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THE APPLICATION OF SWAN TO THE SIMULATION OF A STORM SURGE

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Abstract: SWAN (acronym for Simulating WAves Nearshore) is known as a third-generation wave model which was developed specially to simulate the random short-crested wind-induced waves in coastal regions and inland waters. The model describes the evolution of wave spectrum by solving the spectral action balance equation. Compared with WAM, SWAN includes two additional processes of depth-induced wave breaking and triad wave-wave interactions, which are important for nearshore wave prediction. This paper presents the preliminary outcomes of employing SWAN to simulate waves induced by a tropical storm. Two testing cases are first simulated by using SWAN: one is the refraction of an obliquely incident wave with a single frequency propagating from deep to shallow water; the other is the generation of waves by a constant wind field blowing over a fixed fetch F with unlimited duration t_d. The numerical results of significant wave heights and periods have shown a favorable match to theoretical solutions or empirical equations. Finally, SWAN is used to simulate a realistic case of wave generation and propagation during a tropical storm. In the future work, since SWAN cannot calculate directly the change of mean water level and wind-induced current, the Princeton Ocean Model (POM), which was developed to simulate large-scale ocean circulation, is coupled with SWAN to model the wind-induced current and tidal effects on the storm surge.

Key words: SWAN, Numerical simulation, Wave propagation, Storm surge

1. INTRODUCTION

SWAN (Booij et al., 1999 and Ris et al., 1999) is a third generation wave model that can be used to predict wave conditions varying slowly in space and time near coastal regions for environmental impact studies of sediment transport, shoreline transformation and marine disaster prevention (Wornom et al., 2001). Based on the spectral action balance equation, this model was specially designed to compute spectra of random short-crested wind generated waves on rectangular or curvilinear grids. SWAN uses the wave action density spectrum instead of energy density spectrum because in the presence of currents, action density spectrum is conserved whereas energy spectrum is not. It assembles in the right-hand side of this action density equation nearly all of the physical processes that account for wind input, whitecapping, bottom friction, depth-induced wave breaking and nonlinear wave-wave interactions in coastal and inland waters. Since these physical processes appear to be modular in the programming code, further improvements are ready to be done in a structural manner. Compared with WAM, which was developed to simulate deep water wave propagation, SWAN accounts for depth-induced wave breaking and triad wave-wave interactions that may be important for nearshore wave predictions.

The structure of this paper is as follows. The model is briefly described in section 2. Testing cases of this model with discussions are presented in section 3. The application of

SWAN to the simulation of a storm surge around Singapore is described in section 4. The prospect of future work is given in section 5.

2. MODEL DESCRIPTION

SWAN describes the evolution of waves over coastal regions with wind input, energy dissipation, wave-wave interactions and parameter changes due to variation of water depth and the effect of currents. This two dimensional wave spectrum can be described by the spectral action balance equation as follows:

$$\frac{\partial N}{\partial t}+\frac{\partial (c_x N)}{\partial x}+\frac{\partial (c_y N)}{\partial y}+\frac{\partial (c_\sigma N)}{\partial \sigma}+\frac{\partial (c_\theta N)}{\partial \theta}=\frac{S}{\sigma} \tag{1}$$

where N is the action density spectrum, which is equal to energy density spectrum divided by the relative frequency. In this equation, σ and θ are wave relative frequency and wave direction, respectively. The first term in the left-hand side of the above equation represents the local rate of change of wave action density spectrum in time. The second and third terms represent propagation of wave action in geographical space with velocities c_x and c_y in x and y- directions, respectively. The fourth term represents shifting of the relative frequency due to variations in depths and currents with propagation velocity c_σ in σ- space. The fifth term represents depth-induced and current-induced refraction with propagation velocity c_θ in θ-space. The expressions for all of propagation velocities are taken from linear wave theory. The term at the right-hand side of the wave action balance equation is the source term of energy density representing wave generation, energy dissipation and non-linear wave-wave interactions.

$$S = S_{\text{in}} + S_{\text{ds}} + S_{\text{nl}} \tag{2}$$

Waves obtain energy input from wind (S_{in}). Three processes for energy dissipation in SWAN are whitecapping, bottom friction and depth-induced wave breaking where bottom friction dominates in shallow water whereas whitecapping is the main source of energy dissipation in deep water. Energy is transformed between waves by nonlinear interactions. In shallow water, triad wave-wave interactions play a major role. However, quadruplet wave-wave interactions are important in deep water.

