MODELING WIND WAVE DEVELOPMENT BASED ON PHASE-RESOLVING WAVE MODEL AND ITS APPLICATION TO TYPHOON JEBI in 2018

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INTRODUCTION

The extreme wave hazards caused by typhoons in bays are increasing. An accurate deformation evaluation of typhoon-induced high waves in coastal regions is critical to mitigate disasters. High wave deformation is an intermediate phenomenon rarely modeled by current wave models, the phase-resolving and spectral wave models.

This study aims to develop a phase-resolving wave model that considers the development of wind waves in shallow water under strong wind conditions. A wind-wave growth term, which includes the local wave deformation, is introduced into the phase-resolving wave model. XBeach (Roelvink et al.(2009)), an open-source model based on the nonlinear shallow water equation with non-hydrostatic pressure, is used for the numerical calculation. The wind wave growth term is parameterized, and the new momentum expression for wave development is verified through sensitivity experiments. The proposed model simulates the overtopping volume under the calculation condition of typhoon Jebi in 2018.

INTRODUCE WIND-WAVE GROWTH TERM

Wind-wave growth term is expressed based on Miles' theory (Miles(1957)). The pressure distribution on water surface p_a can be written as:

$$p_a = \frac{\rho_a}{\rho}\frac{2\beta}{\kappa^2}\frac{\partial\eta}{\partial x} \tag{1}$$

where, ρ_a is air density, ρ is water density, β is Miles energy transport coefficient, κ is Karman constant, η is water surface height. The pressure gradient term in shallow water equations is expressed:

$$\frac{1}{\rho}\frac{\partial p}{\partial x} = -g\frac{\partial\eta}{\partial x} + \frac{\partial p_a}{\partial x} = -g\frac{\partial\eta}{\partial x} + \frac{\rho_a}{\rho}\frac{2\beta}{\kappa^2}\frac{\partial^2\eta}{\partial x^2} \tag{2}$$

The last term in Eq.(2) is defined as the wind wave growth term. We assume $\eta = \sin(kx - t)$, therefore, the wind wave growth term in Eq.(2) will be

$$\frac{\rho_a}{\rho}\frac{2\beta}{\kappa^2}\frac{\partial^2\eta}{\partial x^2} = -\frac{\rho_a}{\rho}\frac{2C_{miles}}{\kappa^2}\eta \tag{3}$$

Here, $C_{miles} = \beta k^2$. In addition, the momentum transport process is examined. Mitsuyasu (1985) indicates that the momentum which the sea surface receives from wind is used for wave development and then transported to current through turbulences at the surface due to wave breaking. Therefore, in this study, the total momentum from wind to sea surface is expressed as a summation of the momentum for the wave development and currents:

$$\bar{\tau}_{total} = \overline{\rho_a {u_*}^2} \tag{4a}$$
$$= \overline{\alpha\rho_a {u_*}^2} + \overline{(1-\alpha)\rho_a {u_*}^2} \tag{4b}$$
$$= \bar{\tau}_{wave} + \bar{\tau}_{current} \tag{4c}$$

where, u_* is friction velocity and α is the momentum distribution coefficient. The momentum for wave development $\bar{\tau}_{wave}$ should correspond to the force $\bar{F}_{miles}$ which acts on a water column due to pressure distribution at the surface. Since F_{miles} can be written as $-\rho_a {u_*}^2 \frac{2\beta}{\kappa^2} k^2\eta(h+\eta)$ assuming $\eta = \sin(kx - t)$,

$$\overline{\alpha\rho_a {u_*}^2} = \overline{\rho_a {u_*}^2 \frac{2\beta}{\kappa^2} k^2\eta(h+\eta)} = \rho_a {u_*}^2 \frac{2\beta}{\kappa^2} k^2\overline{\eta^2} \tag{5}$$

The spatial average at fetch i is obtained by averaging the square of the water surface height η for 200m before and after the arbitrary fetch in each time step ($\overline{\eta^2}_i = \mathrm{mean}({\eta_{i-200}}^2 \sim {\eta_{i+200}}^2)$). In the idealized numerical calculation, the wavelength of the incident wave is to be about 121m. Therefore 200×2m η data covering three waves is used for the spatial average. From Eq.(5), the wind wave growth coefficient C_{miles} is defined as:

$$C_{miles} = \beta k^2 = \frac{\alpha\kappa^2}{2\overline{\eta^2}} \tag{6}$$

C_{miles} is implemented to the wind wave growth term given in Eq.(3). The wind wave growth coefficient C_{miles} is a function of wave height η and decreases as waves develop.

The ratio of momentum used in wave development should decrease as waves evolve. Therefore, the momentum distribution coefficient α should vary with the wave height. There are two ways to determine α.

[Method A] The momentum distribution coefficient α is given as:

$$\alpha = -A\overline{\eta^2} + 1 \tag{7}$$

The coefficient A is optimized by comparing SWAN results.

[Method B] The momentum distribution coefficient α is given as:

$$\alpha = -A\overline{\eta^2}^* + 1 \tag{8}$$

where, $\overline{\eta^2}^* = \overline{\eta^2}\left(\frac{g}{{U_{10}}^2}\right)^2$, g is gravity and U_{10} is 10m height wind speed.

