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Numerical Analysis of Wind-Wave Climate Change and Spatial Distribution of Bottom Sediment Properties in Sanbanze Shallows of Tokyo Bay

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ABSTRACT

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An integrated model for the prediction of waves and currents as well as bed shear stresses was developed and applied to Sanbanze Shallows of Tokyo Bay. The wave model consists of a wave hindcasting sub-model for the whole of the bay and a wave propagation sub-model for detailed wave computation in Sanbanze Shallows. The wave hindcasting model follows the Shore Protection Manual (SPM) formulas for both shallow and deep-water cases with modification in fetch calculation. A random wave propagation model based on a modified energy balance equation by MASE (2001) is adopted for the computation of the detailed wave field in the shallow waters. The radiation stress gradient was estimated based on the spatial variation in waves considering the vertical profile of the stress after XIA *et al.* (2004). The radiation stress terms were incorporated into the momentum equations of the coastal circulation model developed by SASAKI and ISOBE (1999). The model was validated through comparison between numerical results and time variation in wave and current at two stations in Sanbanze Shallows in September of 1999. The computational results show that the present model can reproduce the trend of time variation in wave and current successfully. The computed bed shear stress distribution, which is dominated by waves rather than currents, correlates with the bottom sediment grain size distribution in the field collected by CHIBA PREFECTURE (1998).

ADDITIONAL INDEX WORDS: *Neareshore current, Bed shear stress, Sediment grain size*

INTRODUCTION

Sanbanze Shallows is one of the scarce and valuable tidal flats and shallow waters remaining at the head of Tokyo Bay, Japan after the long period of reclamation of the foreshore. Most of its area is muddy-sand bottom rich in organisms whereas some parts are muddy beds resulting from the appearance of slack waters, considered to be the cause of water and sediment pollution in the area. In particular, the bed around the corner of Sanbanze Shallows surrounded by Urayasu and Ichikawa in Figure 1 is mud and its water is stagnant and sometimes polluted resulting in deterioration in fishery of short-necked clams. Against this background, measures such as restoration of a sandy tidal flat over the muddy beds have been discussed among governments, researchers and citizens.

To predict the effects of these remedies it is of great importance to reproduce the physical processes in the shallow water. Sanbanze Shallows is a tidal flat and shallow water area connected to oceanic waters of Tokyo Bay through the mouth with steep bottom slope. This topographic characteristics lead to rather complex behaviour of circulations between the oceanic waters and the water in the shallows. Thus it is necessary to compute physical environments in the shallows together with the oceanic waters simultaneously considering the interactions between them. In addition, the effect of waves is also significant, governing the sediment properties such as grain size distribution as well as affecting the current fields through the effect of radiation stresses.

One of the objectives for the present study is to develop an integrated model for realistic reproduction of wave and current fields in the shallows. We design the wave model consisting of a wave hindcasting model and a wave propagation model, computing the wave field in the whole domain of Tokyo Bay from the former one whereas the detailed wave fields from the latter by setting the boundary information from the former one. Since the current fields must be rather complex, we conduct calculation of current fields in the whole domain of the bay, which is easy to consider the interaction between the two water bodies though the computational cost may become high. We also take an approach to reproduce field measurements to evaluate the model performance. Finally, we apply the present model to Sanbanze Shallows and obtain the spatial variation in bed shear stress and make discussion on the effect of wave and current fields on the sediment properties in Sanbanze Shallows.