3. TESTING OF SWAN WAVE MODEL

SWAN is the numerical model for waves propagating over coastal and inland waters. Based on state-of-the-art formulations, SWAN is able to simulate various physical problems. Palmsten (2001) has taken systematic testing of SWAN over the southwest Washington inner continental shelf where high energy environment exists. Unfortunately, there are still some numerical properties of SWAN Palmsten didn't interpret or test thoroughly. One of purposes of this paper is the further test of wind-induced waves during a storm for its dependence on spatial and directional resolutions as well as the physical processes. The numerical results of SWAN are also compared with theoretical or empirical solutions.

3.1 WAVE REFRACTION IN COASTAL AREA

In SWAN, when Cartesian coordinate is used, geographic space is discretized with rectangular grids $\Delta x \times \Delta y$. The sensitivity of numerical results to the spatial resolution can be tested by a single frequency wave propagating obliquely from deep to shallow water. Suppose the wave with T_s=10s is propagating with the incident angle 30° (to the normal direction of the shoreline) from deep water (50.1m) to shallow water (0.1m) in an area of 15km alongshore times 4km offshore. The beach slope is 1:80. The variation of horizontal resolution has almost no effect on the numerical results since waves are nearly homogenous in this direction. However, the effect of the spatial resolution in y-direction is obvious as shown in Fig. 1. When waves approach the beach, waves change direction due to refraction.

By the time waves break, the crests are almost parallel to the beach. Fig. 1 shows that the closer waves approach the shoreline, the more sensitive the numerical results are to the spatial resolutions because of the quicker change of wave direction. From Fig. 1, the numerical result approximates the theoretical analysis when the spatial resolution is reduced to zero, but Δ*y*=100m can adequately resolve the wave refraction for this test.

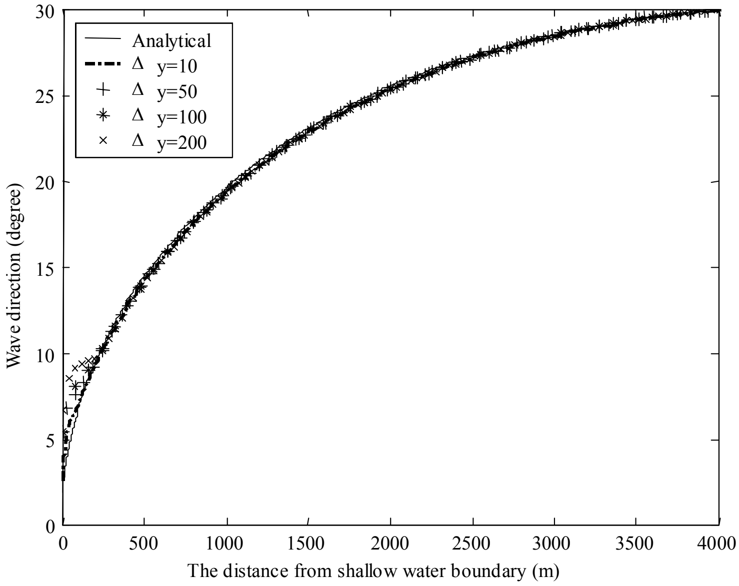

Fig. 1 The propagation of obliquely incident wave from deep to shallow water
The wave incident angel is 30° and Δy represents spatial resolution
in *y*-direction. Δθ=1° is used for all the above cases

The directional resolution is another important parameter to consider. The same case as mentioned above is studied but the directional resolution varies from 1° to 8° Fig. 2 shows that the numerical result approaches the analytical solution as the magnitude of the directional resolution reduces. When the directional resolution reduces to 4°, further reduction of Δθ will not change the results significantly.

