Three Dimensional Structure of Tidal Currents in Tokyo Bay, Japan*

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Abstract: Tides and tidal currents in Tokyo Bay are calculated by using a three dimensional numerical model, where vertical eddy viscosity coefficient is computed by the Prandl's mixing length theory. The results well reproduce the two-dimensional structure of tides and tidal currents in Tokyo Bay, Japan. On the basis of these results, we calculate the vertical tidal current whose amplitude is smaller than $10^{-3}$ cm/s in the most places of Tokyo Bay. At the mouth of Tokyo Bay, where water depth varies rapidly, the amplitude of vertical tidal current attains to the order of $10^{-3}$ cm/s. The tidal stresses calculated in two ways, e.g. two dimensional and three dimensional methods, have no differences in principle in most places of Tokyo Bay.

1. Introduction

It is well known that the currents play an important role in the material transport processes and the tidal currents consist of the major parts of the movements of water in coastal seas. Because the tidal currents have some potential effects to the primary production, the structure of tidal currents, especially its three dimensional structure is worth to study.

The tides and tidal currents in Tokyo Bay have been studied by Yamada (1971), Unoki et al. (1980) and Nagashima and Okada (1984) based on the observed data. Yanagi and Shimizu (1993) calculated the two dimensional tidal currents as a part of the research on the sedimentation processes in Tokyo Bay.

It can be said that we have known the general characters of tides and tidal currents in Tokyo Bay. But as for the vertical tidal currents we have neither observed data nor calculated results about its order or the place where the vertical tidal current is large. And for the research of material transport processes, we need a basic three dimensional current field. For these purposes, we calculate the three-dimensional structure of tides and tidal currents in Tokyo Bay in this paper.

2. Model

2.1 Formulation

Based on the fact that tidal waves are gravitational long-waves (by nature), the first order linear equations is:

\[
\begin{align*}
\frac{\partial u}{\partial t} - fu & = -g \frac{\partial \zeta}{\partial x} + \frac{\partial}{\partial z} \left( \nu \frac{\partial u}{\partial z} \right), \\
\frac{\partial v}{\partial t} + fu & = -g \frac{\partial \zeta}{\partial y} + \frac{\partial}{\partial z} \left( \nu \frac{\partial v}{\partial z} \right), \\
\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x} \int_{-h}^{0} udz + \frac{\partial}{\partial y} \int_{-h}^{0} vdz & = 0,
\end{align*}
\]

(2-1-1) (2-1-2) (2-1-3)

where the continuity equation (2-1-3) has been integrated from the sea bed to the sea surface.

The boundary conditions are:

\[
\begin{align*}
z = -h: \quad & \frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = 0, \\
z = -0: \quad & u = v = w = 0,
\end{align*}
\]

(2-1-4) (2-1-5)

along the shore boundary $C_1$:

\[
\cos \alpha_x \int_{-h}^{0} udz + \cos \alpha_y \int_{-h}^{0} vdz = 0,
\]

(2-1-6)

along the open boundary $C_2$:

\[
\zeta = S.
\]

(2-1-7)

In the above, $x, y, z$ constitute a Cartesian coordinate system at the right-hand side, the plane $x, y$ coincides with the undisturbed sea surface, and $z$ is positive upward; $t$ denotes the time; $u, v$ denote the components of tidal currents in $x,$
\[ \nu = \nu_0 + l \left( \left( \frac{\partial u}{\partial z} \right)^2 + \left( \frac{\partial v}{\partial z} \right)^2 \right)^{1/2} \]  \tag{2-1-8}

the mixing length \( l \) is

\[ l = \kappa_0 (z+h+z_0) \left( 1 - \frac{x}{1+s} \right) \]  \tag{2-1-9}

Where \( \kappa_0 \) is the Karman constant approximately equal to 0.4, and \( z_0 \) is the sea bed roughness length, \( s \) is a parameter introduced by FANG and ICHIYE (1983) which express the roughness of sea surface. \( \nu_0 \) is a small number \( (=2.0 \text{cm}/\text{sec}) \) which prevent the vertical eddy viscosity coefficient from equaling to zero.

