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Behavior-oriented numerical modeling of nearshore oceanic current and application on sea harbor

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The West Guangdong longshore current (WG current) is a unique oceanic current system. Plenty of field survey datasets indicated that it flows uni-directionally from north-east to south-west in the entire year even during the south-west monsoon season. At present, the natural formation mechanism of the WG current remains controversial, and the traditional process-oriented modeling method could not deal with the dilemma of the scaling mismatch between the regional ocean circulation (several thousand kilometers) and harbor structure (several hundred meters). To solve this problem, in this paper, a behavior-oriented modeling concept was developed, wherein the contribution of the WG current was considered by incorporating additional net flow flux in the hydrodynamic model to separate it from the tidal currents. Through rigorous validations according to the site observed datasets, the proposed modeling concept was found to have good precision. Using the Jida Harbor as a real-life case, the modeling results showed that after the combination of the tidal current and WG current, the westward cross-flow speed in the approach channel could exceed 0.5 m/s, and at the harbor entrance the WG current induces an intense local circulation cell while ebbing, which may bring in additional maneuver risk to the ships.

[**Keywords**: Oceanic current; Numerical model; Behavior-oriented concept; Additional flow flux]

Introduction

The West Guangdong (WG for abbreviation) coast, China, directly faces the open Pacific Ocean (Fig.1). At present, many large sea harbors are being planned for construction along the coastline. In the designing process of a sea harbor, the characteristics of the nearshore current motion have significant impact on the selection of the harbor layout. For instance, if the designed channel axis is perpendicular to the main current direction, the cross-flow could push the shipping vehicles to the channel edge from their original route and increase the track zone width. Besides, the circulation flow induced inside the harbor entrance could also make the ship encounter opposite forces at its bow and stern, and consequently bring in additional maneuver difficulty when the ship navigates into the inner harbor. Therefore, a comprehensive investigation of the nearshore currents is mandatory before the designing of the sea harbor, including its planar layout and channel alignment.

Most of the nearshore areas along the Chinese coast are located at the upper continental shelf zone, thus the main driving nearshore dynamics is tidal currents (especially the M2 constituent), while the direct impact of oceanic circulation is rare. However, the WG coast faces the open Pacific Ocean, and it is also close to the Pearl River Estuary, where a large quantity of salty-fresh mixed water discharges into the coastal area. Based on a series of historical literature and in-situ observed datasets[1,2,3,4,5,6,7], it is reported that an oceanic current moves south-westward along the WG coast all over the year, especially its direction is opposite to the south-west monsoon in the summer, and the speed of the oceanic current has irregular seasonal variation. This typical oceanic current is then called West Guangdong Longshore Current (WG current for abbreviation). The WG current is a special oceanic current system moving along the WG coastline, and its impact zone could even reach the nearshore area where the water depth is less than 10 m, which has a great difference from other typical large-scaled oceanic current systems. Beginning from the

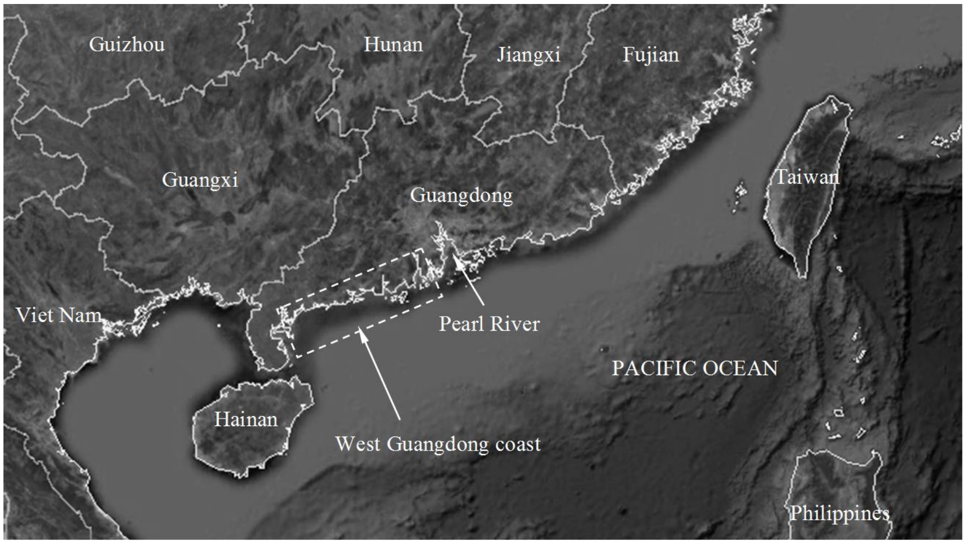


Fig. 1 — Location of the West Guangdong coast

1980s, many researchers have analyzed and investigated the WG current applying different methodologies, including in-situ measurement and numerical simulation. However, owing to its complex nature, until today the formation mechanism of the WG current still remains controversial.

Numerical models have been widely used in the study of nearshore hydrodynamics, and for most cases they have provided satisfactory results. For the historical nearshore current modeling method, usually only the tidal current is considered, which means the astronomic tide is used as the driving force. However, the average tidal range of the WG area is only 1.6 m[2,3], thus the tidal current speed is small, and due to the in-situ observation results, the speed of WG current is even in the same level of the tidal current speed. Therefore, in the modeling of the nearshore currents for the WG coastal area, the impact of the WG current must be taken into consideration.