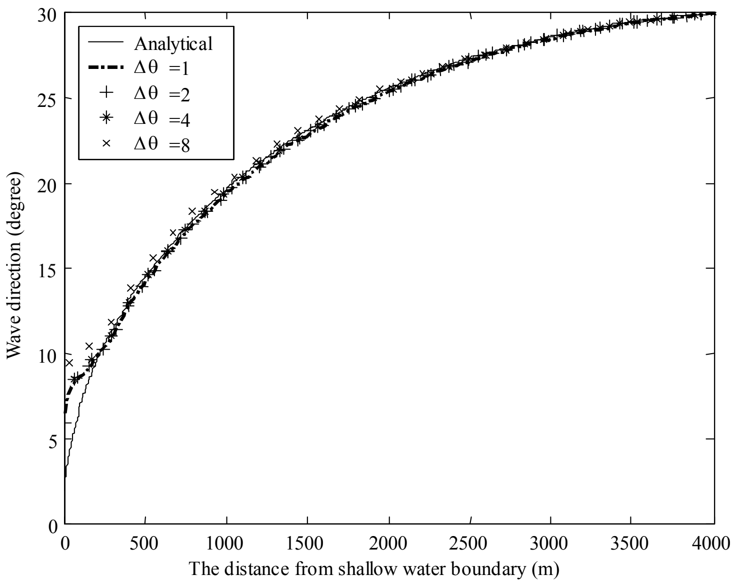

Fig. 2 The propagation of obliquely incident wave from deep to shallow water. The wave incident angel is 30° and Δθ represents directional resolution. Δ*y*=125m is used for all the above cases

3.2 WIND GENERATED WAVES

Wind transfers energy to water by means of their interaction at the interface. If the wind duration (t_d) exceeds the time required for the waves to travel the entire fetch length (i.e., $t_d > F/c_g$, F is the fetch length and c_g represents wave group velocity), the characteristics of the waves at the end of the fetch will depend on the fetch length and the wind speed. For fetch limited conditions, the significant wave height (H_s) and wave period (T_s) are given by the following empirical equations:

$$\frac{gH_s}{U^2} = 0.283\tanh\left[0.0125\left(\frac{gF}{U^2}\right)^{0.42}\right] \qquad \frac{gT_s}{2\pi U} = 1.2\tanh\left[0.077\left(\frac{gF}{U^2}\right)^{0.25}\right] \tag{3}$$

U and g are wind speed and gravity, respectively. Suppose a wind of constant speed (25m/s) is blowing over a stretch of deep water ($16 \times 16\ \text{km}^2$) with wind direction perpendicular to the boundary. The numerical results of SWAN are compared with those from empirical equations in Fig. 3 and Fig. 4. The numerical value T_s is taken as 93.1% of wave peak period T_p (Yu, 2000), which is generated directly from SWAN.

