Laboratory Study of Turbulent Kinetic Energy within Mangrove Forest under Waves

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Abstract

Laboratory study was set out to investigate the flow structure and turbulent kinetic energy (TKE) within mangrove forest considering flexible canopies and rigid stems under various wave conditions. Canopies and stems have different effects on turbulence generation. The flexible leaves in canopy scale can promote the dissipation of TKE and the rigid stem scale contribute to the generation of turbulence. Importantly, the difference of TKE with and without vegetation, ΔTKE varied with wave frequency and peaked at 0.833 Hz for the canopy and vegetation-free upper layer, but increased with wave frequency in stem scale. Moreover, TKE in mangrove forest increased monotonically with \( u_{w,\text{RMS}}^2 \) for each stem density. This study proposed a modified model for the TKE prediction within canopy scale considering the role of flexible leaves and rigid stems together. Besides, \( \frac{TKE}{u_{w,\text{RMS}}^2} \) presented a good correlation with the ratio of wave excursion (\( A_w \)) to stem spacing (\( S \)), \( A_w/S \) and declined rapidly with \( A_w/S \) especially when \( A_w/S < 0.1 \) for both stem and canopy scale. This empirical relationship can be a predictor for TKE within mangrove forest. Further, considering the scale between wave energy dissipation by vegetation and production of TKE, the third model was validated in mangrove forest and predicted well.

Keywords: mangrove forest, wave, flow structure, turbulent kinetic energy, prediction model

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1. Introduction

Coastal vegetation serves an ecological barrier for reducing the waves and storm surges and plays a vital role in the marine regions (Türker et al., 2006). It is well known that the presence of seagrass meadow and mangrove forest can damp the local energy of wave and current as well as protect the shorelines from erosion (Lei and Nepf, 2016; Lowe et al., 2005a). It also can provide nutrition and shelter for fish, benthic organism and plankton, which lead to positive biological consequences (Pujol et al., 2013; Schmidt et al., 2011; Yi et al., 2017). In addition, the reduction of hydrodynamic intensity and sediment resuspension due to the vegetation can promote water transparency, under-water light access and bed stabilization (Shields et al., 1995; Zhu et al., 2015).

Many previous studies have shown the wave and current energy can be dissipated by vegetation drag (Anderson and Smith, 2014; Hu et al., 2014; Lei and Nepf, 2019; Luhar and Nepf, 2013). Some of incoming energy was converted to turbulent kinetic energy (Raupach and Shaw, 1982). And the performance of wave attenuation by vegetation was affected by the wave conditions and botanic characteristics. Furthermore, the nutrient cycling, sediment transport within the canopy were related to velocity and turbulence profiles in both the unidirectional currents and wave-dominated flows (Tinoco and Coco, 2014; Yang et al., 2016). Thus, advancing the understanding of turbulence generation within vegetation can improve the prediction for the processes of nutrient uptake by vegetation and sediment mobilization in shallow aquatic regions. Pujol et al. (2010) have studied the vertical turbulent kinetic energy profiles within various kinds of vegetation induced by an oscillating grid. It indicated that canopies can reduce the near-bed turbulence. This damping was enhanced by increasing stem density and inhibited by increasing stem diameter. Pujol and Nepf (2012) described experimentally the turbulent kinetic energy production and wave energy dissipation associated with the breaking wave within the mimic seagrass meadow. The elevated near-bed water velocities induced higher stem-wake turbulence. Pujol et al. (2013) investigated the distributions of turbulence in canopy scale for various wave frequencies and vegetation properties, e.g., plant flexibility, height and density. The difference of turbulent kinetic energy between vegetated and unvegetated bed ($\Delta TKE$) showed the production of $TKE$ caused by the wave-canopy interaction. Rigid
plants can induce higher $TKE$ than flexible. Ros et al. (2014) conducted a set of laboratory experiments to show the $\Delta TKE$ and $\Delta C$ (defined as the concentration of sediment compared the vegetated and unimpeded case) for different wave frequencies, solid plant fractions and water levels. It was observed that rigid vegetation generally promote the turbulence production and the flexible vegetation was contrary. What’s more, higher near-bed turbulence intensity prompt the suspended sediment concentration. And the $TKE$ values showed a correlation with the ratio of wave orbital amplitude ($A_w$) to stem spacing ($S$). Yang et al. (2016) suggested that the sediment-initiated motion was more influenced by the near-bed turbulence intensity than bed shear stress and the near-bed $TKE$ can be estimated by the sum of vegetation-generated and bed-generated turbulence. Although these findings dealt with the turbulence generated by the completely rigid or flexible vegetation for the waves or currents, the interaction between coastal mangroves and waves were determined not only by the rigid stems, but also the flexible canopies (He et al., 2019; Suzuki et al., 2019). It is unclear how the natural mangrove forest influence the turbulence structure above and within the vegetation.

Several $TKE$ prediction models have been used to investigate the turbulence intensity within vegetation under the currents or waves. Nepf (1999) proposed a model to describe the drag, turbulence and diffusion for flow penetrating the cylinders. Based on the turbulent kinetic energy budget balance between the stem wake production and viscous dissipation, the wake generation can be estimated as the work input. Considering the viscous dissipation was replaced by the scaling, $k_i^{3/2}/l_i$, Tanino and Nepf (2008) farther proposed a $TKE$ prediction model within random, rigid cylinders for unidirectional current based on the balance between the rate of work done by drag and wake production. Recent advances in this $TKE$ prediction model have facilitated investigation of submerged vegetation under wave conditions. Zhang et al. (2018) applied the model of Tanino and Nepf (2008) for wave conditions within mimic flexible seagrass. The stem region and canopy region turbulence were estimated and predicted. In addition, the turbulence generation was linked to the wave dissipation and a good agreement between the measured and predicted $TKE$ results was shown. Tang et al. (2019) measured the turbulence within submerged, rigid cylinders and gave a wave-modified stem-turbulence model considering the bed-generated
turbulence. Chen et al. (2020) studied the vertical TKE distributions within vertical varying rigid cylinder density under combined wave-current flows. Further, they modified the TKE prediction model with an intercept for best fitting. These studies generally analyzed the individual rigid or flexible canopy for TKE prediction. However, up to now, no research has considered the effects of stems and branches-leaves together in canopy scale of mangrove forest on the turbulent kinetic energy. The coexistence of flexible canopy and rigid stem should be considered for the turbulence investigations within natural mangrove forest.