2.2 Procedure

The above equations with the constant vertical eddy viscosity coefficient had been solved by means of the splitting velocity method (Sun, 1992) which was applied to tidal problem in Bohai Sea (Wang, 1989) or the East China Sea (Wang, 1992). In their calculations, the authors mainly follow the line of Hansen's boundary-value problem which need many observed data along the coastal line. Usually this is very difficult. By the thought that a correct tidal current field could produce a correct tidal elevation, we would like to follow the idea of hydrodynamics numerical methods. Along this line, Yang (1992) has calculated the tide in Bohai Sea. In our paper, we made some improvements over his works and calculated the tides in Tokyo Bay.

Here, we want to use the A.D.I method (Reedertse et al., 1973), which had been proved as an effective and corrective method in coastal numerical calculations, to treat the time-depending differential terms in the above equation. In the first half time step, we have:

\[ \frac{\Delta u^{n+1/2} - u^n}{0.5 \Delta t} - f_0 u^{n+1/2} = -g \left( \frac{\partial \xi}{\partial x} \right)^{n+1/2} \]

\[ + \frac{\partial}{\partial z} \left( \nu \frac{\partial u^{n+1/2}}{\partial z} \right), \]  \tag{2-2-1}

\[ \frac{\Delta v^{n+1/2} - v^n}{0.5 \Delta t} - f_0 v^{n+1/2} = -g \left( \frac{\partial \xi}{\partial y} \right)^n \]

\[ + \frac{\partial}{\partial z} \left( \nu \frac{\partial v^{n+1/2}}{\partial z} \right), \]  \tag{2-2-2}
Here $Pe$, $Pu$, $Ge$, $Gu$ represent the vertical profile functions of the tidal currents respectively and superscripts $n$, $n+1/2$, $n+1$ represent different time levels. Substitute (2–2–7) and (2–2–8) into the momentum equations (2–2–1) and (2–2–2) in the first half time step or substitute (2–2–9) and (2–2–10) into the momentum equations (2–2–4) and (2–2–5) in the second half time step, we can get a series of one dimensional differential equations about the vertical profile functions $Pe$, $Pu$, $Ge$, $Gu$ as follows:

$$
\frac{\partial}{\partial z} \left( \nu \frac{\partial F}{\partial z} \right) - \frac{2}{\Delta t} F = B; \quad (2–2–11)
$$

where $F = Pe^{n+1/2}$, $Ge^{n+1/2}$, $Pu^{n+1}$, or $Gu^{n+1}$, $B = 1;
$

as $F = Pu^{n+1/2}$, $B = -fu^{n+1/2} - \frac{2}{\Delta t} u^{n};$  

as $F = Gu^{n+1/2}$, $B = fu^{n+1/2} - \frac{2}{\Delta t} u^{n+1/2};$  

as $F = Gu^{n+1}$, $B = fu^{n+1} - \frac{2}{\Delta t} u^{n+1/2}.$

This equation is just a one-dimensional differential equation which can be solved by many methods (SUN, 1992). If we have some interests about the profile of tidal currents near the sea bed, we can use the logarithm coordinate transfer in the vertical direction such as FANG and ICHIYE (1983). Here, we just use the general methods to solve these equations in which we replace the unknown vertical eddy viscosity coefficient by using the upper time level’s value. If we take the vertical eddy viscosity coefficient as a constant, we will need not calculate it and even can get the analytical solution about $Pe$ and $Ge$. In fact, apart from the calculation of the vertical eddy viscosity coefficient in each time step, there is no difference between the Prandtl’s mixing length theory and constant vertical eddy viscosity coefficient model in our numerical model.