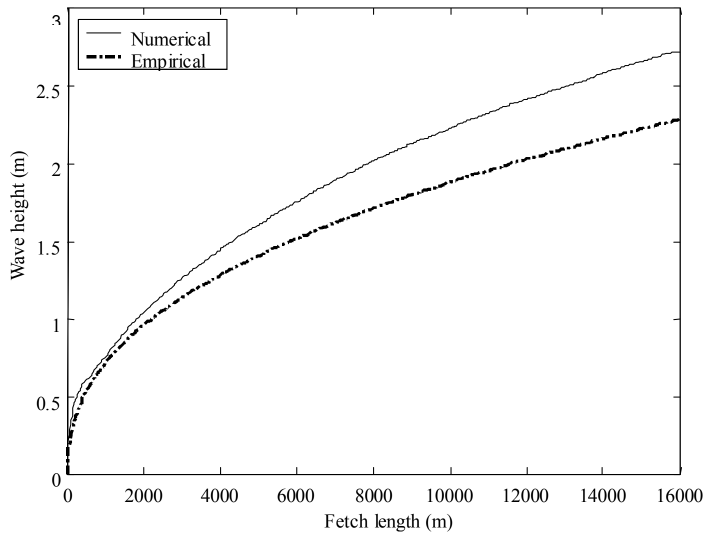

Fig. 3 The comparison of significant wave height by SWAN (solid line) with the empirical equation (dash-dotted line)

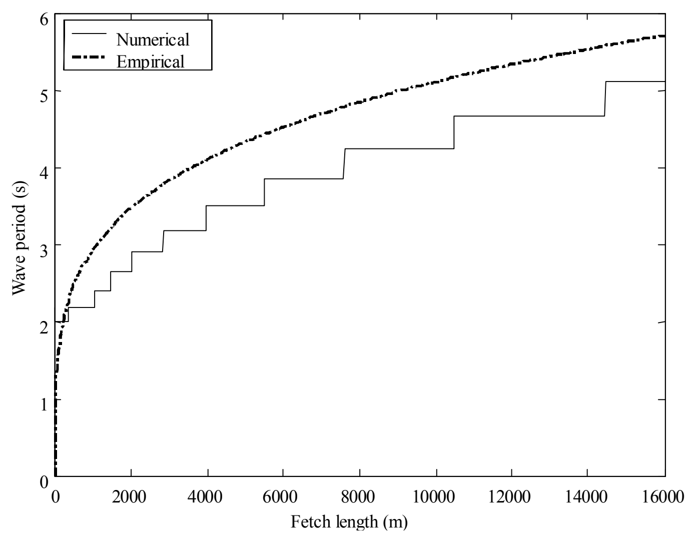

Fig. 4 The comparison of significant wave period by SWAN (solid line) with the empirical equation (dash-dotted line)

Based on Ippen (1966), the energy is transmitted by normal stress at the very early stages and the transmission by tangential stress is dominant when ratio of wave speed to wind speed is over 0.37. The energy added by wind goes into building the wave height and increasing the wave speed. Fig. 3 and 4 show that the calculated results of both significant wave height and period increase along the fetch length, which is consistent with the theory. The numerical value of significant wave height is however larger than the empirical value due to the underestimation of wave period.

4. SIMULATION OF WAVES IN SINGAPORE WATER

Singapore lies in a low wave energy environment being protected by the Malay Peninsula in the north, Sumatra in the west and Rhio Archipelago in the south. During the Monsoon season, strong waves induced by storms of South China Sea can travel to here and may flood part of coastal area. The maximum wave height recorded in this region is about 1m with a period of 2.5 to 3 seconds during the normal season. In this study, we will assume a storm surge from South China Sea with significant wave height 2m and significant wave period 30s that enters Singapore water with the main direction perpendicular to the east boundary. Considering coastal geography and wave conditions near Singapore, a reflection coefficient with a value 0.15 is used for all land boundaries.

From Fig. 5, wave height is relatively large at the southeast coastline of Singapore where flood was reported. Because of wave refraction, part of wave energy goes north to the river and south out of the outlet. Wave energy is significantly dissipated on the west coast since many islands lie between Singapore and Pulau Batam.

