Abstract

Extending the experiences of a series of studies on tidal current simulations on seas surrounding Taiwan, the near shore currents on eastern sea surrounding Suao Harbor are investigated. Effects of the Kuroshio prevailing near coast are evaluated. Adopting the nested-grids scheme, the tidal currents are simulated by using the depth integral two-dimensional hydrodynamic model: MIKE21_HD. Simulations results show that the currents appeared around the harbor is mild. However, there are strong currents occurred around the islet of Sansentai, a reef sea locating at harbor’s northeast side with distance about 2 km away from the entrance. The strong currents occurred not only because of the topographical effects of the local reef, but the regional effects of the coast of Yilan, the ridge of Suao, and the large scale submerged salient existing outside the estuary of Lanyang River. Furthermore, due to the currents simulated by including only the effects of tides match well with measurements in verifications, so we confirm that the Kuroshio should not strong enough to extend its effects on the currents near the east coast of Taiwan.

1 Introduction

The Suao Harbor, a fine natural port and one of the seven commercial ports of Taiwan, locates on the northeast coast and circumjacent to the western Pacific Ocean. The location associated with the circumjacent topographies including the East Asia Continental Shelf, the Okinawa Trough, the Suao Ridge, and the Ryukyu Trench, are shown on Fig.1. Those circumjacent large-scale topographies used to be considered on simulating the currents around coasts of Taiwan (Juang and Chiang, 2000; 2001; 2004).

For the demands of harbour environment management, ship manoeuvring, marine hazard mitigation and disaster prevention, and oil-spilled contingency, sustained measurements of near shore wind, waves, and currents at specific locations around the harbour have been executing (Tseng et al., 2003) since the harbour built and operated in 1965.
Fig. 1 The location of the Suao Harbor and the circumjacent top graphics

The yearly-averaged wind rose diagram from years of 1985 to 1996 is shown on Fig. 2. It is noted that the wind directions are wide spreading and wind speeds are mild. Main wind direction is NW, and most of time the wind speeds are lower than 5 m/s. The monsoon winds are insignificant. However, stronger winds with speed reaching to 14 m/s could occur during typhoon seasons.

There are two sites for waves and currents measurements (Tseng et al., 2003). One locates outside the reef area, which is 2.0 km away from the harbor entrance, with water depth of 23 m. The other one locates right outside the entrance with distance of 700 m and water depth about 25 m. The former site had been operated since 1998. But now it is abandoned due to high labor and maintains cost. The latter
one has been operating successfully since 2002. The monthly rose diagrams of waves and currents, which measured on Aug. and Oct. 2002, are shown on Figs. 3 and 4, respectively. From waves rose diagrams, Fig.3, it is noted that waves directions mainly distributed between ENE and SSW, and only mild waves conditions occurred in general seasons. However, more serious waves conditions occurred with wave heights larger than 2 m during the monsoon seasons. On the other hand, from currents rose diagrams, Fig.4, it is noted that the currents are also mild with velocities generally less than 40 cm/s, and directions mainly distributed from NNE to SSW. Obviously, the currents mainly flow in direction of along the coast, and the winds and the currents are not well coherent. Therefore, the near shore currents seem to be dominated by the tidal currents. Nevertheless, stronger currents with velocities higher than 80 cm/s had been observed on the reef site. For further reference, part of the hourly records of winds and currents measured at reef site in Nov. 1999, associated with the tides predicted on the same period are shown on Fig.5 in which the wind speed had been scaled down by factor of 1/10.

Regarding the ocean currents, comprehensive investigations, which were surveyed by applying the ship-boarding Acoustic Doppler Current Profiler (Sb-ADCP) during the periods from 1999 to 2001 (2.5 years), had been done by National Center for Ocean Research, Taiwan. The appearance of yearly-averaged composite currents that analysed at the upper layer of depth of 20 m is shown on Fig.6 (NCOR, 2004). It is noted that there is the Curoshio with strong velocities prevailing from south to north direction over the whole east coast. Coastal engineers, therefore, seriously concern the effects of the Curoshio on the near shore hydrodynamics. However, comprehensive investigations relating to hydrodynamics are still lacks.