This study is to estimate the vertical flow structure and turbulence distribution above and within mangrove forest and the influence of wave factors such as wave frequency, wave height and stem density combining the vegetated cases and equivalent experiments without vegetation. In this study, a modified TKE prediction model was proposed for mangrove forest, which consists of flexible canopies and rigid stems to simulate the natural Rhizophora. Moreover, this study is to develop the relationships between the $\frac{TKE}{u_{w,RMS}^2}$ and $\frac{A_v}{S}$ within mangrove forest to establish an empirical formula for TKE prediction. Finally, the TKE prediction model based on the scaling of wave energy dissipation and turbulence production is validated for the canopy scale and stem scale of mangrove forest.

2. Materials and Methods

The experiments were carried out in the wave flume of Zhejiang University in Zhejiang province, China. The wave flume is 25.0 m long, 0.7 m wide, 0.7 m deep. Active absorption piston wave generator driven by servo motor, which can absorb reflected waves is installed at the head of the flume. The wave generator can adjust the wave-generating signal through wave height information, which is measured by the wave gauge at the front end of the wave paddle to eliminate the influence of wave reflection. The target wave generation quality is not disturbed by the length of the wave-generating time.

2.1. Vegetation quantification

To make sure shoal waves raise to the elevation of the vegetation field slightly, a 1:10 Perspex slope with 1 cm thick was conducted 13.46 m from the wave paddle. Four 0.96 m
long, 0.695 m wide, 1 cm thick Perspex perforated baseboards were installed next to the slope to place plants, which can keep the vegetation in a staggered pattern and vary greatly in terms of the stem density. The synthetic mangrove forest covered the flume bottom from 13.76 m to 17.60 m in 0.70 m width. 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 was shown in Fig. 1.

Fig. 1. Sketch of the wave flume and the artificial vegetation setup (not drawn in scale). The hollow rectangles represent wave gauges and the schematic diagram of ADV is also marked.

Considering the dynamic and geometric similarity to *Rhizophora*, the mangrove model in this study was composed of flexible canopy section and rigid stem section with a geometric scale 1:20. The effect of root was negligible in submerged mangrove (He et al., 2019), which was neglected here. For more details, as shown in the following Fig. 3, the canopy section consists of many flexible branches and leaves 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 $h_c=21$ cm.
**Fig. 2.** Configuration of artificial mangrove forest (not drawn in scale). The $D$ is averaged canopy diameter, $d$ is the stem diameter, $S$ is the space between stem and adjacent stem.

The mangroves were built on the perforated sheets firmly, which were placed in a staggered arrangement (Fig. 2) and the deflection was negligible. The overall vegetation layout was shown in Fig. 3.

Based on the criteria determining the level of density of mangroves reported by Mursalim et al. (2020), four stem densities (0, 40, 60 and 80 stems/m²) were carried out in this study. The method adopted for control of the density was to change the spacing of each adjacent plant stem $S$ and the stem density can be calculated as:

$$N = \frac{2}{\sqrt{3}} S^{-2}$$  \hspace{1cm} (1)
Fig. 3. Installed artificial vegetation bed ($N=80$ stems/m$^2$).

2.2. Measuring technique

Eight HR Wallingford resistance-type wave gauges (WG) sampling at 200 Hz were used for free water surface measurement (Fig. 1). For more details, WG1-3 were set up at $x=11.85$ m, 12.10 m and 12.50 m from the wave paddle for wave separation. The incident wave height and reflected wave height were separated by the two-point method (Goda and Suzuki, 1977). The separation results suggested that the wave reflection induced by the vegetation was less than 5% and can be neglected, which was consistent with Anderson and Smith (2014). WG4-7 were arranged at equal intervals 0.768 m from the front of the vegetation field for the measurements of wave height reduction along the mangrove forest. WG8 was set up at 1.50 m behind the vegetation field at $x=18.332$ m and can be combined with WG9, WG10 to separate the transmitted wave height in order to eliminate the influence of the end of flume. The accuracy of each wave gauge was 0.001 cm to ensure the quality of measurement. The root mean square (RMS) wave amplitude, $a_{rms}$, was determined by the RMS of the measured phase-averaged water surface, $\eta_{rms}$, which given as following:

$$a_{rms} = \sqrt{2\eta_{rms}}$$ (2)

To evaluate the turbulent intensity above and within mangrove forest, the Nortek Acoustic Doppler Velocimeter (ADV) at a sampling rate of 200 Hz for 120 s was located at the same cross section of the WG5 in the leading edge of vegetation area ($x=14.528$ m).
It was used to measure the instantaneous velocity from the stem region \((z=6\, \text{cm})\) up to vegetation-free upper layer \((z=24\, \text{cm})\) with an interval distance of 3 cm.

Twenty-five wave cases were generated in this experiment as shown in Table 1, including the combination of various incident wave heights and wave periods for each vegetation arrangement and the control group without vegetation. Each wave case was carried out at least three times and generated 450 s to make sure the accuracy and stability of the experiments.