METHODS

Since Sanbanze Shallows is a tidal flat and shallows facing the oceanic water of the bay, the wave and current field in Sanbanze Shallows is mostly governed by the incident wave from the offshore and the intrusion of the oceanic water from the bay. It is, thus, necessary to include these effects when considering the wave-current characteristics and resultant sediment properties in Sanbanze Shallows. First, we conducted wave hindcasting over the whole of Tokyo Bay. Then, using the hindcasting results as the offshore boundary condition in the Sanbanze Shallows narrow domain, shown as the rectangle in Figure 1, we computed detailed wave field in the domain using a modified energy balance equation model including the effect of wave diffraction as well as

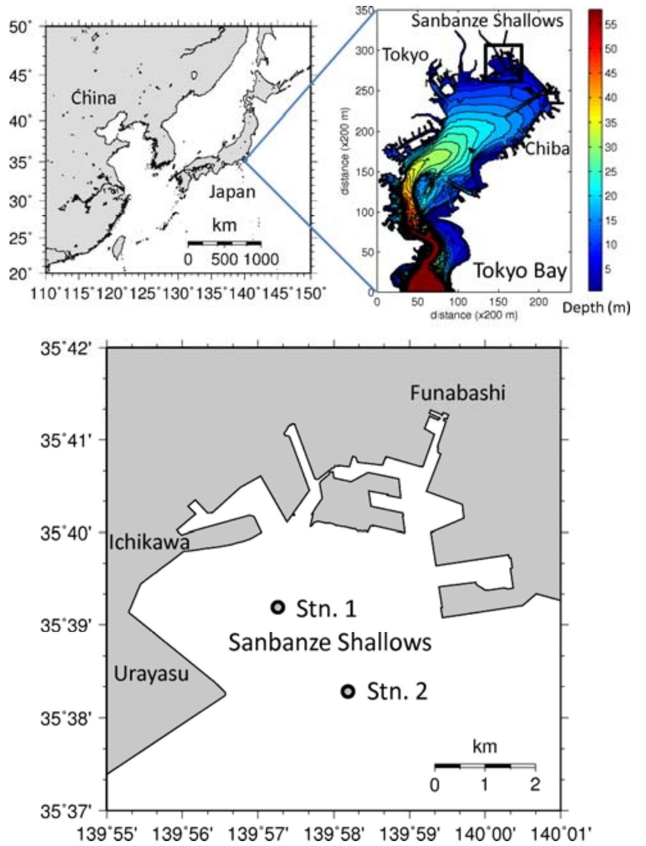

Figure 1. Map of Japan, Tokyo Bay with depth contours, and Sanbanze Shallows.

wave deformation and breaking. Further, we computed current fields in the whole of Tokyo Bay based on a primitive equation model including the effect of wave radiation stresses. The radiation stresses were determined from the results of the wave deformation computation. From these computational results of wave and current field, we further estimated bed shear stresses in Sanbanze Shallows. The details of the models are described as follows.

Wave Hindcasting Model

We adopted the wave hindcasting model of US ARMY CORPS OF ENGINEERS (1984), which is applied to the whole of the bay. The formula for the estimation of the significant wave height in shallow waters is given by:

$$\frac{gH}{U_a^2} = 0.283 \times \tanh\left[0.53\left(\frac{gd}{U_a^2}\right)^{\frac{3}{4}}\right] \times \tanh\left\{\frac{0.00565\left(gF/U_a^2\right)^{1/2}}{\tanh\left[0.53\left(gd/U_a^2\right)^{3/4}\right]}\right\} \tag{1}$$

where H is the significant wave height, F is the fetch, U_a is the wind speed, g is the acceleration of gravity and d is the water depth.

Wave Propagation Model

We adopted the wave propagation model proposed by MASE (2001) for the detailed computation in Sanbanze Shallows. This model is based on a modified energy balance equation including an energy dissipation term and the effect of diffraction given by:

$$\begin{aligned}&\frac{\partial(v_x S)}{\partial x} + \frac{\partial(v_y S)}{\partial y} + \frac{\partial(v_\theta S)}{\partial \theta}\\ &= \frac{\kappa}{2\omega}\left\{\left(CC_g \cos^2\theta S_y\right)_y - \frac{1}{2}CC_g \cos^2\theta S_{yy}\right\} - \varepsilon_b S\end{aligned} \tag{2}$$

where S is the angular-frequency spectral energy density, (x, y) is the horizontal Cartesian coordinates, θ is the angle measured counterclockwise from the x-axis, k is a free parameter for the diffraction effect, and ε_b is the energy dissipation coefficient due to wave breaking.