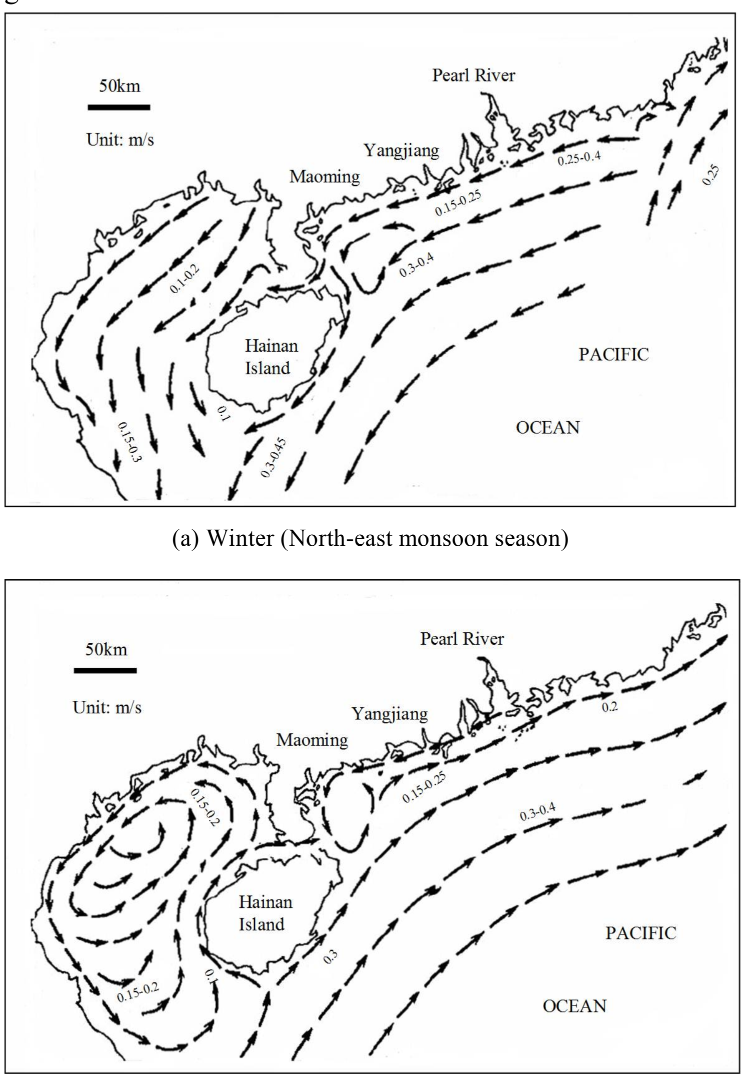
For natural mechanism of the oceanic currents (also called as ocean circulation), their driven forces are mainly controlled by macro-scale processes, e.g., the seasonally monsoon variation and the temperature/ salinity-induced baroclinic effect. Therefore, at present the 3-D regional ocean baroclinic model packages such as POM [8], ECOM[9], FVCOM[10] were mostly used to model the ocean circulation systems. However, because the scale of the typical ocean circulation ranges from several hundreds to thousands of kilometers, and usually the scale of a sea harbor is only several hundred meters, the significant scale mismatch makes the model establishment extremely difficult, and the modeling precision is then hard to ensure. Additionally, at present the formation nature of the WG current is still not well determined[1,2,3]; therefore, the tidal current-ocean circulation coupled hydrodynamic modeling is hard to achieve, which brings in a dilemma for a specified sea harbor case study. Therefore, under this case, we have to pursue another modeling methodology.

After a series of philosophical discussions, de Vriend et al[11] have summarized the present modeling methodologies, and they recommended two different ideas of modeling concepts: (1) process-oriented modeling and (2) behavior-oriented modeling. In general, for a typical engineering application case study, rather than the detailed tidal-oceanic current coupling process, we actually concern more about the reasonable modeling results as our aim was to provide precise designing parameters to a specified engineering case. Through analysis, conceptually the impact of oceanic current for a local model could be described as an additional flow flux. Therefore, in this paper, a new concept was proposed to model the tidal-ocean coupling effect by applying an additional flux source at the boundary of the local model, while the distribution of this additional flux is analyzed from the field survey datasets. This method combined the advantages of both process-oriented modeling and behavior-oriented modeling concepts. Using this methodology, a typical case study was carried out and the impact of the WG current to the harbor was further analyzed.

Investigation of the WG current

The South China Sea area is located at the monsoon zone, and the monsoons come from south-west in summer and north-east in winter. For a typical oceanic circulation flow, commonly the flow direction approximately follows the main monsoon direction. However, by using drift bottles to track the flow streamline, Qiu et al[1] found out that the oceanic current direction along the WG coast always points to south-west even in summer, which is opposite to the monsoon direction. After analysis, they proposed that the current belongs to the secondary circulation system in the northern South China Sea and is related to the high-salinity Kuroshio Current intrusion between the Taiwan Straits and the Luzon Straits. Ying[2], Yang et al[3] and Pang et al[4] respectively used morphology analysis, drift bottle and salinity data from Pearl River Estuary and proposed that the WG current may be induced by the baroclinic effect of the salty-fresh water mixing outside the Pearl River Estuary. Li et al[5] modeled the ocean circulation system of the northern South China Sea by the monsoon process using a regional ocean circulation model, but their results did not agree with the observation results. Yan and Chen[6] analyzed the annual measurement datasets from a fixed buoy located at the WG offshore area (at water depth 20 m), and proposed that the precipitation during the typhoon process also contributes to the formation of WG current. Actually, at present the natural mechanism of WG current is still not well clarified. Wang et al[7] gave a primary estimation of the circulation motion feature in the northern South China Sea and proposed that the WG current speed is around 0.20 to 0.25 m/s, and its influence zone limits within -50 m (MSL) as indicated in Figure 2.

The astronomic tide of the WG coastal area is



(b) Summer (South-west monsoon season)

Fig. 2 — Movement route of the surface oceanic currents

controlled by the northern South China Sea tide system. Yu[12], Ding[13] and Zhang[14] modeled the tide feature of the South China Sea. Based on their conclusions, the astronomic tide pattern of the WG area is irregular semidiurnal with an average tidal range of 1.5 m to 1.6 m, and the mean nearshore tidal current speed ranges from 0.2 to 0.3 m/s.

To better investigate the nearshore current movement characteristics for the WG coastal area, the Changjiang Water Resources Commission, China, have carried out a series of field surveys at the WG area during three different tidal cycles in 2004 and 2011 using ADCP: (1) Spring tide in 2004.10.30~2004.10.31, (2) Spring tide in 2011.05.19~2011.05.20, and (3) Neap tide in 2011.05.25~2011.05.26.

The locations of the measurement stations are presented in Figure 3. The observation stations were fixed during each measurement tidal cycle, and the current data were automatically recorded hourly. During the above surveys, the current speed and direction data were measured simultaneously. To obtain the depth-averaged parameters, the current speed and direction were measured in six vertical layers, including the surface, 0.2D, 0.4D, 0.6D, 0.8D and the bottom, where D is the total water depth related to the tidal level. The depth-averaged current speed and direction were calculated using an integral algorithm of all the vertical layers.

Figure 3 and 4 present the depth-averaged current time-series for each survey, while Table 1 lists the analyzed statistical parameters. Through analysis, some conclusions were made as follows.

(1) All the measurement datasets showed that the WG current has significant contribution to the coastal current system. Based on the measurement results of 2004-10, the nearshore current motion presents a bi-directional feature, but generally the westward current speed is larger than the eastward current speed. From the measurement results of 2011-05, in both spring and neap tidal cycles the nearshore currents flow uni-directionally to the south-west. That means, under the action of the WG current, the nearshore current system is not purely determined by the tidal currents.

(2) Generally, the mean current speed for all stations ranges from 0.1 to 0.3 m/s, and the maximum current speed ranges from 0.2 to 0.6 m/s. Based on the datasets surveyed during spring and neap tidal cycles in 2011-05, the maximum current speeds increase with tidal range, which indicates the net contribution of the tidal current.