### Table 1

| Water depth \((h)\) | Wave height \((H_i)\) | Wave period \((T)\) | Wave length \((L)\) | \(h/h\) | Density \((N)\) |
|-----------------|-----------------|-----------------|-----------------|-----|---------------|
| 0.30 m          | 0.040 m         | 0.8-1.6 s       | 0.96-2.53 m     | 0.7 | 0/40/60/80 stems \cdot m^{-2} |
|                 | 0.045 m         |                 |                 |     |               |
|                 | 0.050 m         | (interval of 0.2 s) |               |     |               |
|                 | 0.055 m         |                 | 0.7            |     |               |
|                 | 0.060 m         |                 |                |     |               |

### 2.3. Methods of analysis

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

\[
u_i = u_c + u_w + u' \quad (3)
\]

where \(u_c\) is the time-averaged velocity, this is mainly because that the interaction between wave and vegetation, which can generate mean current in the direction of wave propagation (Luhar et al., 2010). \(u_w\) is the unsteady wave motion, which was obtained by using a phase averaging technique, \(u'\) is the turbulent velocity fluctuation. These were same for \(v\) in the \(y\)-direction and \(w\) in the \(z\)-direction. The phase-averaged velocity, denoted \((\bar{u}(\varphi), \bar{v}(\varphi), \bar{w}(\varphi))\), was defined by averaging each phase bin all over wave periods, every wave cycle was separated into \(\tau = T \times f_s\) \((f_s\) is sampling frequency) phase bins. For more details, the time-averaged velocity was obtained as (Lowe et al., 2005a):

\[
u_c = \frac{1}{2\pi} \int_{0}^{2\pi} \bar{u}(\varphi) d\varphi \quad (4)
\]
The RMS of $u_w$ was considered as the characteristic value of wave orbital velocity at each measurement position, which was calculated according to the following equation:

$$u_{w,RMS} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} (\bar{u}(\phi) - u_i)^2 d\phi}$$

(5)

The linear wave theory leads to the following prediction for the $u_{w,RMS}$:

$$u_{w,RMS} = \sqrt{\frac{1}{2\pi} \int_0^{2\pi} \left( a\omega \frac{\cosh(kz)}{\sinh(kh)} \cos(kx - \omega t) \right)^2 d\phi} = \sqrt{\frac{1}{2} a\omega \frac{\cosh(kz)}{\sinh(kh)}}$$

(6)

where $a$ is the wave amplitude, which was measured at WG5, $\omega$ is the wave radian frequency, $k$ is the wave number, and $z$ is the vertical coordinate.

The instantaneous turbulent fluctuations were defined as the deviation of the instantaneous velocity, $u_i(\phi)$, from the phase-averaged velocity, $\bar{u}(\phi)$. The RMS fluctuations within each phase bin ($u_{rms}$, $v_{rms}$, $w_{rms}$) were used to estimate the turbulent kinetic energy in that phase bin, $1/2(u_{rms}(\phi)^2 + v_{rms}(\phi)^2 + w_{rms}(\phi)^2)$. The time-averaged turbulent kinetic energy, $TKE$, was defined as the average across all phase bins (Zhang et al., 2018):

$$TKE = \frac{1}{4\pi} \int_0^{2\pi} \left[ u_{rms}(\phi)^2 + v_{rms}(\phi)^2 + w_{rms}(\phi)^2 \right] d\phi$$

(7)

The $TKE$ deviation between the cases with and without mangrove forest, expressed as a percentage, was calculated according to:

$$\Delta TKE = \frac{TKE_v(z) - TKE_{wv}(z)}{TKE_{wv}(z)} \times 100$$

(8)

in which the $TKE_v$ is $TKE$ measured at $z$ with the presence of the mimic mangrove forest and $TKE_{wv}$ is the $TKE$ measured without vegetation. Positive $\Delta TKE$ implies a generation of $TKE$ caused by vegetation and negative $\Delta TKE$ indicates a reduction of $TKE$.

For turbulent kinetic energy prediction within the vegetation under waves, the $TKE$ prediction model proposed by Tanino and Nepf (2008) was applied in this study. Previous studies have good verifications and results for waves through this model (Tang et al., 2019; Zhang et al., 2018). The rate of viscous dissipation is replaced with the scaling, $k_t^{3/2} / l_t$, here $k_t$ is the predicted turbulent kinetic energy and the $l_t$ is the characteristic eddy length.
scale (Tennekes and Lumley, 1972). Considering the balance of viscous dissipation and the wake production, the turbulence intensity in stem scale of mangrove forest was estimated as the following equation:

$$k_i = \delta_s^2 \left[ C_{D,s} \frac{l_{ir}}{d} \frac{Nd^2}{2(1-\phi_s)} \right]^{\frac{2}{3}} u^2$$  \hspace{1cm} (9)

where \(u\) is the streamwise velocity, which can be replaced by the characteristic wave orbital velocity \(u_{w,RMS}\), \(C_{D,s}\) is the drag coefficient of stem, \(\phi_s\) is the solid volume fraction of stems, which was calculated as \(\phi_s = N\pi d^2 / 4\), \(N\) is the stems per bed area, \(\delta_s\) is the scale factor for stem scale model. Tanino and Nepf (2008) indicated that the integral length scale \(l_i = \min\{d, s\}\), here, the \(d\) is the diameter of stem and \(s\) is the surface to surface distance between a plant and adjacent plant.