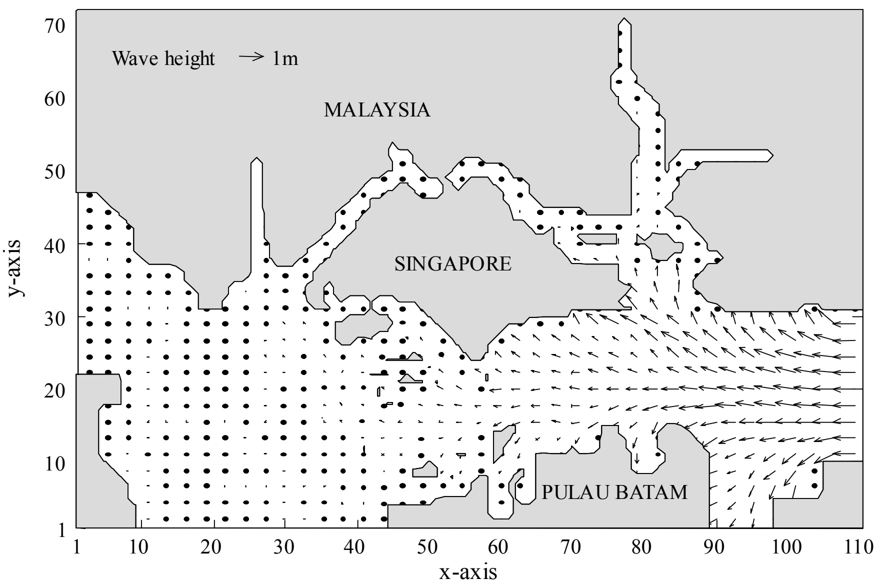

Fig. 5 Computed pattern of the significant wave height and mean wave direction in Singapore water. The magnitude and direction of arrows represent wave height and direction, respectively.

5. FUTURE WORK

SWAN is specially designed for simulating wave propagation in coastal areas. It assembles nearly all of relevant physical processes of wave generation, dissipation and wave-wave interactions. However, there are still some physical processes SWAN does not take into consideration, such as wave-induced current which is quite important in coastal areas where currents are usually strong (Zhang et al., 1996). Also, the temporal variation of tides is also needed to consider because the mean water level changes greatly between low tide and high tide (Choi et al., 2002). To demonstrate the effects of the current and the mean water level on the wave transformation, the following numerical experiments are conducted. Consider an area of 15km alongshore and 6km offshore. The beach has a constant slope. When tide ebbs, the mean water level falls slowly and this induces current to advance offshore. Assume waves propagate normally onshore and a linear variation of current goes normally offshore with the maximum velocity 1m/s at the shallow water boundary (0.2m) and the minimum velocity 0.004m/s at the deep water boundary (50m). In Figure 6, the comparison of numerical results of SWAN is given with current term turned on or not. Obviously, the wave height is changing more as the current becomes stronger. In the same area, if mean water level is 1.5m bigger in high tide than that in low tide, Fig. 7 shows the difference of significant wave height between ebb tide and flood tide. Because mean water level is larger in flood tide, waves transmit further onshore and the breaking point is delayed until the water depth becomes shallower. In the future work, the Princeton Ocean Model (POM, Mellor, G. L., 1998), which was developed to simulate large-scale ocean circulation, will be coupled with SWAN to model the wave, the wind-induced current and tidal effects on the storm surge. The influence of the wave diffraction, which is neglected in SWAN, will be further assessed.