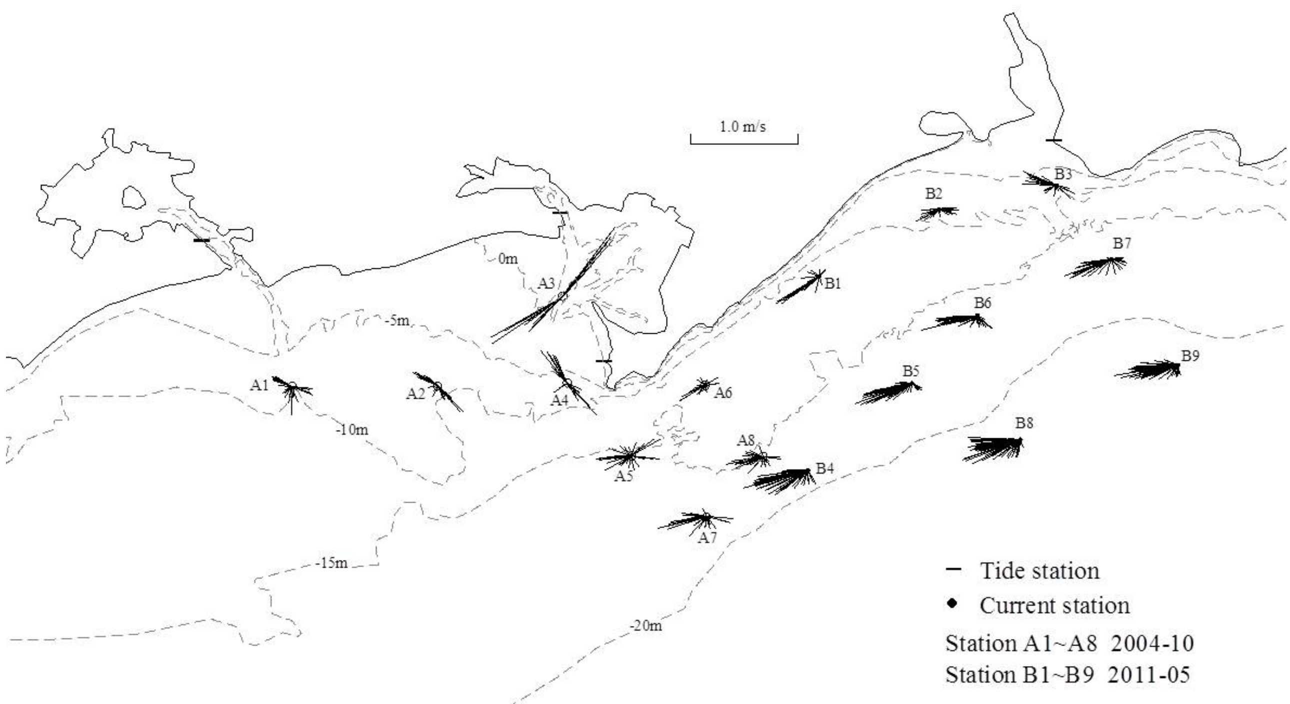


Fig. 3 — In-situ measured current vector under the spring tide condition.

Theoretically, for natural tidal current movement mechanism, the trajectory of the flow streamline tends to be closed. Of course, in realistic coastal area, other processes e.g. the tidal wave deformation, wind, waves and temperature/salinity-induced flow also have impact on the nearshore currents. That is, if we integrate all the current components within a tidal cycle, the result is usually not rigorously zero, which is called tidal-averaged residual flow. For most cases, if the nearshore current system is dominated by tidal currents, the residual flow speed should show an unstable feature and usually has an order of several centimeters per second (cm/s).

During the above in-situ surveys, the wind speed beyond the sea surface is less than 5 m/s and the wave height does not exceed 0.5 m; therefore, the wind/wave induced residual flow should be very small compared to the major tidal currents. Therefore, the residual flow speed could be approximately regarded as equal to the WG current speed regardless of the non-linear interaction process, which is also trivial under this case. The calculation formulation of the residual flow is

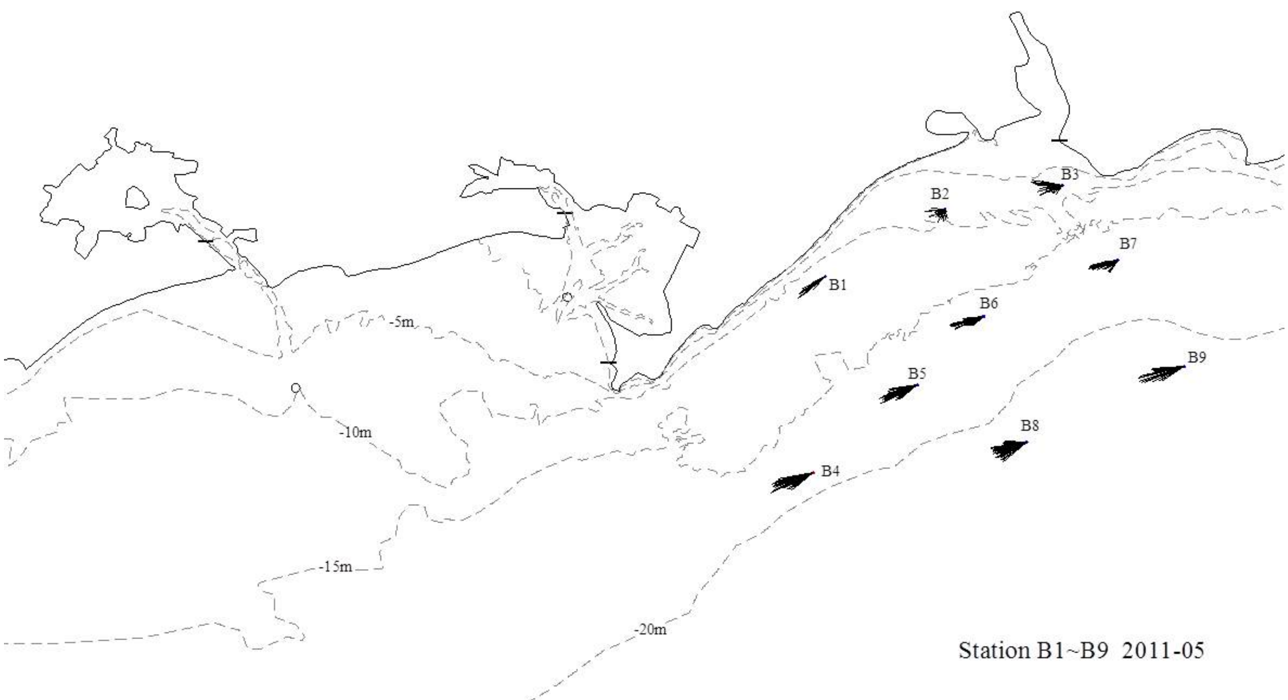


Fig. 4 — In-situ measured current vector under the neap tide condition.