A modified version of TKE prediction model within canopy scale was proposed in this study considering the turbulence generation due to the stems item and additional item induced by branches and leaves in canopy scale. The interaction between these two terms might be nonlinear. For simplification, assuming that the total TKE in canopy scale is the sum of stem item and canopy item, the canopy scale TKE can be estimated as:

$$k_i = \delta_s^2 \left[ C_{D,s} \frac{l_{ir}}{d} \frac{Nd^2}{2(1-\phi_s)} \right]^{\frac{2}{3}} u^2 + \delta_c^2 \left[ C_{D,c} \frac{l_{ic}}{D} \frac{ND^2}{2(1-\phi_c)} \right]^{\frac{2}{3}} u^2$$  \hspace{1cm} (10)

in which \(D\) is the canopy diameter, \(C_{D,s}\) is the drag coefficient of stem, \(C_{D,c}\) is the drag coefficient of canopy, \(\phi_c\) is the solid volume fraction of canopies, which can be obtained by the displacement method, \(\delta_c\) is the scale factor for canopy scale. One purpose of this study was to verify equation (10) as a predictor of wake production in canopy scale for wave propagation in different solid volume fractions.

3. Results and discussion

3.1. Velocity field within mangrove forest

Firstly, the measured vertical velocity fields of control group including time-averaged velocity, \(u_c\) and RMS wave orbital velocity, \(u_{w,RMS}\) were shown in Fig. 4a-b. Similar to
the results of Zhang et al. (2018), the values of $u_c$ were generally negative and vertically uniform, which is mainly due to the nonlinearity of wave. It is worth denoting that the magnitude of $u_c$ increased near the bed because of the bed-generated nonlinearity. Also, higher incident wave induced greater $u_c$. Fig. 4b showed there are significant differences of $u_{w,RMS}$ in these three wave conditions. $u_{w,RMS}$ increased with the incident wave height. For more details, the measured depth-averaged $u_{w,RMS}$ was 10.78 cm/s for $H_i=6$ cm, $T=1.6$ s and 9.14 cm/s for $H_i=5$ cm with same wave period. $u_{w,RMS}$ values increased from bed to the water surface gradually and fitted the linear wave theory well. As shown in Fig. 4c-d, in the presence of vegetation with stem density $N=80$ stems/m$^2$, $u_c$ and $u_{w,RMS}$ above and within the mangrove forest have changed. Compared with Fig. 4a, $u_c$ in Fig. 4c varied greatly in the vertical direction especially for the canopy and stem scale, these results are likely to be related to the mean flow generation caused by the interaction between the propagating wave and vegetation (Abdolahpour et al., 2017). The values of $u_{w,RMS}$ were in agreement with the theory predicted by the measured wave height of WG5, but the correlation was worse than the control group for $H_i=6$ cm, $T=1.6$ s due to the change of $u_c$ and the vegetation-generated turbulence. Fig. 4e-f showed the comparison of vertical velocity profiles between dense ($N=80$ stems/m$^2$) and sparse ($N=40$ stems/m$^2$) vegetation in a same wave case, $H_i=6$ cm, $T=1.2$ s. This difference could be attributed to the performance of nonuniform wave attenuation by vegetation for different solid volume fractions (Ozeren et al., 2014; Wu et al., 2016). Due to the work done of drag force caused by each plant (Dalrymple et al., 1984), vegetation with higher stem density lead to higher wave height reduction. So the magnitude of $u_c$ and $u_{w,RMS}$ with dense cases were lower than sparse.
Fig. 4. Vertical flow structures of the time-averaged velocity, $u_e$ and RMS wave orbital velocity, $u_{w,RMS}$. Subplots (a) and (b) are the control group for different wave cases. Subplots (c) and (d) have a mangrove forest of $N=80$ stems/m$^2$ for various wave cases. Subplots (e) and (f) are cases for comparison of dense ($N=80$ stems/m$^2$) and sparse ($N=40$ stems/m$^2$) stem density. Two dashed horizontal lines imply the range of canopy ($z=7-21$ cm), the solid lines indicate the predictions of linear wave theory.

3.2. Turbulent kinetic energy distributions

In Fig. 5a, there is a clear trend of decreasing $TKE$ from the water surface to bed. For the case of bare bed ($H=6$ cm, $T=0.8$ s), although the wave decay was lowest, whose local wave amplitude was 2.91 cm and larger than cases in presence of mangrove forest, the
values of $TKE$ were the smallest in each measurement position especially in stem scale, which was $0.48 \text{ cm}^2/\text{s}^2$. When the wave tank was occupied by vegetation of $N=80 \text{ stems/m}^2$, the $TKE$ values increased generally and the most significant increase was at $z=6 \text{ cm}$ with 42%. It is mainly due to the interaction between waves and mangrove stems, which leads to an increase of turbulence intensity caused by the stem-wake. What’s more, the rigid stems keep stationary and the maximum relative motion between water and stems occurred. It can enhance the vortex intensity in stem scale. The variation of $TKE$ values was small in canopy scale and vegetation-free upper layer. The former was corresponding to the investigations of Pujol et al. (2013) and Ros et al. (2014) that the flexible vegetation can lead to a reduction of turbulent kinetic energy. Because flexible leaves with a smaller geometric scale can move with the motion of wave, to some extent, the wake-induced vortex was separated into smaller ones, which enhanced the dissipation of $TKE$. The latter is because the damping effect of vegetation becomes weak above the mangrove forest. In addition, the $TKE$ in sparse density was larger than dense in canopy scale and increased with the water level. One possible explanation for this might be the inhibition from flexible canopy, which can promote dissipation. Another possible explanation for this is that the aforementioned nonuniform of wave energy dissipation for different densities: cases with sparse stem density induced higher local wave energy intensity, which resulted in a stronger turbulent kinetic energy.

