Modeling of Coastal Waves and Hydrodynamics in Mangrove Forests

○Che-Wei CHANG (張 哲維), Nobuhito MORI (森 信人)

Mangrove forests, as an ecosystem-based approach for coastal disaster risk reduction (Eco-DRR), were found effective against extreme tsunamis, storm waves and surges in historical records, e.g. Danielsen et al. (2005), Tanaka et al. (2007) and Goda et al. (2019). Comparing with other types of coastal vegetation, mangroves have a higher capability of attenuating wave energy due to their special feature – the complex root system. By reducing the flow speed and increasing the friction, mangrove roots enhance wave dissipation by means of turbulent interactions.

Despite the importance of prop roots, most of the existing numerical models simplified the tree structures (e.g. cylinders) instead of addressing the structural complexity of mangroves, which may lead to inaccurate quantification of mangrove effects. Recent laboratory findings (e.g. Maza et al. 2019, Chang et al. 2019) also confirmed the necessity of integrating mangrove structures in terms of energy dissipation. Thus, this study aims to develop a numerical model, with proper incorporation of mangrove effects based on the experimental findings, to study wave propagation through mangrove forests. A recent field survey on mangrove structures will also be briefly introduced.

Numerical Modeling

A Boussinesq-type model developed by Kim et al. (2009) was adopted in this study to simulate the propagation of coastal waves through mangrove forests. The depth-integrated model in Kim et al. (2009) is based on the governing equations derived for weakly dispersive, turbulent and rotational flows, in which the viscous effects contributing to the vorticity fields due to the bottom shear were incorporated. This is different from the traditional approach, which mostly relied on additional terms to account for the external forces (e.g. bottom friction) to the inviscid Boussinesq equations. In the following, we first present the conservative form of the Boussinesq equations with correction terms:

$$\frac{\partial H}{\partial t}+\frac{\partial HU_\alpha}{\partial x}+\frac{\partial HV_\alpha}{\partial y}+\mathbf{P}_c=0 \quad (1)$$

$$\frac{\partial HU_\alpha}{\partial t}+\frac{\partial HU_\alpha^2}{\partial x}+\frac{\partial HU_\alpha V_\alpha}{\partial y}+gH\frac{\partial \zeta}{\partial x}+H\mathbf{Q}_m^x+U_\alpha\mathbf{P}_c+\mathbf{R}_t^x=0 \quad (2)$$

$$\frac{\partial HV_\alpha}{\partial t}+\frac{\partial HU_\alpha V_\alpha}{\partial x}+\frac{\partial HV_\alpha^2}{\partial y}+gH\frac{\partial \zeta}{\partial y}+H\mathbf{Q}_m^y+V_\alpha\mathbf{P}_c+\mathbf{R}_t^y=0 \quad (3)$$

in which $\mathbf{P}_c$ includes the second-order dispersion and vorticity correction while $\mathbf{Q}_m$ includes both the frequency dispersion corrections and the rotational corrections. Noted that the additional term $\mathbf{R}_t$ in momentum equations is used to implement the mangrove effects. The detailed derivation can be found in Kim et al. (2009).

Parameterization of Mangrove Effects

As the present numerical model is a depth-integrated approximation, a proper parameterization for the mangrove effects is needed. Using the Morison-type formula (Morison et al. 1950), we model the mangrove effects as:

$$\mathbf{R}_t=\frac{1}{2H}\mathrm{C_D}N_t\int_{-h}^{\eta}\mathbf{U}|\mathbf{U}|d\mathbf{A}(z)+\frac{1}{H}\mathrm{C_M}N_t\int_{-h}^{\eta}\frac{\partial \mathbf{U}}{\partial t}d\mathbf{V}(z) \quad (4)$$