To assist in catching the hydrodynamics on near shore, a depth integral two-dimensional hydrodynamic model: MIKE21_HD (DHI, 1998) is adopted in this study so that the currents around the harbour could be computed and identified, and the effects of the Curoshio could be evaluated.
Fig. 5 The directions (a) and speeds (b) of winds (in red) and currents (in black), respectively, measured at reef site in Nov. 1999 associated with the prediction tides (c). Wind speed scaled down with factor of 1/10.
Fig. 6 The appearance of the ocean currents around Taiwan (NCOR, 2004)
2 The Numerical Model and the Nested Computation Domains

The two-dimensional hydrodynamic model: MIKE21_HD, which developed by DHI water & Environment, Denmark, defines in right-hand Cartesian coordinate system: \((x, y)\) with the continuity and the momentum equations, respectively, are

\[
\begin{align*}
\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} &= 0 \quad (1) \\
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{pq}{h} \right) + gh \frac{\partial \zeta}{\partial x} + \frac{gp}{C^2} \frac{\partial}{\partial x} \left( h \tau_{xx} \right) + \frac{\partial}{\partial y} \left( h \tau_{xy} \right) &= 0 \quad (2) \\
\frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left( \frac{q^2}{h} \right) + \frac{\partial}{\partial y} \left( \frac{pq}{h} \right) + gh \frac{\partial \zeta}{\partial y} + \frac{gp}{C^2} \frac{\partial}{\partial y} \left( h \tau_{yx} \right) + \frac{\partial}{\partial x} \left( h \tau_{yy} \right) &= 0 \quad (3)
\end{align*}
\]

Where \(t\) is the time (s), \(\zeta(x,y,t)\): the surface elevation, \(p, q(x,y,t) = (uh, vh)\): the depth integral flux densities \((m^3/s/m)\) in \(x\) and \(y\) direction, respectively. \(u, v\): the derived depth-averaged current velocity, respectively. \(h(x,y,t)\): the water depth, \(\Omega = 2\omega \sin \phi\): the latitude dependent Coriolis parameter \((s^{-1})\); \(\omega = 7.3 \times 10^{-5}\): the angular frequency of the earth; \(\phi\): the latitude, \(\rho\): the water density \((kg/m^3)\), \(\tau_{xx}, \tau_{xy}, \tau_{yy}\): the components of effective shear stress, \(g = 9.8ms^{-2}\): the acceleration due to gravity on the earth, \(C(x,y)\): the Chezy resistance \((m^{1/2}/s)\), \(f_w\): the wind friction factor, \(V_x, V_y\): the wind speed \((m/s)\) and components in \(x\) and \(y\) direction, respectively, \(P_a(x,y,t)\): the atmospheric pressure \((kg/m/s^2)\).

MIKE21_HD makes use of the Alternating Direction Implicit (ADI) finite difference technique to solve the system equations in the space-time domain. The grid spacing in \(x\) and \(y\) direction is restricted to be constant, and therefore the computation domain has to be rectangular, and the equation matrices that result for each direction and each individual grid line are resolved by Double Sweep (DS) algorithm.

In coordinating with modeling operations, the boundary conditions should be well set up a priori as usual. However, open sea with complex topographies is encountered in the interested area (Fig.1). To overcome the essential problems of modeling, in particular, the space resolutions that should be good enough to include the topographical effects, nested computation domains are organized and shown on Fig.7. Among that, the regional, the sub-regional, and the local computation domains are shown on Figs.8, 9, and 10, respectively.

On the regional computation domain with grid resolution of 5 km, Fig.8, the topographical effects of the East Asia Continental Shelf, the Okinawa Archipelago, the Luzon Archipelago, and the Taiwan Strait are considered. On the sub-regional computation domain with grid resolution of 300m, Fig.9, the topographical effects including the Suao Ridge, the shoreline circumjacent to Suao Harbor, and the large-scale submerged salient outside the Lanyang River are considered. On the
local computation domain with fine grid resolution of 50m, Fig.10, the main
topographical effects considered including capes and reefs around Suao Harbor.

Reviewing on the regional computation domain, although it is so large as to
interested researchers will worry about that the tidal characteristics might not be
presented correctly by using the two-dimensional hydrodynamic model, however,
Juang et al. (2000; 2001) had demonstrated that the computed tidal characteristics,
both of the tidal elevations and currents around Taiwan, are still in good agreement
with the local measurements.