The results, as shown in Fig. 5b, indicated the significant differences of $TKE$ in diverse wave heights and periods, respectively. Compared with the case of $H_i=4 \text{ cm}$, $T=0.8 \text{ s}$ and $H_i=6 \text{ cm}$, $T=0.8 \text{ s}$ with $N=80 \text{ stems/m}^2$, it is clear that higher incident wave height induced greater $TKE$ values at each measurement point especially for stem scale. The $TKE$ at $z=6 \text{ cm}$ when $H_i=6 \text{ cm}$ was $0.68 \text{ cm}^2/\text{s}^2$ and 59% larger than $H_i=4 \text{ cm}$. The increase of $TKE$ was attributed to the enhanced wave height, which makes more energy convert to the turbulent kinetic energy as propagating in mangroves. Combined the vertical $TKE$ profiles of $H_i=6 \text{ cm}$, $T=0.8 \text{ s}$ and $H_i=6 \text{ cm}$, $T=1.6 \text{ s}$, it indicated that wave with higher wave frequency leads to larger $TKE$ values in the vegetation-free upper layer and canopy region of mangrove forest. This finding is consistent with that of Ros et al. (2014), which showed that the turbulence generation increased with the wave frequency. But it was opposite of
Pujol et al. (2013), which suggested that turbulence generation decreased with wave frequency because the rate of energy dissipation was not uniform over a range of wave frequencies. In this experimental study, the local wave heights for these two cases at the velocity measurement point were close. Consequently, the influence of wave period for $TKE$ might not be caused by the local wave height, but by enhanced wave nonlinearity of higher wave steepness. Much stronger wave-canopy interaction makes the turbulent kinetic energy increase for lower wave period in canopy scale. However, the $\Delta TKE$ was not monotonically increasing with wave frequency, which was discussed later.

![Fig. 5. Vertical profiles of turbulent kinetic energy, $TKE$ and the $TKE$ deviation between the cases with and without mangrove forest, $\Delta TKE$. (a) is vertical $TKE$ distributions for various stem densities when $H_i=6$ cm, $T=0.8$ s. (b) is vertical $TKE$ distributions for different wave conditions with $N=80$ stems/m$^2$. (c) is the relationship between $\Delta TKE$ and the wave frequency for different stem densities (canopy scale). (d) is the relationship between $\Delta TKE$ and the wave frequency for spatial variation in the vegetation field, where the vegetation-free scale is above the vegetation ($z=21$ cm), canopy scale is averaged from the $z=7$ cm to 21 cm, stem scale is the measured point at $z=6$ cm.]
In order to quantify the turbulence generation by the interaction between waves and mangrove forest, the deviation of turbulence kinetic energy between vegetated and control group cases, $\Delta TKE$ for different frequencies were shown in Fig. 5c-d. Fig. 5c gave the $\Delta TKE$ distributions in canopy scale when $H_i=4$ cm for different stem densities. The values of canopy scale were obtained by the averaged velocity and $\Delta TKE$ over the canopy region. It is apparent that the $\Delta TKE$ values decreased with solid volume fraction for each wave frequency in a range from 0.625 Hz to 1.25 Hz. In detail, the $\Delta TKE$ values of $N=80$ stems/m$^2$ were close to zero, indicating that turbulent kinetic energy was similar to that without vegetation. The $\Delta TKE$ values of $N=40$ stems/m$^2$ reached to 30% when $f=0.833$ Hz. It supported the results from Pujol et al. (2013), but it is contrary to Ros et al. (2014). It is because higher stem density can produce more work done by drag force as wave propagating, which can induce more energy dissipation. In particular, the local wave amplitude was highest at the WG5 when $N=40$ stems/m$^2$ and lowest for $N=80$ stems/m$^2$. As mentioned above, higher wave height leads to more turbulence generation. Importantly, the $\Delta TKE$ values for each stem density showed a similar trend against wave frequency, the $\Delta TKE$ increased with increasing wave frequency in the range of 0.625-0.833 Hz and 1.0-1.25 Hz, decreased with increasing wave frequency of 0.833-1.0 Hz. The peak $\Delta TKE$ occurred at $f=0.833$ Hz, which implied that the turbulence generated by mangrove forest was most active when $f=0.833$ Hz in this experiment. In addition, the trend also showed that the canopy region of mangrove forest promoted the turbulence generation in the presence of rigid stems and flexible branches-leaves because the rigid stems seemed to play a major role.

From Fig. 5d, there is a significant difference in the $TKE$ production by three regions of mangrove forest in $N=40$ stems/m$^2$ ($H_i=4$ cm). For the vegetation-free upper layer, negative $\Delta TKE$ were found for all wave frequencies. The $\Delta TKE$ increased with increasing wave frequency in the range of 0.625-0.833 Hz and 1.0-1.25 Hz, decreased with increasing wave frequency of 0.833-1.0 Hz, the $\Delta TKE$ peaked at $f=0.833$ Hz. These results were likely to be related to wave energy dissipation by vegetation. The reduced local wave height caused the reduced wave velocity in the vegetation-free upper layer, where the water movement was less affected by vegetation. It could lead to lower turbulence intensity and
negative $\Delta TKE$ values. Well inside the mangrove forest canopy, the $\Delta TKE$ values were positive and the dependence of $\Delta TKE$ on wave frequency was similar to the vegetation-free upper layer and the maximum values of $\Delta TKE$ was also observed at $f=0.833$ Hz and reach to 30%. Although the local wave velocity for each wave frequency has decreased, the turbulence intensity was enlarged by the interaction between waves and canopy region. It is worth mentioning that the peak value of $\Delta TKE$ was at $f=0.833$ Hz might be that the frequency was near the resonance frequency. For the cases within the stem scale, it can be seen that the $\Delta TKE$ values were positive and larger than the cases within and above canopy. The $\Delta TKE$ values in stem scale nearly increased with the increasing wave frequency in the scope of the test. Although the $u_{w,RMS}$ decreased from 6.729 cm/s toward 3.655 cm/s, the $\Delta TKE$ increased from 16.91% at $f=0.625$ Hz to 66.26% at $f=1.25$ Hz. Differences in $\Delta TKE$ trend in stem scale may have influenced by the wave nonlinearity of high frequency.

