mimic mangrove is larger than the cylinder diameter or blade width in previous studies (Anderson and Smith, 2014; Ozeren et al., 2014). In detail, the artificial mangrove forest in submerged showed a better correlation with the fitted curve than the emergent. In addition, the cases of vegetation in dense configuration fit better than the sparse, it yielded a higher coefficient of determination, $R^2$ of 0.825. But the fitted line for the sparse empirical data of $C_D - KC$ showed a poorer fit with $R^2=0.71$, which may not
provide a good prediction for the drag coefficient particularly for the emergent vegetation conditions.

**Fig. 9.** The relationships between the drag coefficient $C_D$ of model mangrove and the *Keulegan-Carpenter* number $KC$ for both the submerged and emergent conditions. The fitted curve is also shown for each condition of density, respectively.

**Table 2**

| Stem Density(N) | $B$  | $\kappa$ | $c$  | $R^2$ |
|----------------|------|----------|------|-------|
| 40 stems/m²    | 0.287| 0.51     | 0.819| 0.71  |
| 80 stems/m²    | 0.368| 0.475    | 0.914| 0.825 |

The Ursell number, $U_r$, is also a good parameter to evaluate the drag coefficient effectively, which can be calculated with the wave height and wave period through Eq. (14). $U_r$ is a parameter that characterizes wave nonlinearity, and longer wave in shallow water depths has a higher $U_r$ value. Augustin et al. (2009) explored the relationship of friction factors versus Ursell number in submerged and emergent, rigid, and flexible vegetation. Lou et al. (2018) have shown the correlations between drag coefficient and Ursell number in sparse, dense, and vertically varying stem configurations with higher $R^2$ values, relatively. **Fig. 10** presents the $C_D$ of mangrove forest expressed by the $U_r$ in the densities of 80 stems/m² and 40 stems/m² for all submergence ratios. The well-fitted curves are also shown for dense and sparse stem density and the fitted parameters were listed in **Table 3**. The values of $C_D$ had a decreasing trend with the increasing $U_r$ number, it may be inferred that the drag coefficient of vegetation decreased as the wave nonlinearity enhanced. The relationship of $C_D - U_r$ appeared to a similar tendency with $C_D - Re$ and
$C_D - KC$, the slope of the fitted curve was very large in lower value of the $U_r$ especially when $U_r < 10$. As the degree of nonlinearity of the wave increased, the decline rate appeared to be gradually decreasing and nearly zero. Besides, the correlations of the $C_D$ versus the $U_r$ indicated a relative higher $R^2$. For more details, the $R^2 = 0.820$ for the vegetation in dense, and $R^2 = 0.864$ for the sparse. It is clear that the dense configuration showed a better correlation than the sparse, and vegetation in submerged better than emergent. However, since the plant geometric parameters were not considered in the Ursell number, it only applies to plants with specific geometric characteristics. Compared with the relationships of $C_D - U_r$, the $C_D - Re$ and $C_D - KC$ are more suitable for reproducing the WDV in practical applications.

![Figure 10](image.png)

**Fig. 10.** The relationships between the drag coefficient, $C_D$ of mangrove forest derived by the new analytical model and the Ursell number $U_r$ in dense and sparse stem density. The solid line is as a fit curve and shown for each stem density.

**Table 3**

The correlation coefficients $B$, $\kappa$, $c$ for the formula of drag coefficient $C_D$ versus the Ursell number ($U_r$) in conditions of various stem density

| Stem Density ($N$) | $B$   | $\kappa$ | $c$  | $R^2$ |
|-------------------|-------|----------|------|-------|
| 40 stems/$m^2$    | 0     | 4.958    | 0.427| 0.748 |
| 80 stems/$m^2$    | 0.071 | 4.193    | 0.444| 0.820 |

**5. Conclusions**

The laboratory study was carried out to investigate wave attenuation induced by mangrove forest consisted of flexible canopies and rigid stems for various plant characteristics and wave conditions. The vegetation bed showed an efficient
performance of wave energy dissipation, and the wave decay coefficient, $K_r$, drag coefficient $C_d$ were considered to determine it. It indicated that the wave height reduction was most dependent on the wave period, $T$, submergence ratio, $\alpha$ and stem density, $N$ with the changes of these parameters in a certain range. It was observed that WDV was negatively correlated to the $T$ especially for a relatively shorter period, but the effect of the $T$ on longer wave attenuation became mild. Besides, the WDV was significant in the leading zone of the vegetation field. The mangrove forest in the dense configuration of $N=80$ stems/m$^2$ was effective than the sparse configuration of $N=40$ stems/m$^2$ in all tests but less than double. Therefore, it was recommended that not the most, but the appropriate stem density should be chosen for coastal salt marshes in practice. The effect of the $\alpha$ on WDV seemed similar for model mangrove forest both in dense and sparse stem density. A higher value of $\alpha$ results in more wave height reduction and the $\alpha$ was more influential for wave decay in submerged vegetation. However, the changing trend became slight when the mangrove forest changed from the submerged to an emergent state. Besides, the incident wave height performed a slight influence on wave damping, and the effect of WDV increased as the wave height increased in a certain range.

A new analytical model was proposed in this study, which presented a satisfactory agreement between the measured and analytical wave height. The drag coefficient, $C_d$ was calibrated for the mangrove forest in dense and sparse stem densities using this new analytical model and showed a better relationship of $C_d$–Re compared with the model of Dalrymple et al. (1984). The $C_d$ values decreased with Re, $KC$ and $U_r$, and slightly better correlated with Re. So revisiting the derived $C_d$ can reproduce the local wave height in the vegetation field through the fitted semi-empirical formula. The results showed a very good agreement between the predicted wave height and measured wave height in each location along the mangrove forest. The $C_d$ values in emergent were greater than submerged in the same Re and $U_r$. The mangroves in sparse stem density showed a better correlation of $C_d$ respect to Re than dense, but the mangroves in dense
configuration presented a better relationship of $C_D - KC$ and $C_D - U_r$ than sparse.

**Appendix A**

**Acknowledgments**

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