On the open sea boundaries locating on the regional computation domain,
time-varying levels of tides predicted a priori by applying the NAOTIDE (Matsumoto
et al., 2000) on specific locations are imposed. The boundary conditions then are
constructed through the linear interpolations between locations and time steps. The
others open sea boundary conditions setting up on the succeeding sub-regional
and local computation domains are directly inheriting from the hydrodynamic
results that are previously computed in the up-layer domains. Moreover,
concerning the numerical stability, the soft start scheme is applied on setting up the
initial condition (DHI, 1998).

Regarding the NAOTIDE, it is a program to predict ocean tidal height at given time
and location using ocean tide model developed by assimilating nearly 5 years of
TOPEX/POSEIDON altimeter data (Cycle 10-198). The capabilities of NAOTIDE
applied on predicting the short-period tides on the west coast of Taiwan were
verified, and high accuracy were confirmed (Chang and Hwang, 2001).
Fig. 8 The regional computation domain around Taiwan
3 Tidal Currents Computations and Results

Local currents are generally composed of the wind-driving currents, the tidal currents, the near shore currents induced by wave breaking, and the ocean currents. Considering the local topography effects and the verifications with measurements, only the first two current components are included in the simulations. Time-varying and space-uniformed winds measured at Suao are applied.

The currents computed on sub-regional domain, i.e. the seas around Taiwan are shown on Fig.11 in which the tidal levels of Taichung are referred and shown under the figure, arrows represent currents velocities and directions, and hue scale associated with the contours indicate surface water levels. From figure, currents with strong velocities are noted at locations of both south and north entrances of the Taiwan Strait while water levels of Taichung in flooding period after low and in ebbing period after high, respectively. Currents with convergent and divergent appearances are also found. However, the currents around the coast of Suao are relatively weak due to the water level gradients are mild.

Inheriting the hydrodynamic characteristics of currents computed on the seas around Taiwan, the currents computed on the east coast are shown on Fig.12 in which the local tidal levels of Suao are referred. From figure, very weak currents appear over the east coast because the tidal level gradients are insignificant. However, mild currents still maintain around the coast of Suao due to the effects of topographies. Therefore, Currents flow from north to south directions when local tidal levels reaching low, and from east to northwest when local tidal levels reach high. Furthermore, a separation zone seems exhibit indistinctly around the north cape of Suao Harbor while currents flow westward along the Suao Ridge.
Fig. 11 The appearances of currents (arrows) and water surface levels (hue and contours) computed on sub-regional domain around Taiwan during periods of flooding (a) and ebbing (b) with the tidal level referred to Taichung.

Fig. 12 The appearances of currents computed on sub-regional domain on the east coast of Taiwan during periods of flooding (a) and ebbing (b) with the tidal level referred to Suao.
Fig. 13 The bathymetry (hue and contours) and the appearances of currents (arrows) computed on sub-regional domain around the coast of Suao during periods of flooding (a) and ebbing (b) with the tidal level referred to Suao.

To have an insight into the effects of topographies as well as the coastal shoreline, currents computed on sub-regional domain with more finer resolution are shown on Fig. 13 in which the local tidal levels of Suao are referred and shown under the figure, arrows represent currents velocities and directions, and hue scale associated with the contours indicate the bathymetries. When the tides in Suao Harbor reaching high water level during flooding period, the currents are flowing westward along the southern slope of the Suao Ridge, and then running over the ridge to the northwest direction. Strong currents are observed on sites locating around the northern cape of Suao and over the large scale submerged salient outside the Lanyang River. Moreover, due to the barrier of the Suao Ridge, currents flowing southward are also observed around the southern cape of Suao. Obviously, there is a separation zone that formed nearing the southern coast of Suao. When the tides reaching low water level during ebbing period, the ebbing currents are mainly southward and strong currents are appearing on sites around the northern cape of Suao and over the submerged salient outside the Lanyang River. One more phenomenon that worth mention is when the southward currents run over the Suao Ridge, its main stream is flowing on the shallow water inside the rim of the East Asia Continental Shelf, instead of flowing directly into the western Pacific Ocean. The western Pacific Ocean itself, therefore, seems also forming a water barrier for southward currents on the east coast of Taiwan.