3.3. TKE prediction within mangrove forest

3.3.1. TKE within stem scale

The region from $z=0$ to 7 cm was the stem region, including stationary rigid rods and the wake dynamics were similar to array of cylinders under the action of waves. So it was determined by the Keulegan-Carpenter number, which was defined as:

$$ KC = \frac{(u_{max} - u_c)T}{d} $$

(11)

where the $u_{max}$ denotes the maximum phase-averaged velocity (Sumer et al., 1997), the parameter $A_w / S$, which obtained by the ratio of wave orbital excursion $A_w$ ($u_{w,RMS}T / 2\pi$) and stem spacing $S$ (Lowe et al., 2005a; Lowe et al., 2005b; Ros et al., 2014). The relationship for measured turbulent kinetic energy, $TKE$ and squared RMS wave orbital velocity $u_{w,RMS}^2$ with different stem densities in stem scale ($z=6$ cm) for $T=1.4$ s was shown in Fig. 6. It is clear that the $TKE$ values increased monotonously with $u_{w,RMS}^2$ and it presented an approximately linear relationship in this range. The result well supported the model equation (9) given in section 2.3, and was consistent with previous studies (Chen et al., 2020; Tang et al., 2019; Zhang et al., 2018). The rate of increase developed with the
solid volume fraction, for example, the increase rate for bare bed was 0.0027, which was close to zero and 0.009 for vegetated cases of $N=80$ stems/m$^2$. There are two factors that influence the turbulence generated by the stem wakes: when $KC<6$, vortex shedding will not occur and shed vortices preserved close to the stem when $A_w/S<1$ (Zhang et al., 2018).

Specifically, for the cases in Fig. 6, $KC$ numbers ranged from 14 to 26 and $A_w/S<1$ in stem scale, it implied that the vortex shedding occurred and remained close to the stem. For more details, when $u_{w,RMS}^2$ was near to 38 cm$^2$/s$^2$ and $KC$ was close to 14 ($H_f=4$ cm), there was little difference in the measured $TKE$ between vegetated cases and unimpeded cases especially for sparse stem density. As the wave amplitude increased, the $KC$ number increased to 24 and the vortex shedding intensified. It turns out that the measured $TKE$ of vegetated cases have a higher difference from the control group. In addition, due to the strong relative motion between waves and rigid stems, the wake production can be enhanced by the increasing stems per area. Therefore, $TKE$ within higher stem density were larger in rigid stem scale, but $TKE$ in canopy scale showed the opposite trend, which was discussed below.

![Fig. 6. The relationship between the measured turbulent kinetic energy, $TKE$ and squared RMS wave orbital velocity, $u_{w,RMS}^2$ with different stem densities in stem scale ($z=6$ cm) when $T=1.4$ s.](image)

Based on the $TKE$ prediction model in stem scale (equation (9)) under the oscillatory flow, the predicted turbulent kinetic energy, $k_i$ were obtained. It is apparent that a very satisfactory agreement between $TKE$ and $k_i$ for each stem density was shown in Fig. 7. Previous studies have illustrated that the drag coefficient of vegetation, $C_D$ was dependent
with the KC number (Bradley and Houser, 2009; Mendez and Losada, 2004), here the \( C_D = 1.4 \) was chosen as the appropriate mean value by the results of Keulegan and Carpenter (1958) considering the range of \( KC \) in this test. Assuming the integral length scale \( l_i = \min \{d, s\} \) (Tanino and Nepf, 2008), here the \( s >> d \), so the \( l_i = d \) for each stem density. The scale coefficient, \( \delta \), was calculated by the fitting results between measured turbulent kinetic energy and predicted turbulent kinetic energy considering that the intercept was zero. Then \( \delta = 0.797 \), it was smaller than the results of unidirectional current (\( \delta = 1.1 \)) because of the spatial and temporal variation of the wave (Zhang et al., 2018). Specially, it was slightly greater than the results of Zhang et al. (2018), which might be caused by the vertical mixing and overall exchange effects.

\[ TKE \text{ (cm}^2/\text{s}^2) \]

\[ k_i \text{ (cm}^2/\text{s}^2) \]

**Fig. 7.** Comparison between the measured turbulent kinetic energy, \( TKE \) and the model predicted turbulent kinetic energy, \( \tilde{k}_i \) with different stem densities in stem scale (\( z = 6 \) cm) when \( T = 1.4 \) s. The solid line indicates a 1:1 agreement.