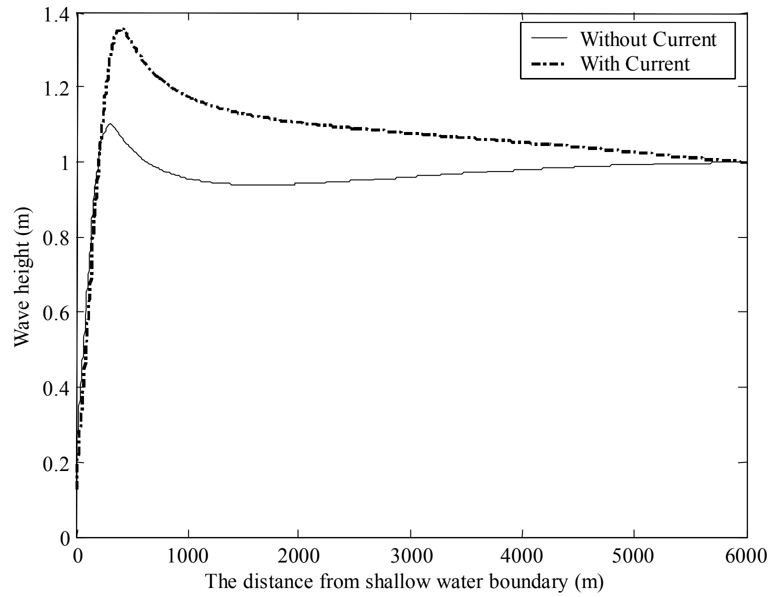

Fig. 6 The comparison of significant wave height with (dash-dotted line) and without (solid line) the effect of current

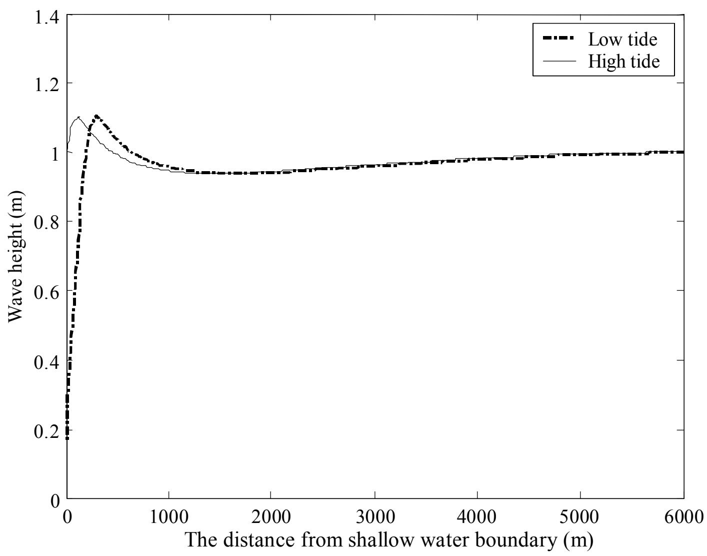

Fig. 7 The comparison of significant wave height at the low tide (dash-dotted line) and the high tide (solid line)

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REFERENCES

Booij, N., Ris, R. C. and Holthuijsen, L. H. (1999), A third-generation wave model for coastal regions, Part I: Model description and validation, *J. Geophys. Res.* Vol. 104, C4, pp.7649-7666.

Ris, R. C., Holthuijsen, L. H. and Booij, N. (1999), A third-generation wave model for coastal regions, Part II: Verification, *J. Geophys. Res.* Vol. 104, C4, pp.7667-7681.

Choi, B. H., Eum, H. M. and Woo, S. B. (2002), A synchronously coupled tide-wave-surge model of the Yellow Sea, *Coastal Engineering*, Elsevier, pp.1-18.

Ippen, A. T. (1966), Estuary and coastline hydrodynamics, McGraw-hill book company, Inc., pp.133-196.

Mellor, G. L. (1998), User's guide for a three dimensional, primitive equation, numerical model, *Prog. In Atmosp. And Ocean Sci.* Princeton University, 41pp.

Palmsten, M. L. (2001), Application of the SWAN wave model to a high-energy continental shelf, Master thesis, University of South Florida.

Wornom, S. F., Welsh, D. J. S. and Bedford, K. W. (2001), On coupling the SWAN and WAM wave models for accurate nearshore wave predictions, *Coastal Engineering Journal*, Vol. 43, No. 3 , pp.161-201.

Yu, Y. X. (2000), Random wave and its applications for engineering, Dalian University of Technology Press, pp.175 (in Chinese).

Zhang, M. Y. and Li, Y. S. (1996), The synchronous coupling of a third-generation wave model and a two-dimensional storm surge model, *Ocean Engng*, Vol. 23, No. 6, pp. 533-543.