Coastal Circulation Model

Adopting a primitive equation model for coastal circulation developed by SASAKI and ISOBE (1999), we modified the model to include the effect of radiation stresses by putting the additional term of the vertical profile of the radiation stress onto the momentum equations after XIA et al. (2004).

The equations for continuity and momentum are given by:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial Du}{\partial x} + \frac{\partial Dv}{\partial y} + \frac{\partial (D\dot{\sigma})}{\partial \sigma} = 0 \tag{3}$$

$$\begin{aligned}&\frac{\partial(Du)}{\partial t} + \frac{\partial(Duu)}{\partial x} + \frac{\partial(Dvu)}{\partial y} + \frac{\partial(D\dot{\sigma}u)}{\partial \sigma} = Dfv - \frac{gD}{\rho}\left[(\rho_0 + \rho'\sigma)\frac{\partial \zeta}{\partial x}\right.\\ &\left.+\rho'(\sigma - 1)\frac{\partial h}{\partial x} + \frac{\partial}{\partial x}\left\{D\int_\sigma^1 \rho' d\sigma\right\}\right] + DA_M\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right)\\ &+\frac{1}{D}\frac{\partial}{\partial \sigma}\left(K_M \frac{\partial u}{\partial \sigma}\right) - \frac{1}{\rho}\frac{\partial\{DS_{xx}(\sigma)\}}{\partial x} - \frac{1}{\rho}\frac{\partial\{DS_{xy}(\sigma)\}}{\partial y}\end{aligned} \tag{4}$$

where (x, y, z) are the Cartesian coordinates, h is the water depth from the still water level, ζ is the free surface elevation from the still water level, $D = h + \zeta$ is the total depth, $\sigma = (z + h)/(\varsigma + h)$ is a sigma coordinate transformation, u and v are the horizontal velocity components for x and x directions, respectively, $\dot{\sigma}$ is the pseudo vertical velocity defined as the total derivative of σ with respect to time t, f is the Coriolis parameter, p_a is the atmosphere pressure, $\rho = \rho_o + \rho'$ is the water density, ρ_o is the reference density and ρ' is the deviation from the reference, g is the acceleration of gravity and A_M and K_M are the horizontal and vertical eddy viscosities, respectively, S_{xx} and S_{xy} are the radiation stresses referring to x and y directions, respectively. The last two terms in equation (4) are additional terms for calculation of the gradient of the radiation stresses.

A semi-implicit finite difference algorithm was adopted to solve these equations, where the vertical advection and diffusion terms together with the surface elevation related to the surface gravity waves were discretised in implicit to enhance the model performance with respect to a computation efficiency and robustness (SASAKI and ISOBE, 1999). Other works related with the interaction between wave and current in a circulation model are given by XIE et al. (2001) and MELLOR (2003).

Bed Shear Stresses

Bed shear stresses, one of the most important parameters to determine sediment properties in tidal flats and shallow waters, consist of the two components: stress due to current and stress due