Table 1 — Current speed statistics under different tidal range conditions.

Survey time	2004-10		2011-05				
Tide process	Spring tide		Tide pattern	Spring tide		Neap tide	
Tidal range (m)	2.00		Tidal range (m)	2.23		0.88	
Station	V_{mean} (m/s)	V_{max} (m/s)	Station	V_{mean} (m/s)	V_{max} (m/s)	V_{mean} (m/s)	V_{max} (m/s)
A1#	0.14	0.28	B1#	0.19	0.49	0.17	0.33
A2#	0.17	0.36	B2#	0.13	0.25	0.11	0.20
A3#	0.42	0.82	B3#	0.17	0.34	0.17	0.30
A4#	0.21	0.42	B4#	0.34	0.63	0.30	0.45
A5#	0.20	0.34	B5#	0.28	0.57	0.25	0.40
A6#	0.10	0.29	B6#	0.22	0.55	0.21	0.33
A7#	0.20	0.48	B7#	0.19	0.47	0.18	0.29
A8#	0.16	0.36	B8#	0.32	0.58	0.27	0.34
/			B9#	0.29	0.61	0.27	0.45

given in Eq. (1)~Eq. (2) as follows.

$$U_A = \frac{1}{T}\int_0^T \int_1^6 U(z,T)\,\mathrm{d}z\mathrm{d}T \quad \ldots(1)$$

$$V_A = \frac{1}{T}\int_0^T \int_1^6 V(z,T)\,\mathrm{d}z\mathrm{d}T \quad \ldots(2)$$

where U_A and V_A are residual flow speeds in east and north directions, respectively; U and V are surveyed current speed in east and north directions, respectively; z is the vertical coordinate; and 1~6 represent vertical layers from bottom to surface. For the calculation method, readers of interest could refer to Xie et al[15] for more details. Table 2 lists the analyzed residual flow speed under different representative tidal cycles. Based on the results, some characteristics are obtained as follows:

(1) Through data analysis, among all the observation stations, the residual flow directions are around 250°, which indicates that generally the net WG current moves south-westward.

(2) During the 2004-10 survey, the mean speed of residual flow for all stations is only 0.06 m/s, but during the 2011-05 surveys the mean residual speed reaches 0.21m/s with the maximum speed exceeding 0.3 m/s. The results indicate that the WG current shows a significant seasonally variation, and the current speed becomes stronger in summer than in winter.

Figure 5 illustrates the relationship between the WG current speed and the distance from the shoreline. It indicates that the WG current speed gradually increases from shoreline to the offshore zone, as at the nearshore area, the headlands along the shoreline could block the upcoming currents from the north-east. By using the polynomial fitting method[15], the current speed has a good relationship with the distance from shoreline with a relativity coefficient of 0.84.

Table 2 — Residual current speed and direction during different tidal cycles

Survey time	2004-10		Survey time	2011-05			
Tide pattern	Spring tide		Tide pattern	Spring tide		Neap tide	
Station	Velocity (m/s)	Direction (°)	Station	Velocity (m/s)	Direction (°)	Velocity (m/s)	Direction (°)
A1#	0.05	229	B1#	0.18	232	0.17	236
A2#	0.04	254	B2#	0.05	202	0.09	227
A3#	0.06	335	B3#	0.10	269	0.16	258
A4#	0.06	328	B4#	0.31	248	0.30	249
A5#	0.06	258	B5#	0.25	248	0.26	248
A6#	0.05	236	B6#	0.17	248	0.21	250
A7#	0.11	245	B7#	0.13	241	0.19	249
A8#	0.08	247	B8#	0.31	252	0.28	250
/			B9#	0.28	258	0.29	255

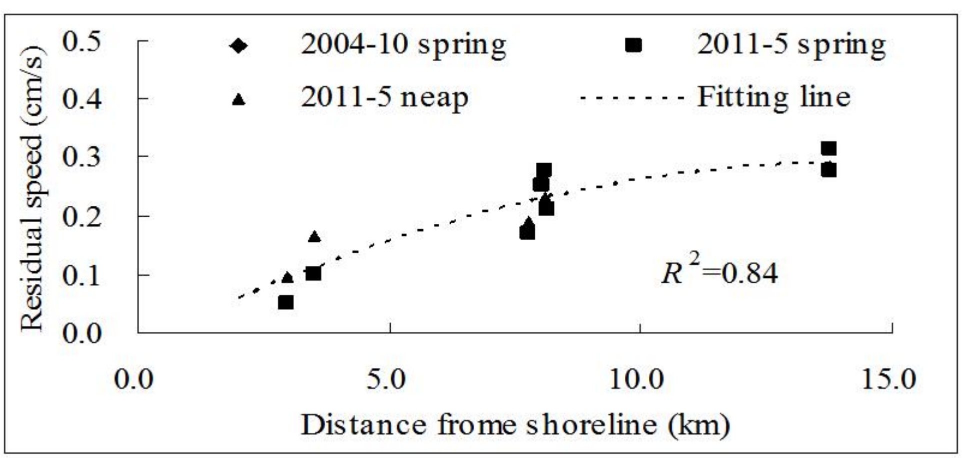


Fig. 5 — Relationship between WG current speed and distance from shoreline.

For evaluating the impact of the WG current to the sea harbor, the Jida Harbor which was planned for construction at the WG coast, was selected as the study case. The planned layout of the harbor is illustrated in Figure 6. The harbor entrance faces to the south. The designed approach channel elevation is -15.0 m from mean sea level, and the channel direction is 178° to 258° with the width of 280 m.

Behavior-oriented modeling method

According to the historical research results, although at present the formation mechanism of the WG current is still not clarified, but in general it is acknowledged that it has a large scale, and could be affected by both monsoon and density baroclinic effects. As s result, if we want to simulate the realistic process of the WG current, we have to choose the 3-D regional ocean circulation models[8,10]. Owing to the macro-scaled nature of the oceanic circulation, spherical coordinates should be used in the modeling system. To the contrary, if we need to precisely describe the current motion process near or inside the harbor, the grid resolution must be delicate enough. Therefore, the scale difference between two model systems brings in a dilemma for modeling study of this specified case.

The historical modeling methodologies of tidal currents usually implied that the driven force of the currents is the spatial and temporal gradients of tidal level. Therefore, when modeling the tidal currents, the open boundary condition should be set to tidal levels. However, the natural driven force of the oceanic currents is irrelevant with tidal level, thus it cannot be modeled by using tidal level variation. Besides, the spatial scale of oceanic currents is extremely large and covers areas far more than the study domain.