where H is the total water depth (= still water level h + free surface elevation η), N_t the stem density and $\mathbf{U}$ the fluid velocity vector. The vertical variation of the frontal area and submerged volume of mangrove trees are both considered in $\mathbf{A}$(z) and $\mathbf{V}$(z). Obviously, the drag coefficient C_D and inertia coefficient C_M need to be prescribed. Therefore, here we introduce the new empirical formulas based on the experimental findings in Chang et al. (2019). In their experiments, 3D-printed tree models that scale down the exact structure of a real mangrove were used and the wave forces exerted on the mangrove model were directly measured. Using the Morison-type equation as in Eq. (4), the force coefficients can be found. An example of the estimated drag coefficients by their experiments is shown in Fig.1, in which the best-fitting equations in terms of two dimensionless parameters are also presented. It should be noted that both the Reynolds number and KC number in Fig.1 are defined using the trunk diameter at breast height (DBH) as the length scale. More formulas can be found in Chang et al. (2019). Incorporating the empirical formulas with Eq. (4), the mangrove effects can then be simulated in the numerical model.

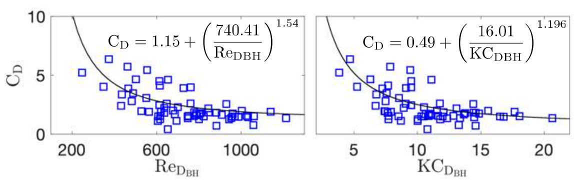

Figure 1 – Drag coefficient vs. Reynolds/KC number (squares: data, solid lines: best-fitting formulas)

An alternative approach (Chakrabarti et al. 2017) to estimate mangrove effects is using the representative velocity $\mathbf{U}_\alpha$ in Eq. (4):

$$R_t = \frac{1}{2H} C_D N_t \mathbf{U}_\alpha |\mathbf{U}_\alpha| \int_{-h}^{\eta} d\mathbf{A}(z) + \frac{1}{H} C_M N_t \frac{\partial \mathbf{U}_\alpha}{\partial t} \int_{-h}^{\eta} d\mathbf{V}(z) \quad (5)$$

in which $\mathbf{U}_\alpha$ is the horizontal velocity vector at the reference level ($z = z_\alpha$). More detailed simulated results will be presented in the meeting.

Field Investigation of Mangrove Structures

Different from the existing numerical models, the present model made a breakthrough, parameterizing the mangrove effects based on the empirical formulas which were obtained by using realistic tree models in the experiments. On the other hand, as shown in several field studies, the complexity of mangrove structures and their large regional variation increase the difficulty to quantify mangrove effects on disaster reductions and future risk assessment. This has been an obstacle to implement mangrove forests afforestation in reality. To overcome the current situation, in addition to the numerical modeling, we recently conducted a field survey, using the latest 3D laser scanner as shown in Fig.2. The scanner was used to capture the detailed structures of mangrove trees, which will help establish a database of the characteristics of mangrove roots to complete the numerical tool for further study. The scanned images can also be used in later laboratory experiments to reproduce 3D-printed tree modes, which will provide more precise and complete parameterization of mangrove effects.

Figure 2 – Application of the 3D scanner in the fields

References

[1]. Danielsen et al. (2005). The Asian tsunami: a protective role for coastal vegetation. *Science*, 310, 643.

[2]. Tanaka et al. (2007). Coastal vegetation structures and their functions in tsunami protection: experience of the recent Indian Ocean tsunami. *Landscape and Ecological Engineering*, 3, 33-45.

[3]. Goda et al. (2019). Cascading geological hazards and risks of the 2018 Sulawesi Indonesia Earthquake and sensitivity analysis of tsunami inundation simulations, *Frontiers in Earth Science*, 7, 261.

[4]. Maza et al. (2019). Experimental analysis of wave attenuation and drag forces in a realistic fringe Rhizophora mangrove forest. *Advances in Water Resources*, 131, 103376.

[5]. Chang et al. (2019). Estimation of wave force coefficients on mangrove models. *Journal of Japan Society of Civil Engineers*, Ser. B2, 75, I_1105-I_1110.

[6]. Kim et al. (2009). A depth-integrated model for weakly dispersive, turbulent, and rotational fluid flows, *Ocean Engineering*, 27, 198-214.

[7]. Morison et al. (1950). The force exerted by surface waves on piles. *Petroleum Transactions*. 189, 149-154.

[8]. Chakrabarti et al. (2017). Boussinesq modeling of wave-induced hydrodynamics in coastal wetlands, *J. Geophys. Res. Oceans*, 122, 3861-3883