As for the water elevations, we can substitute (2–2–7) and (2–2–8) into the continuity equations (2–2–3) in the first half time step or substitute (2–2–9) and (2–2–10) into the continuity equations (2–2–6) in the second half time step.
and get a two dimensional differential equation only about the water elevations as follow:

in the first half time step,

\[ A_{i-1,j} \zeta_{i-1,j} + B_{i,j} \zeta_{i,j} + C_{i+1,j} \zeta_{i+1,j} = T_{i,j} \]  
(2-2-12);

in the second half time step,

\[ D_{i,j-1} \zeta_{i,j-1} + E_{i,j} \zeta_{i,j} + F_{i,j+1} \zeta_{i,j+1} = S_{i,j} \]  
(2-2-13);

where the coefficients of these algorithm equations are the integrated values of \( Pe, Ge, Pv \) and \( Gu \) from the sea bed to the sea surface. By the Thomas Algorithm, we can solve these algorithm equations just on the lines parallel to X-axis in the first half time step and on the lines parallel to Y-axis in the second half time step. The process in which we solve the equations is that at first, we solve \( Ge^{n+1/2}, Gu^{n+1/2} \) and we can get the value of \( u_l^{n+1/2} \), according to (2-2-8). After this step, we solve the \( Pe^{n+1/2}, Pv^{n+1/2} \), and substitute these values into the tidal elevation equation (2-2-12) to get the values of \( \zeta_l^{n+1} \). Then we can get the value of \( u_l^{n+1} \) according to (2-2-7). At the second half time step, we make some changes on the order of the solving processes and almost repeat the same procedure as that at the first half time step.

By this way, it can be known that instead of solving a three dimensional tidal problem, we may solve a two dimensional finite-difference equation and a series of one dimensional differential equation at each horizontal point. And also, if we need, we can get a detail vertical profiles of the tidal currents without too much increase of calculating time.

3. Results

The size of horizontal mesh is 1km in X-direction and Y-direction and we divide the water depth into 10 layers. The time step is 45 seconds which is 2.8 times longer than Courant-Friedrichs-Lewy condition. The sea bed roughness length \( z_0 \) is taken as 0.04 cm according to MATSUMOTO (1983) and SOULSBY (1983). The parameter of \( s \) is taken as 0.1 according to FANG and ICHIYE (1983). The whole time of calculation is four tidal periods.

Figure 1 is the contour line of water depth of Tokyo Bay which is produced by the water depth data used in calculation.

The observed and calculated co-range and cotidal charts of \( M_2 \) and \( K_1 \) are drawn in Figs. 2 and 3, respectively. As for the \( M_2 \) tide, the calculated amplitudes agree to the observation very well but the phases have some difference with the observation. This may be brought by the no slip condition at the sea bed which lead to a large velocity gradient near the sea bed in the vertical direction and then lead to a large sea bed friction. From Fig. 3, it can be seen clearly that the calculated phases of \( K_1 \) tide are nearly the same as the observed ones, but in the head of the bay the calculated amplitudes are smaller than the observed ones. We guess that the less increase of the tidal elevation may be brought by the large dissipation of the kinetic energy caused by the large vertical eddy viscosity coefficient.

The \( M_2 \) tidal current ellipses in Tokyo Bay
Fig. 2. Observed and calculated co-range and co-tidal chart of $M_2$ tide.

Fig. 3. Observed and calculated co-range and co-tidal chart of $K_1$ tide.
have been drawn by Unoki et al. (1980). Here we reprint their chart of tidal current ellipses in winter season, and draw the calculated $M_4$ tidal current ellipses at the same points in Fig. 4 where “upper” represents the results at the depth of 3 meters below the sea surface and “lower” represents the results at the 5 meters over the sea bed. By this way we can know that the calculated horizontal distribution of $M_4$ tidal current ellipses are similar to the observed results. Noticing the characters of the rotation direction of $M_4$ tidal current ellipses, we can find easily that the rotation direction varies from clockwise in the upper layer to the anticlockwise in the lower layer or keeps anticlockwise from the upper layer to the lower layer in the most part of Tokyo Bay. This character is the same as the conclusion of Nagashima and Okada (1984).