### 3.3.2. TKE within canopy scale

The canopy scale of mangrove forest was made up of flexible leaves and rigid stems, which occupied the elevation of \( z = 7-21 \) cm. \( TKE \) and \( u_{\text{w,RMS}}^2 \) were obtained by the mean value of measured points from \( z = 9 \) to 21cm. In this region, there is a certain motion of leaves with waves and the stem almost keeps stationary. The relationship between the measured \( TKE \) and \( u_{\text{w,RMS}}^2 \) within canopy scale for each stem density when \( T = 1.0 \) s was shown in Fig. 8. Zhang et al. (2018) indicated that the \( TKE \) values increased with \( u_{\text{w,RMS}}^2 \) monotonically when \( u_{\text{w,RMS}}^2 \) was above a threshold of 20 cm\(^2\)/s\(^2\). The trend of \( TKE \) against
$u_{w,RMS}^2$ in canopy scale was consistent with that when $20 \text{cm}^2/s^2 < u_{w,RMS}^2 < 80 \text{cm}^2/s^2$ for each stem density in present study. Compared with the results of stem scale, the $TKE$ values showed a similar pattern and the influence of stem density on $TKE$ was smaller for the canopy scale. The difference of $TKE$ were limited for these three densities especially for lower $KC$ number. Specially, $TKE$ values decreased with the increasing stem density for canopy scale, which was contrary to the aforementioned stem scale. Mangrove forest with higher stem density induced lower $TKE$ values and lower stem density induced higher $TKE$ in canopy scale. This result may be explained by the fact that the unequal performance of wave attenuation by vegetation for different solid volume fraction. Fig. 4, Fig. 6 and Fig. 8 indicated that the velocity within vegetation decreased with the increasing solid volume fraction. $KC$ number would be reduced accordingly and the reduced stem wakes weaken the turbulence intensity. Another possible explanation for the difference between canopy scale and stem scale might be that the enhanced volume of flexible canopy restrained the turbulent kinetic energy by promoting the dissipation of turbulent kinetic energy.

![Graph](image)

Fig. 8. The relationship between the measured turbulent kinetic energy, $TKE$ and squared RMS wave orbital velocity $u_{w,RMS}^2$ with different stem densities in canopy scale when $T=1.0 \text{ s}$. $TKE$ and $u_{w,RMS}$ were obtained by the averaged values from $z=9$ to $21\text{ cm}$.

The modified turbulent kinetic energy prediction model was proposed and adopted to the mangrove forest (equation (10)). Firstly, the solid volume fraction of stem in canopy region was calculated as $\phi_s = \frac{N \pi d^2}{4}$. The drag coefficient of stem, $C_{D,s}$, was chosen as 1.4 for the range of $KC$. Then, the solid volume fraction of leaves in canopy region was determined by the displacement method. For simplification, the drag coefficient of flexible
leaves was chosen as 1.95 which was used for flexible blades of Zhang et al. (2018). Assuming the integral length scale \( l = \min \{ D, s \} \), here the \( D > s \), so the \( l = s \) for each stem density. For the best fitting, the scale factor of leaves \( \delta_c = 0.165 \), the scale factor of stem \( \delta_s = 0.770 \) in canopy region, which was slightly smaller than the scale factor in stem scale.

The comparison between the measured turbulent kinetic energy, \( TKE \) and the model predicted turbulent kinetic energy, \( k_t \) with different stem densities was shown in Fig. 9. From that, it can be seen that the model \( k_t \) was a good predictor for the measured \( TKE \) within canopy scale for all conditions, in which the coefficient of determination \( R^2 \) is 0.97.

The drag coefficient, \( C_D \) was variable for different wave conditions, vegetation properties, and solid volume fractions. The \( C_D \) values decreased with Reynolds number \( Re \) and \( KC \) (Hu et al., 2014; Losada et al., 2016), Nepf (1999) indicated that the \( C_D \) decreased with the increasing stem density. Zhang et al. (2018) explored the variable \( C_D \) on the \( TKE \) prediction and the results showed it could not improve the fit. However, according to the model equation, the \( k_t \) is positively related the \( (N / (1 - \phi_s))^{2/3} \). If \( N \) has a large range of changes and \( C_D \) remains the constant, the fitting results will be worse.

![Fig. 9. Comparison between the measured turbulent kinetic energy, TKE and the model predicted turbulent kinetic energy, k_t with different stem densities in canopy scale (z=7-21cm) when T=1.0 s. The solid line indicates a 1:1 agreement.](image)

### 3.4. Importance of Wave Excursion and Stem Spacing

The ratio of wave excursion and stem spacing \( A_w / S \) can be a good predictor for \( TKE \) within vegetation under the waves. Based on the most relevant parameter affecting the wave attenuation by vegetation (Lowe et al., 2005a; Lowe et al., 2005b), Ros et al.
(2014) and Zhang et al. (2018) explored the relationship between the measured $TKE$ and $A_w / S$. The $TKE$ can be enhanced with increasing $A_w / S$, which represented the wake generation became active. Chen et al. (2020) and our results indicated that $TKE$ increased with $u_{w, RMS}^2$ under pure waves with a constant period, which had a similar slope at all vertical layers. We found that previous $TKE$ prediction models within vegetation can be only applied well for waves with constant frequency, but might not be applicable to waves with a series of frequencies. In this study, we established an empirical formula of $TKE$ in vegetation against $A_w / S$ with different wave frequencies. The $TKE$ was nondimensionalized by $u_{w, RMS}^2$, which was given as following form based on the experimental results:

$$\frac{TKE}{u_{w, RMS}^2} = k\left(\frac{A_w}{S}\right)^c + b$$

(12)

here the $k$, $c$, $b$ are fitted coefficients. As shown in Fig. 10, for the cases of stem scale, the $TKE / u_{w, RMS}^2$ decreased rapidly with the increasing $A_w / S$ especially when $A_w / S < 0.1$. The dashed line showed the best fit of the data with $k = 4.173 \times 10^{-4}$, $c = -1.263$, $b = 6.29 \times 10^{-3}$, and the coefficient of determination $R^2=0.84$, which presented a high dependence. For the cases of canopy scale, the $TKE / u_{w, RMS}^2$ also decreased rapidly with the increasing $A_w / S$ especially when $A_w / S < 0.1$. The data points are more centralized with the best fit of $k = 2.29 \times 10^{-3}$, $c = -0.825$, $b = 1.58 \times 10^{-3}$, and the coefficient of determination $R^2=0.88$, which was better than the stem scale. The varied stem density has no great influence on the fitting effect of $TKE / u_{w, RMS}^2 - A_w / S$. The stem scale and canopy scale of mangrove forest showed a similar trend. Further, the fitted parameters $k$, $c$, $b$ might be determined by the plant properties. The comparison between measured and predicted turbulent kinetic energy both in stem scale and canopy scale was shown in Fig. 11. The canopy scale showed a better prediction.
3.5. Wave dissipation by mangrove and turbulence generation