MODEL SETUP

A monochromatic wave is input to test the wind-wave model in idealized conditions. A regular wave with a height of 1 m and a period of 10 s travels in a one-dimensional domain with a depth of 20m. The maximum fetch is 5000m, and the calculation time is 3600s. Wind blows constantly in 10, 20, 30, 40, 50m/s. The η data from 2000 to 3600s after the beginning of the simulation is used for the analysis calculation. This is because the waves became fully developed after 2000 s. Then, only the wave components with frequencies from 0.05 to 0.15 are extracted to obtain only the data for which period is close to the incident waves. The root-mean-square value $\sqrt{\overline{\eta^2}}$ is then calculated and multiplied by 4 to obtain the significant wave height. The slope of the approximation line of the significant wave height is defined as the wave growth rate. It should be noted that the mean water level does not change because the right side of the domain is the open boundary in the idealized calculation.

Under the calculation conditions assuming the 2018 Typhoon Jebi in Osaka bay, irregular waves based on the JONSWAP spectrum with a wave height of 0.1m, peak period of 5s, diffusion coefficient of 1000, and peak amplification factor of 3.3 are input from the left boundary. In each case, the phase of the incident irregular wave is varied by 10 patterns, and ensemble calculations are performed. For simplicity, the wind speed is assumed to be steady, blowing perpendicular to the seawall.

RESULTS AND DISCUSSION

The distributions of significant wave height in each case are compared (Figure 1). The result when the wind wave growth coefficient C_{miles} is constantly 0.06 and the momentum distribution coefficient α is not introduced (red line) shows that the waves are overdeveloped, especially in the 4000 to 5000m fetch ranges and underdeveloped in the range of 100 to 400m. By introducing C_{miles} as a function of η and the momentum distribution coefficient α, the overdeveloping in 4000 to 5000m has been improved (green line). In this case, α=0.2, which means 80% of the momentum is distributed to the current and 20% to wave development, is adopted. The underdevelopment in 100 to 400m is still observed. The cyan and orange lines are the results when variable α is used. α equation is determined by SWAN optimization([Method A]) in cyan case, and by maximum wave energy $\overline{\eta^2}$ ([Method B]) in orange case. In both cases, significant wave heights developed almost linearly, showing a good agreement with SWAN result (gray line) which is based on wave energy calculation. This implies the momentum for wave development is properly represented in this model. The orange case which is using α based on the maximum wave energy $\overline{\eta^2}$ ([Method B]) shows a small overdevelopment in 4000 to 5000m. However, it can be pointed out that those results show improved wave development. Also, they are in good agreement with the relationship between significant wave height and fetch (fetch law) by using the parameterized momentum distribution coefficient α depending on η. Figure 2 shows the time series of the overtopping volume in each case under the typhoon Jebi condition. As you can see, the overtopping volume is greatly improved by introducing the momentum distribution coefficient α (green line). In addition, the results using α which is parameterized with respect to the wave height η (cyan and orange line) shows the closer overtopping volume to the measured value. This can be a result of the appropriate representation of the momentum for wave development. In terms of the overtopping volume only, the case with α based on the maximum wave energy $\overline{\eta^2}$ ([Method B]) shows the best result.

CONCLUSION

In this study, we have considered wind-wave growth term to the shallow water equations in the conventional phase-resolving wave model to calculate both the wind-wave development and the wave deformation. In addition, the momentum balance between waves and currents is introduced to express the appropriate momentum budget for wave development. The proposed model can express wave growth properly which shows a strong agreement in wave growth rate with fetch law.

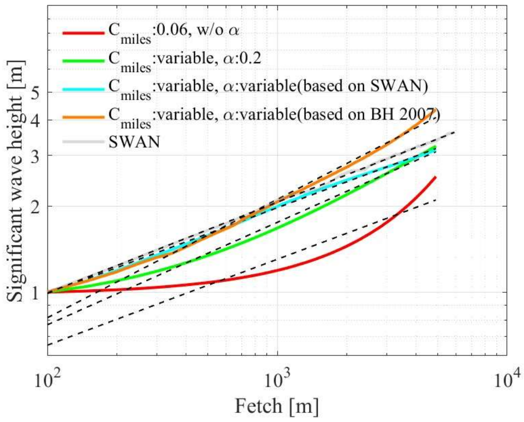

Figure 1 - Spatial distribution of significant wave height and approximate line (red line: C_{miles} =0.06 and α is not implemented, green line: C_{miles} is a function of wave height and α=0.2, cyan line: both C_{miles} and α are a function of wave height and α is optimized by SWAN, orange line: both C_{miles} and α are a function of wave height and α is determined by the maximum wave energy, dotted lines are the approximate line of each case, wind speed: 30m/s

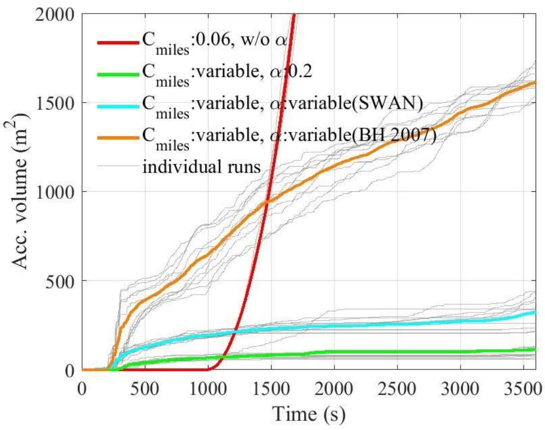

Figure 2 - Time-series of the accumulated overtopping volume (red, green, cyan, and orange lines show the same cases as Figure1, gray line: the result for individual run)

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