Referring the local tidal levels of Suao, the detail appearances of currents computed on the local domain, i.e. around the Suao Harbor are shown on Fig. 14. It is noted that around the entrance of the Suao Harbor, both of the flooding and ebbing
Fig. 14 The appearances of currents computed on local domain around the Suao Harbor during periods of flooding (a) and ebbing (b) with the tidal level referred to Suao.

currents are mild with velocities about 30 cm/s only. However, during the flooding period, the northward currents with stronger velocities reaching to 70 cm/s are observed on the sites of the shallow reefs, i.e. the water between the northern cape of Suao and around the reef of SansenTai that locates about 2.0 km away from the coast. Therefore, a counterclockwise circulation is indistinctly formed on north water of the northern cape of Suao due to the effects of the topographical shielding. During the ebbing period, the currents originally flowing in southeastward directions are finally deflected into southward due to the significant barrier effects of the shallow reefs as well as the northern cape of Suao. Currents exhibiting confluent with stronger velocities reaching to 80~100 cm/s are also observed on the sites of the shallow reefs locating northeastward of the Suao Harbor. On the lee side behind the reef of SansenTai, a separation zone and a distinctive clockwise circulation are noted, and these currents worth taking special cares on ship maneuvering.

4 Computation Verifications

Referring to the measurement sites shown on Fig.10, the verifications of the computation currents and tidal levels that extracted from local computation domain at site near the harbor entrance are shown on Fig.15. It is noted that not only the tidal levels match well each other, but also the computation currents including both of the directions and velocities are in good agreement with the measurement ones. Furthermore, the currents flowing in northward directions when water levels
reaching high during flooding periods stronger than that flowing in southward directions when reaching low water levels during ebbing periods, which appeared on measurements are fully caught and re-presented by the computations. Although only the effects of tides, winds, and relating topographies are included in these currents simulations, present computation currents still show good enough accuracy to exhibit the comprehensive hydrodynamics around the harbor entrance.

Further verifications of the computation currents extracted at reef site, which is about 2.0 km away from the harbor entrance, are shown on Fig.16 in which the periods of computation (on Nov. 2002) and measurement (on Nov. 1999) is different from each other. Nevertheless, with almost the same trend of tidal levels within duration of half month, the computation currents including both of the directions and velocities are still in good agreement with the measurement ones.

Basing on the successful verifications shown above, the currents appearing around the harbor entrance and even neighbouring to the reef sea, which dominated only by the tides and winds are confirmed. The effects of the Curoshio on the near shore hydrodynamics that have been seriously concerned by coastal engineers during the past decades, therefore, could also be eliminated or neglected.

![Fig. 15 Verifications of the computation (in red) directions (a) and speed (b) of currents and tidal levels (c) extracted on local domain with the ones (in black) measured at site near the harbor entrance on Nov. 2002.](image1)

![Fig. 16 Verifications of the computation (in red) directions (a) and speed (b) of currents and tidal levels (c) extracted on local domain on Nov. 2002 with the ones (in black) measured at reef site on Nov. 1999.](image2)
5 Conclusions

Throughout the studies of the currents simulations on the east coast of Taiwan and around the Suao Harbor, Following conclusions are derived:

(1) Applying the 2-D hydrodynamic model: MIKE21_HD associated with adopting the nested computation domains, the currents appearing around the Suao Harbor could be correctly simulated by including only the effects of winds and tides.

(2) Both the regional and the local topographies present their significant effects on currents. Those topographies are the coast of Yilan, the ridge of Suao, the large scale submerged salient existing outside the estuary of Lanyang River, and the capes associated with the reefs sea around the harbour.

(3) There are two currents barriers existing around the Suao Harbor. The shallow reefs locating between the northern capes of Suao and the water about 2.0 km away from the harbour entrance form one in which stronger currents are always appeared. The other one is formed by the western Pacific Ocean, which cause the southward ebbing currents on the reefs water to be deflected to the coast.

(4) For the successful verifications of the currents simulated by including only the effects of tides and winds match well with measurements, so we confirm that the Kuroshio should not strong enough to extend its effects on the currents near the east coast of Taiwan. This confirmation must be true at least within the water that is 2.0 km away from the coast.

(5) The comprehensive computation currents with accuracy good enough to fit the relating demands of harbour managements and operations.

6 References


Juang, W.J. and C.C. Chiang. Tidal Currents Simulation on the East Coast of Taiwan