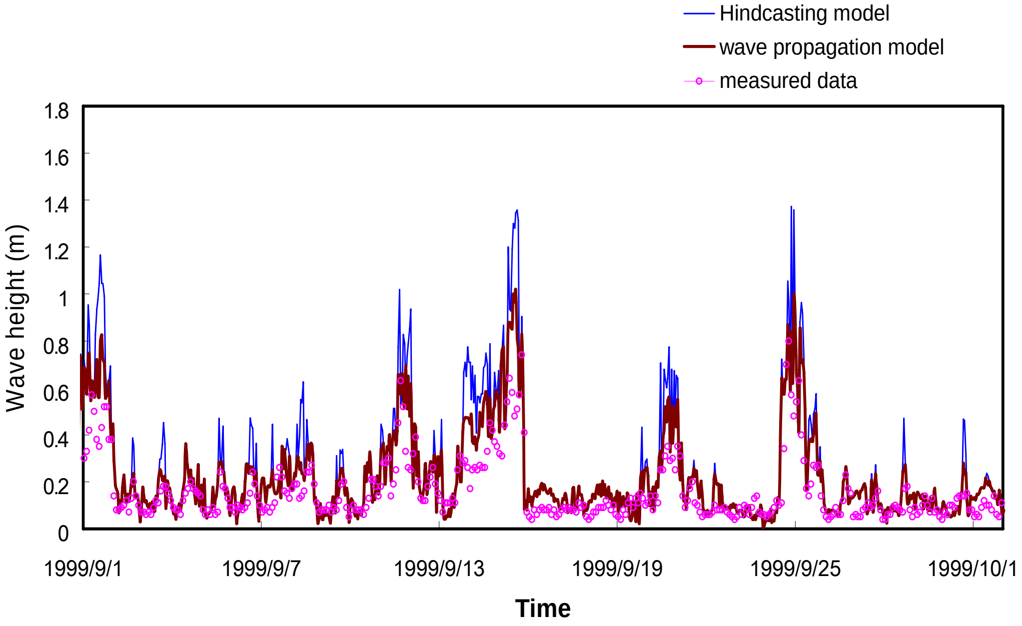

Figure 2. Comparison of time variation in wave height at Stn. 1 in Figure 1 between measured one by Chiba Prefecture (1998) and computed ones based on the hindcasting model and the wave propagation model.

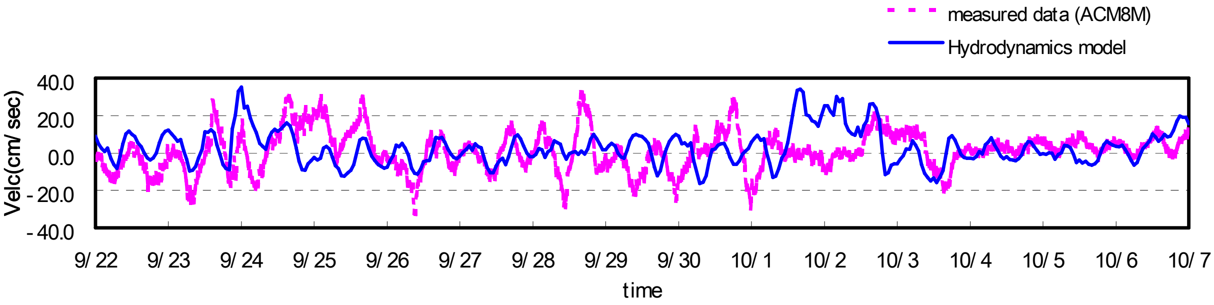

Figure 3. Comparison of horizontal current at Stn. 2 in Figure 1 between measured one by Chiba Prefecture (1998) and computed.

to wave motion. The bed shear stress τ_c due to current τ_c is related to the roughness of the bed, and calculated using the standard logarithmic resistance law as shown in equation (5):

$$\tau_c = \rho g\left(u_b^2 + v_b^2\right)/C_h^{\,2} \qquad (5)$$

where ρ is the water density, u_b and v_b are the bottom current velocities for x and y directions, C_h is the bed shear stress coefficient for current component after Kim and Lee (2003).

The mean bed shear stress due to wave τ_w is given by:

$$\tau_w = 1/2\,\rho f_w U_b^{\,2} \qquad (6)$$

where f_w is the friction factor following Swart (1974), U_b is the amplitude of the horizontal wave orbital velocity on the bed described by:

$$U_b = \frac{\pi H_s}{T}\frac{1}{\sinh\left(2\pi h/L\right)} \qquad (7)$$

where H_s is the significant wave height, T and L are the significant wave period and wave length, respectively, and h is the water depth from the still water level.