Figure 5 is the vertical distribution on $M_4$ tidal current ellipses at the points shown in Fig. 1. The left ones is the observed results (reprinted from the book of Tokyo Bay, ed. by Ogura, 1993) and the right ones is the calculated results. From this figure we can see that apart from the rotation direction of the tidal currents, the calculated tidal currents are nearly the same as the observed ones. In fact, we can not know the rotation direction of the observed tidal currents from the observed tidal currents ellipses, so we can not say anything about this point.

The amplitude and phase of calculated $M_4$ and $K_1$ tidal currents at the depth of 10 meters are shown in Fig. 6 which show that the amplitude of $M_4$ tidal currents is 30–40 cm/s at the mouth of Tokyo Bay, 15 cm/s in the central part of the bay and 5–10 cm/s in the head of the bay. This result is the same as the observed ones (Unoki et al., 1980). From Fig. 6, we can also know that the tidal currents along the west coast are stronger than those along the east coast of Tokyo Bay. This phenomenon had been found by Yamada (1970). The phase distribution of $M_4$ and $K_1$ tidal currents show that the shallower the water depth is, the earlier the turn of tidal current is.

After the above comparisons, it can be said that we have well reproduced the tides and tidal currents in Tokyo Bay by a three dimensional scheme.

The vertical component of tidal currents have been thought to have some potential effects on the primary production in the coastal sea. It is valuable for us to calculate the vertical component of tidal currents in Tokyo Bay. The formula used in the calculation of $w$ is

$$w|_{z} = - \int_{-h}^{h} \frac{\partial u}{\partial x} \, dz' - \int_{-h}^{h} \frac{\partial v}{\partial y} \, dz'$$

(3-1)

Figure 7 is the calculated amplitude of the
vertical tidal currents. From this figure, we can know that the order of vertical tidal current in most of Tokyo Bay is smaller than $10^{-2}$ cm/s. In the region such as the mouth of the bay where the water depth varies rapidly, the vertical tidal current can get the order of $10^{-2}$ cm/s. If we divide the speed of horizontal tidal currents to that of vertical tidal current, we can know the ratio is about $10^4$. This order is the same as the aspect ratio of the horizontal length scale of Tokyo Bay, 60 km, to the characteristic depth of Tokyo Bay, 20 m, which is usually used to estimate the order of the vertical tidal currents.

4. Discussion

It is a difficult point to decide the values of the vertical eddy viscosity coefficient in the numerical calculation of coastal oceanography. In our calculation, we take the vertical eddy viscosity coefficient as a constant (50 cm$^2$/s) at first and get the co-range and co-tidal chart of $M_2$ tide as shown in Fig. 8 which could be said having the same distributing tendency as the observed ones. But as trying other constants such as 10 cm$^2$/s or 100 cm$^2$/s, we got some little different results from Fig. 8. This suggests that we have to choose a high level turbulence closure model such as the Prandtl’s mixing length theory to enclose our turbulent model.
Here we show the horizontal distribution of calculated $\langle \nu \rangle$ at the depth of 10 meters in Fig. 9 and the vertical distribution of calculated $\langle \nu \rangle$ for $M_2$ tide at one point with the depth of 29 meters in Fig. 10 whose horizontal position is expressed by "+" in Fig. 9. Here $\langle \cdot \rangle$ expressed the average over one tidal period. On the fact that we have well reproduced the tides and tidal currents in Tokyo Bay, we think that the value of $\langle \nu \rangle$ calculated by the Prandtl's mixing length theory can be accepted although these values are larger than the general concept. In fact the order of 10 cm/s has been used for many times (WANG, 1989, 1992) and the result of
Fig. 7. Horizontal distribution of the amplitude of $M_2$ and $K_1$ vertical tidal currents at the depth of 10 meters.

Fig. 8. Calculated co-range and co-tidal of $M_2$ tide as $v=50\text{cm}^2/\text{s}$.

Fang and Ichiye (1983) has also been this order. From Fig. 9, we can see that at the mouth of bay where the tidal currents and water depth vary rapidly the value of $\langle v \rangle$ is large. From Fig.10, we can see that below the middle layer of the whole water depth, the $\langle v \rangle$ take its maximal value and the distribution curve from the sea bed to the sea surface approach a parabola which is similar to the experimental result reported by Sumi (1991). In fact, this form is also usually used in three dimensional coastal ocean models (NihoUl, 1977; Tee, 1979). From this chart, we can also see that because the number of mesh points in vertical deirection is just 10, there is a little anomalous near the sea bed.