To sum up, for a particular engineering case, because the harbor scale is far less than that of the oceanic currents, while the tidal current and ocean circulation have totally different formation mechanisms, the fully process-based modeling was hard to achieve, and another modeling method was required to be developed.

Based on the philosophical discussions given by de Vriend et al [11], for a specified modeling case study, two modeling concepts could be applied: (1) Process-oriented modeling and (2) Behavior-oriented modeling. Actually, for a typical engineering case, rather than the natural evolution feature of the WG current, our key concern is more about the detailed current field characteristics of the harbor area. Therefore, following the behavior-oriented modeling concept, we did not have to "truly" model the realistic coastal processes of the WG current, but to focus more on its net impact to the harbor.

As another aspect, the net impact of the oceanic current to a specified harbor engineering application could boil down to the background nearshore current flux. Therefore, by reasonably "constructing" the additional flow flux sources in the model, we could

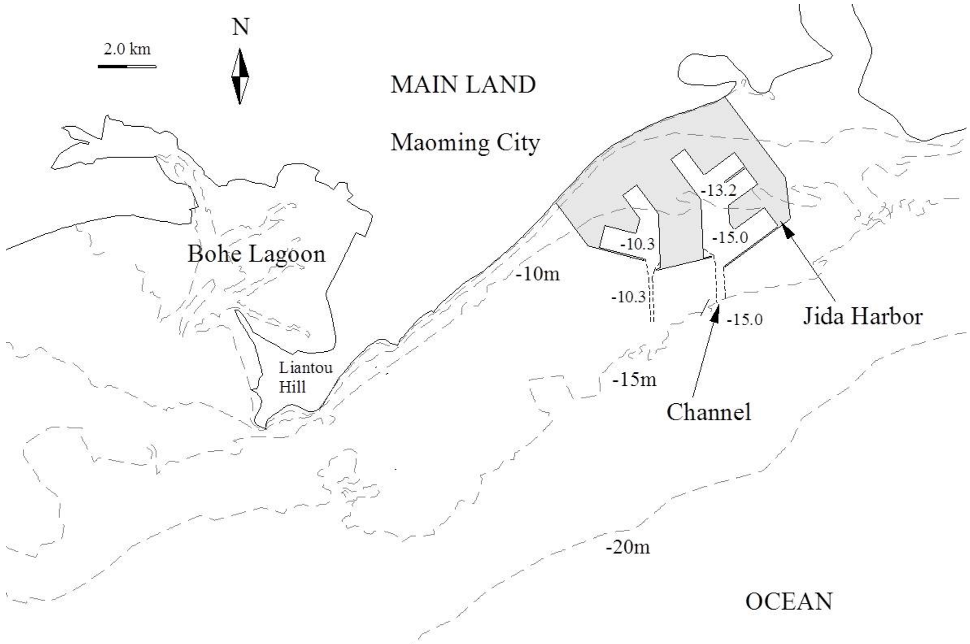


Fig. 6 — Location and planar layout of the Jida Harbor.

then effectively separate the impact of oceanic current from tidal currents. However, it should still be specially stressed that by using this method, the aim was only to ensure the validity of the current movement feature near the harbor area, but not to the regional current field.

For the hydrodynamic modeling, the MIKE 21 FM (flexible mesh) package developed by DHI was selected, and the governing equations are shown in Eqns. (3) to (5), where h is the total water depth, g is gravity acceleration, η is free surface elevation, u and v are depth averaged velocity components in x and y direction, f is Coriollis coefficient, A is horizontal viscosity solved by Smagorinsky formulation, τ_{bx} and τ_{by} are bed shear stress components in x and y direction, S is the discharge source, and u_s and v_s are velocities of the additional flux. For a shorter paragraph, readers of interest could directly refer to the MIKE 21 user manual for more details of the model computation theory.

Figure 7 presents the model domain and mesh resolution. The regional model is the astronomic tide model considering eight main tidal constitutes, which could provide the tidal level boundaries for the local model. The unstructured triangular meshes are applied for model discretization. The minimum spatial step of meshes is 20 m, which could precisely describe the complex boundaries of the shoreline and harbor breakwaters. At the north-east corner of the open boundary a linear inner source is arranged to provide the additional flux of the WG currents.

$$\frac{\partial h}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=hS \qquad \ldots(3)$$

$$\frac{\partial hu}{\partial t}+\frac{\partial hu^2}{\partial x}+\frac{\partial huv}{\partial y}=fuh-gh\frac{\partial \eta}{\partial x}-\frac{\tau_{bx}}{\rho}+\frac{\partial}{\partial x}\left(2hA\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(hA\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)+hu_sS \qquad \ldots(4)$$

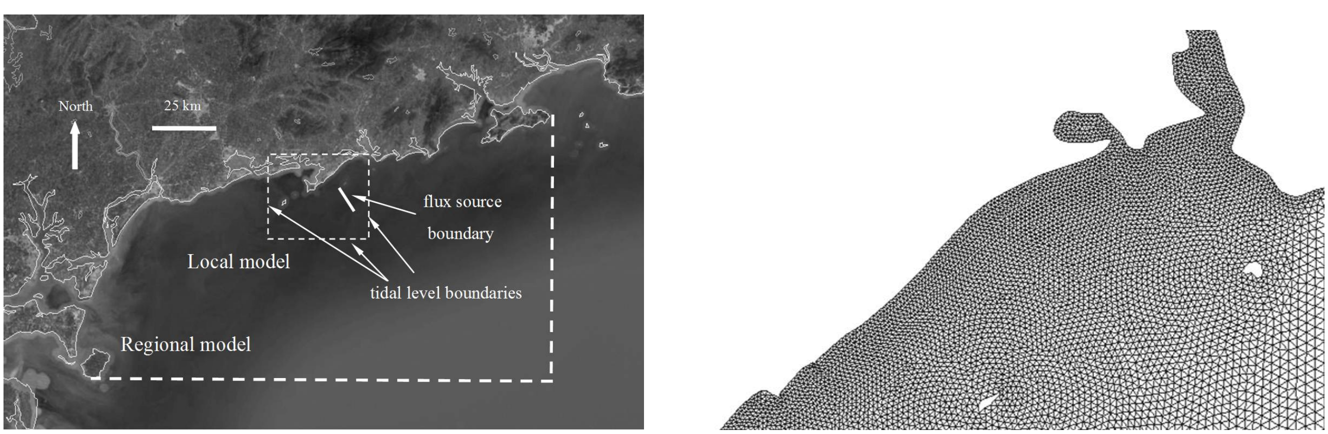
$$\frac{\partial hv}{\partial t}+\frac{\partial huv}{\partial x}+\frac{\partial hv^2}{\partial y}=-fuh-gh\frac{\partial \eta}{\partial y}-\frac{\tau_{by}}{\rho}+\frac{\partial}{\partial x}\left(hA\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)\right)+\frac{\partial}{\partial y}\left(2hA\frac{\partial v}{\partial y}\right)++hv_sS \qquad \ldots(5)$$