Model Forcing

We applied the wave hindcasting model over the whole of Tokyo Bay covered with a 200 m times 200 m horizontal grid system. The hindcasting model was forced by hourly meteorological data collected in Chiba Observatory of Japan Meteorological Agency to obtain time series of wave field in the bay. Then, using the results of the whole domain computation, detailed wave field was calculated by applying the wave propagation model over a 50 m times 50 m grid system. In this simulation, the input parameters are selected as $\kappa = 2.5$, $\varepsilon = 1.0$.

We then computed current fields in the whole of the bay covering Sanbanze Shallows including the effect of radiation stresses. The model was forced by the tidal level at the bay mouth based on the Tide Table of Japan Meteorological Agency, daily river discharge data collected by Ministry of Land Infrastructure and Transport as well as the previous hourly meteorological data.

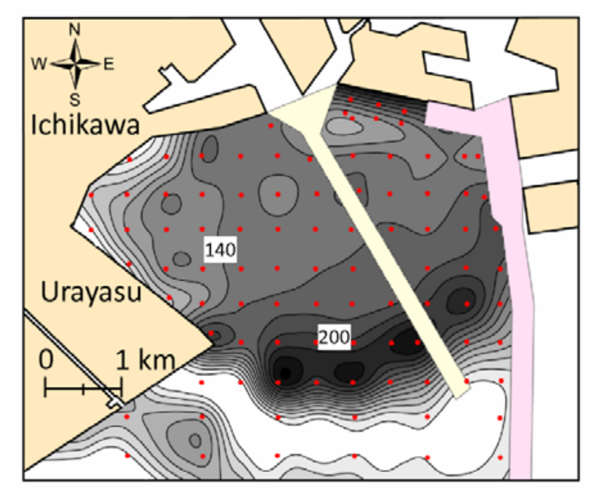

Figure 4. Sediment grain size distribution (μm) in Sanbanze Shallows. The measurements were performed at the points in the figure by CHIBA PREFECTURE (1998).

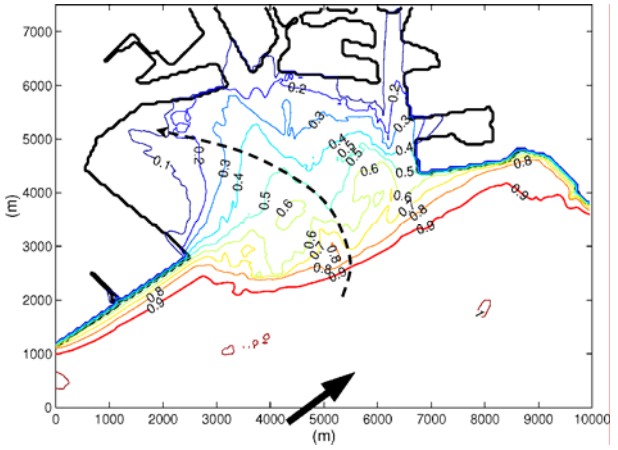

Figure 5. A typical wave height (m) variation under southwest-ward wind condition.

The bed shear stresses due to waves and currents were calculated based on the wave model over the narrow domain and the circulation model in the whole domain, respectively.

RESULTS AND DISCUSSION

Model Validation

In order to evaluate the performance of the present wave model, computed results were compared with field data measured from 1st September to 10th October of 1999 at Stn. 1 in Figure 1. This station is located middle part of Sanbanze Shallows. The comparison was shown as the blue line of graph in Figure 2. From this graph we can say that the hindcasting model can reproduce the time series trend of the measured data well. However, from the quantitative point of view the computed results overestimate the measured ones especially during high wave conditions. This is because the wave hindcasting model does not include the wave breaking effect. Application of the wave propagation model improves this discrepancy well as shown in Figure 2 since it considers the effect of wave breaking reducing the wave height in inner part of the shallows as well as refraction and diffraction.