It is well known that the tide-induced residual current, which has important effects on the material transports processes in the coastal sea, is produced by the nonlinear effects of the tidal current. The tidal stress has been accepted as a force which have the same effects to the sea water as the wind or the buoyancy (NihoUl and Ronday, 1975; Yanagi, 1989). In a two dimensional tidal model, the tidal stress is calculated by:
Fig. 9. Calculated horizontal distribution of $\langle \nu \rangle$ at the depth of 10 meters.

\begin{align}
S_x &= \left\langle \bar{u} \frac{\partial \bar{u}}{\partial x} + \bar{u} \frac{\partial \bar{u}}{\partial y} \right\rangle \\
S_y &= \left\langle \bar{v} \frac{\partial \bar{u}}{\partial x} + \bar{v} \frac{\partial \bar{u}}{\partial y} \right\rangle
\end{align}  \quad (4-1, 4-2)

where $\bar{u}, \bar{v}$ represent the water depth averaged velocity, $\langle \rangle$ represent the average over one-tidal cycle. In a three dimensional tidal model, the tidal stress is

\begin{align}
S_x &= \left\langle u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} \right\rangle \\
S_y &= \left\langle u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} \right\rangle
\end{align}  \quad (4-3, 4-4)

As these two ways are usually used in the calculation of tidal stress, we would like to check the difference between these two ways. Figure 11 is the results we get by these two ways in which "2-D" represents the results calculated by formula (4-1) and (4-2), "3-D" represents the results at the depth of 10 meters calculated by formula (4-3) and (4-4). "3-D" represents the results at the same depth calculated by the first two terms in formula (4-3) and (4-4). From these results we can know that the difference between 2-D and 3-D models is very small in most parts of Tokyo Bay. The contribution coming
from the last term of formula (4-3) and (4-4) is also small in most parts of Tokyo Bay. By comparing to the tidal stress in Osaka Bay (YANAGI and TAKAHASHI, 1995), we can also know that the tidal stress in Tokyo Bay is smaller than that in Osaka Bay by one or two orders. On the other hand, it is clear that we can ignore the contribution of $K_1$ tidal currents when we calculate the tide-induced residual currents in Tokyo Bay.

5. Conclusion

(1) The tides and tidal currents in Tokyo Bay calculated by a three dimensional model well reproduce the observed ones. The vertical eddy viscosity coefficient has a great influence on the accuracy of calculated results.

(2) The vertical tidal current is smaller than $10^{-2}$ cm/s in most parts of Tokyo Bay. In the places such as the mouth of Tokyo Bay, where the water depth varies rapidly, the vertical tidal current can attain to the order of $10^{-1}$ cm/s.

(3) The tidal stress calculated by two dimensional model and three dimensional model have no difference in principle in most parts of Tokyo Bay. The tidal stress caused by $M_2$ tide in Tokyo Bay suggests that the tide-induced residual current is large near the bay mouth but small in most parts of Tokyo Bay. The tide-induced residual current caused by $K_1$ tide can be ignored in Tokyo Bay.
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References


東京湾の潮流の3次元構造

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要旨：三次元数値モデルを使って、東京湾の潮汐と潮流を計算した。鉛直層動粘性係数はPrandtl’s混合距離論によって求めた。計算の結果は東京湾の潮汐と潮流の水平二次元構造をよく再現した。これらの結果をもとに潮流の鉛直成分を計算した。東京湾の大部分の所では潮流の鉛直成分の振幅は$10^{-1}\text{cm/s}$より小さいが、湾口のような水深の変化が激しい所では$10^{-2}\text{cm/s}$を越えることがある。三次元モデルと二次元モデルにより計算した潮汐応力を比べると、東京湾の大部分の所では両者に本質的な差がないということが分かる。