Model Validation

According to the data analysis in the above sections (Table 1 and Table 2), the background WG current speed varies significantly with seasons. That means we cannot precisely predict the WG current speed under any given period. However, for a specified harbor engineering application, in practice the current fields under actions of both pure tidal current and tidal-WG coupled current are equally important because they represent two different characteristic conditions. Therefore, for better knowing different processes under both conditions, we were required to model the tidal currents and coupled currents, separately. Consequently, the hydrodynamic model should be validated twice, including (1) under the pure tidal current condition and (2) under the coupled condition with the typical WG current.

Validation of pure tidal current condition

From the in-situ measurement data listed in Table 2, the WG current has impact on the nearshore area in all seasons along the WG coast. During the 2004-10 survey, the WG current speed was relatively small with average residual current speed of only 0.06 m/s. Therefore, in the process of tidal current validation, we



(a) Model domain (b) Mesh resolution

Fig. 7 — Model domain and mesh resolution.

extracted the residual flow from the original measured velocities for each station (A1~A8), and obtained a new set of current velocity datasets. Figure 8 gives the comparison between analyzed and simulated tidal level and current speed/direction. For a shorter paragraph, only several representative stations close to the harbor are presented (T2, T3, A5, A8). The results show that the modeling results agree well with the analyzed data, and it also means that the residual flow extraction method successfully separates the tidal currents from the coupled condition.

Validation of the tidal-WG coupled current condition

The tidal-WG coupled current movement was simulated using datasets measured in 2011-05 under spring tide condition. The net effect of WG currents was modeled by adding a linear flux source near the open boundary (see Fig.7a). For construction of the source flux values, the relationship presented in Figure 5 was applied. Figure 9 gives the comparison between the observed and simulated tidal level and current speed/ direction. Similarly, only several representative stations close to the harbor are presented (T2, T3, B5, B6). The

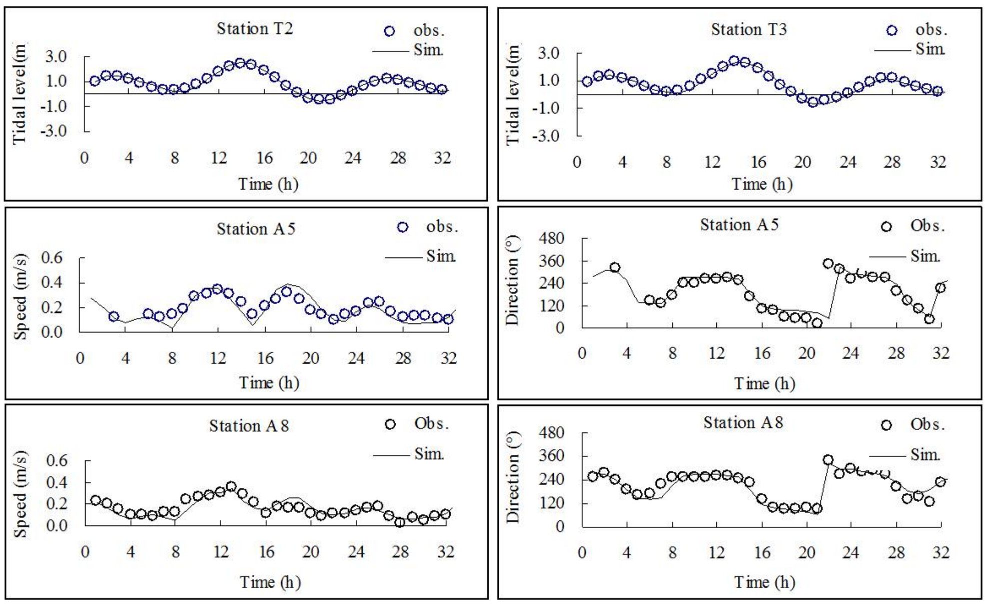


Fig. 8 — Current speed validation for pure tidal current condition.

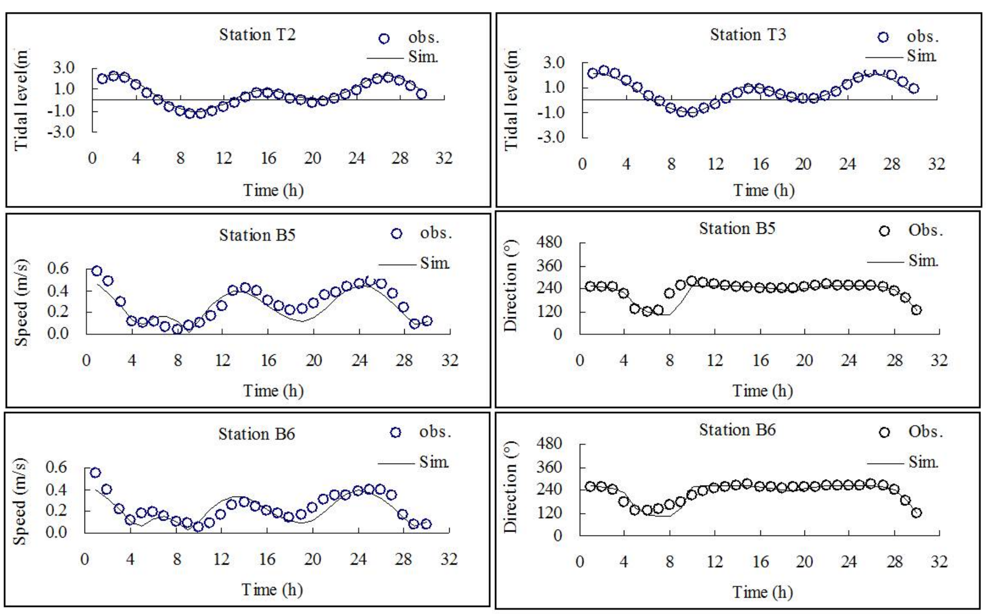


Fig. 9 — Current speed validation for coupling WG and tidal current condition.