The results of the wave model were implemented into the circulation model through the additional radiation stress terms in the momentum equations. The performance of the present circulation model was tested comparing to the measured velocity data collected from 22nd September to 10th October of 1999 at Stn. 2 in Figure 1. Figure 3 shows a comparison of the surface level velocity at the station between computed and measured. The overall performance of the calculation is considered to be well, however there are some discrepancies, the computational results mostly underestimating the measured data. One of the causes would be the difficulty in the definition of the water depth at the measured station. The definition of the surface level is vague since the water depth varies from almost 0 (dried) to 1.5 m during the flood tide period. In addition, the profile of the vertical current is sometimes not uniform, showing a steep gradient of velocity profile in the vertical, which results in a large difference in velocity with a small change in distance of measuring point in the vertical.

Sediment Properties in Sanbanze Shallows

The sediment grain size distribution in Sanbanze Shallows was measured by CHIBA PREFECTURE (1998) as shown in Figure 4. The sediment grain size shows about 0.2 mm around the mouth of Sanbanze Shallows and becoming finer as going into the inner part. This trend must be corresponding to the spatial variation in the bed shear. To confirm this matter, we computed detailed wave fields under typical stormy conditions in which offshore incident waves are from southwest, propagating into the Sanbanze Shallows. Figure 5 shows the computed wave field for this case. The wave breaks around the mouth of the Sanbanze Shallows and propagates into the inner domain due to diffraction. The wave height nearby the Urayasu is, however, rather small since the area is a shadow zone. The computed bed shear stress due to waves taking one year average in 1999 is shown in Figure 6. The higher stress appears around the mouth of the Sanbanze Shallows corresponding to the coarse sediment grain size in Figure 4 whereas the lower stress occurs in front of the Urayasu resulted in the finer sediment grain size.

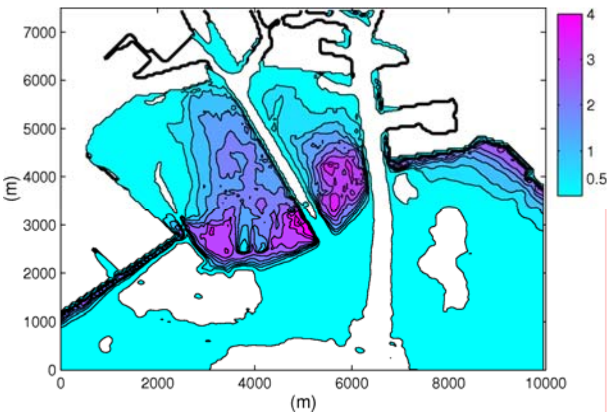

Figure 6. Computed spatial variation in wave bed shear stress ($\times 10^{-3}$ N/m^2).

CONCLUSION

We developed a wave and circulation model integrating the wave hindcasting model, wave propagation model and coastal circulation model. Detailed wave fields in Sanbanze Shallows of Tokyo Bay were obtained by using the wave propagation model together with the results of wave hindcasting model as the open boundary condition. Bed shear stresses were also computed from the wave fields through the linear wave theory. The coastal circulation model was applied to obtain the current fields considering the effect of radiation stresses estimated by the results of the wave fields. The model was forced by time series of boundary conditions such as meteorological properties, river discharges and tidal levels. Verification of the model was performed through the comparison with the field data for waves and currents.

The model can reproduce time variation in waves rather well if considering the effect of wave breaking and diffraction using the wave propagation model. This fact shows that the strategy of the present approach, a two-step calculation of detailed wave fields, seems to be satisfactory. For the current simulation there is some discrepancy with the field data, which is left for the future work.

Then, we performed a computation under a typical stormy condition when principal waves propagate from southwest to northeast. The incident wave breaks around the mouth of Sanbanze Shallows and is propagated to the inner domain with decreasing wave height. The distribution of bed shear stress due to waves, dominant component compared to that due to currents, show a high correlation with the distribution of the measured sediment grain size, the larger value occurs at the mouth of the Sanbanze Shallows representing coarse sediment in the field whereas smaller value observed in front of Urayasu resulting in the muddy bottom.

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