Wave energy dissipation by vegetation was caused by the work done of drag force (Dalrymple et al., 1984). Nepf (1999) pointed out the turbulence generation within plant wakes was related to the drag of vegetation. Assuming the dissipated wave energy was converted to the turbulence within vegetation, Zhang et al. (2018) proposed the $TKE$ prediction model based on the equality of the rate of turbulence production ($P$) and the rate of wave energy dissipation by vegetation ($\varepsilon$), the $\varepsilon$ was determined from the variation of RMS wave amplitude, $a_{rms}$ measured along the mangrove forest:
\[
\varepsilon = \frac{\partial (E_{c_s})}{\rho h_i \partial x} = \frac{\partial \left( \frac{1}{2} g c_s a_{rms}^2 \right)}{h_i \partial x}
\]

where the \( E \) is the wave energy density, \( c_s \) is the wave group velocity, \( g \) is the acceleration of gravity. Using the viscous dissipation scaling, \( \varepsilon \sim (k_i)^{3/2} l_i^{-1} \), the \( k_i \) can be given as following equation:

\[
k_i = \delta (\varepsilon l_i)^{2/3} = \delta \left( \frac{g c_s l_i}{2 h_i} \frac{\partial a_{rms}^2}{\partial x} \right)^{2/3}
\]

where the \( \delta \) was scale factor, the \( da_{rms}^2 / dx \) was estimated by fitting the gradient of \( a_{rms}^2 \) along the vegetation. This model was applied to the mangrove forest here. The eddy length-scale \( l_i = d \) for the stem scale and \( l_i = s \) for the canopy scale of mangrove forest, respectively. Considering the intercept equals to zero, the \( \delta \) was fitted the measured TKE and \( k_i \) by the equation (14), the comparison between measured TKE and model prediction, \( k_i \) of various wave conditions for each stem density was shown in Fig. 12. The scale factor of stem scale, \( \delta_s = 0.0916 \), and the corresponding coefficient of determination \( R^2 = 0.98 \). The scale factor of canopy scale, \( \delta_c = 0.038 \), the coefficient of determination \( R^2 = 0.96 \). This model for the TKE prediction of these two parts of mangrove forest presented a good agreement. It also can be a great predictor for the TKE estimation within mangrove forest under waves. Importantly, this model does not require more information about the vegetation compared with the equation (9) and equation (10), but it needs the wave heights along the vegetation (Zhang et al., 2018). Apart from the plant characteristics, the effect of horizontal and vertical positions in the vegetation on TKE was considered in the scaling factor. It may cause higher values at the front and top of the vegetation, where the turbulence was stronger at these locations.
Fig. 12. Comparison between measured TKE and model predicted turbulent kinetic energy, \( k_c \), of various wave conditions for each stem density. (a) Stem scale when \( T=1.4 \) s. (b) Canopy scale when \( T=1.0 \) s. The solid line indicates a 1:1 agreement.

4. Conclusions

This paper studied experimentally the velocity structure and turbulence within mangrove forest, which consisted of rigid stem and flexible canopy under regular waves. The TKE and \( \Delta \text{TKE} \) profiles in three regions of mangrove forest were investigated. Firstly, the vertical TKE increased gradually from the bed to upper layer. Higher wave period and incident wave height can induce greater TKE values. In addition, there is a significant difference in turbulence among the three regions of mangrove forest. For stem scale, the stem wake promoted the turbulence generation, which can be enhanced with stem density. For canopy scale, the presence of flexible leaves seemed to inhibit the TKE, the \( \Delta \text{TKE} \) in canopy scale decreased with the enhanced stem density. For the vegetation-free upper layer, the \( \Delta \text{TKE} \) was negative for each wave frequency caused by the wave decay. Importantly, the peak of \( \Delta \text{TKE} \) occurred at the \( f=0.833 \) Hz for canopy scale and vegetation-free upper layer in the range from 0.625 to 1.25 Hz. Further, the TKE values in canopy and stem scale increased monotonically with the \( u_{w,RMS} \) for each stem density.

A TKE prediction model was validated for the stem scale of mangrove forest and a modified model was proposed to utilize for the canopy scale considering the coexistence of flexible leaves and rigid stems. The predicted results showed a satisfactory agreement with measured TKE. Furthermore, the \( \text{TKE}/u_{w,RMS}^2 \) within stem and canopy scale decreased rapidly with the \( A_w/S \) especially when \( A_w/S < 0.1 \). The relationship between \( \text{TKE}/u_{w,RMS}^2 \) and \( A_w/S \) have a good correlation, so it can be an important empirical estimator for the TKE within mangrove forest.

Finally, this study contributes to validating the TKE model to mangrove forest under waves considering the balance between the rate of wave energy dissipation and the rate of turbulent kinetic energy production. It showed a good agreement between measured and predicted TKE values. These findings contribute in several ways to advance our
understanding of turbulence and provide a basis for prediction of turbulent kinetic energy within mangrove forest.

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