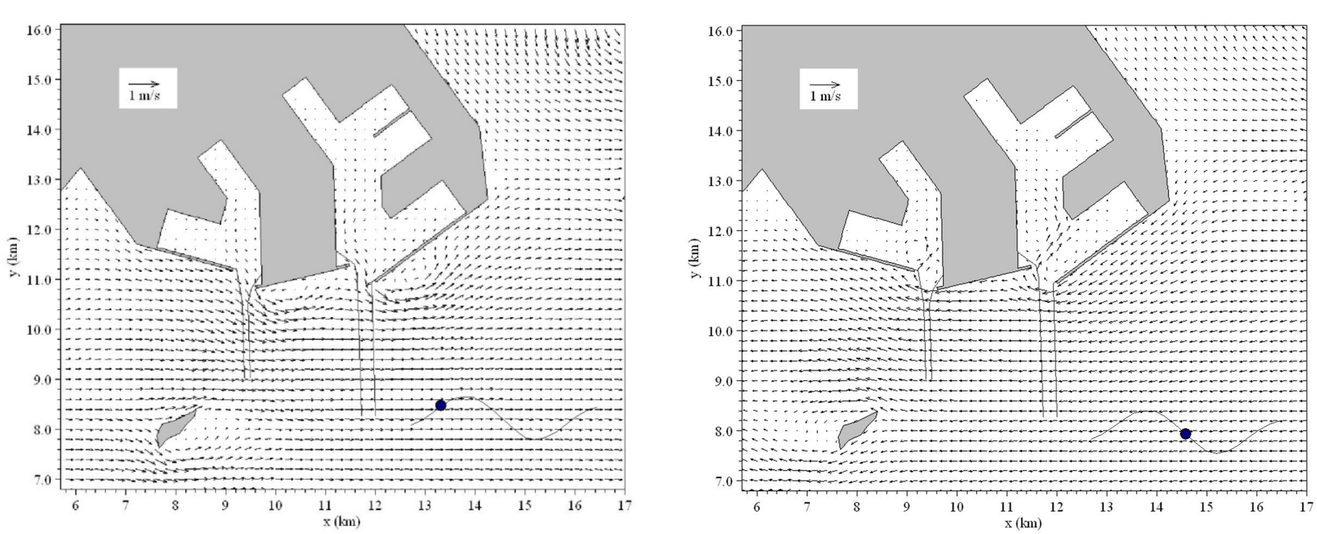
results show that the modeling results agree well with the observed data, which indicates that the method of adding flow flux has satisfactory effects for modeling the tidal-WG coupled condition.

Results and Discussion

Figure 10 and 11 present the simulated current fields under both (1) pure tidal current condition and (2) tidal-WG coupled condition after the construction of the planned Jida Harbor. Some discussion points are made as follows:

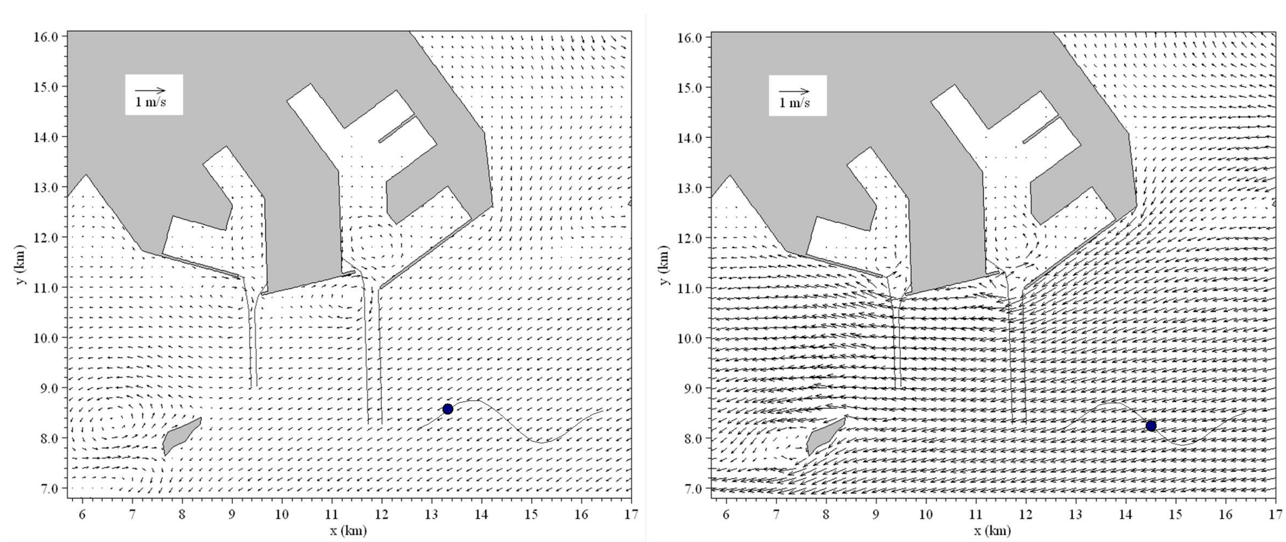
(1) Under the pure tidal current condition, the nearshore current movement shows a typical bi-directional feature, wherein the currents come from south-west in the flooding process and north-east in the ebbing process. Generally, the current speeds for both directions are in similar level.

(2) By superposing the WG current, the nearshore current presents a uni-directional feature and the nearshore current purely points to south-west during the whole tidal cycle. In the flooding process, the original tidal current direction should be north-eastward, but under the reverse pushing effect of the stronger WG current, the nearshore current direction turns to south-west, but the current speed is smaller. In the ebbing process,



(a) Flood process (b) Ebb process

Fig. 10 — Simulated current field for pure tidal current condition.



(a) Flood process (b) Ebb process

Fig. 11 — Simulated current field for coupling WG and tidal current condition

because the natural tidal current has a same direction as the WG current, the west-ward current speed is enhanced.

(3) The channel cross-flow is defined as the velocity component perpendicular to the channel direction. Figure 12 analyzes the maximum cross-flow speed during the modeled tidal cycle under both conditions. Based on the modeling results, because the natural tidal currents move regularly bi-directional, hence the cross-flow speed along the channel is close for both directions under the pure tidal current condition, and the current speed is less than 0.3 m/s. But after superposing the WG current, the channel cross-flow presents a totally different feature, showing that the eastward speed decreases and the westward speed increases. Near the harbor entrance and the channel end, the maximum westward cross-flow speed could reach 0.5 m/s.

When the nearshore currents bypass the harbor entrance, circulation cells usually appear at the downstream side owing to the flow compensation effect. To assess the impact of the WG current to the harbor entrance, Figure 13 and 14 illustrate the current fields near the entrance under both pure tidal current and tidal-WG coupled conditions, respectively. Through comparisons, some features are found as follows.

(1) Under the action of pure tidal current, two

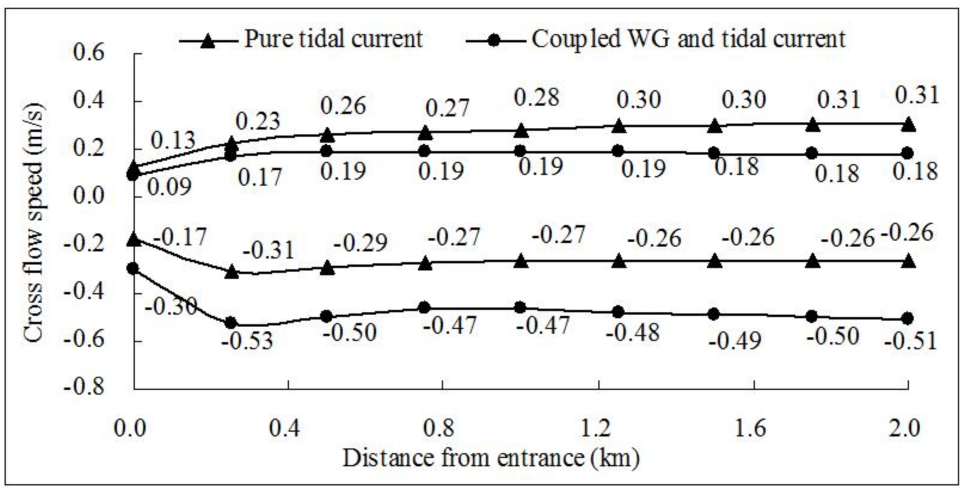
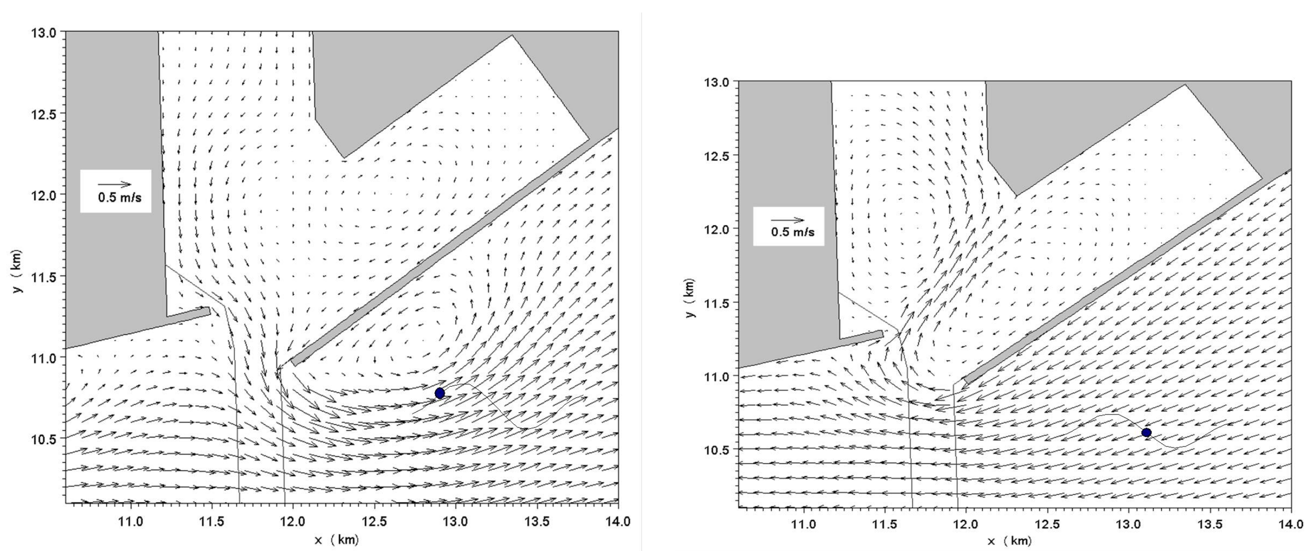
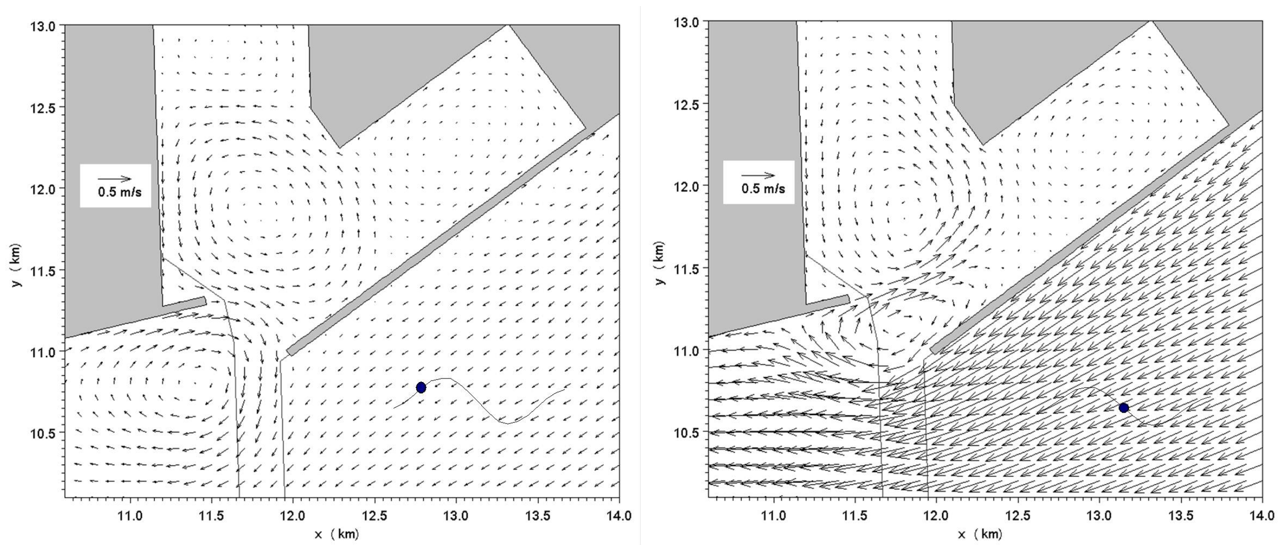


Fig. 12 — Maximum cross-flow speed distribution in the approach channel (positive values represent eastward, negative values represent westward).



(a) Flood process (b) Ebb process

Fig. 13 — Circulation flow structure for pure tidal current condition.



(a) Flood process (b) Ebb process

Fig. 14 — Circulation flow structure coupling WG and tidal current condition.

reverse circulation cells develop inside the harbor entrance. Because the nearshore tidal currents have bi-directional feature, the location of circulation cell center varies with tidal level. During the ebb process the circulation flow speed is in the range of 0.2~0.4 m/s, which is larger than that during the flood process (0.1~0.2 m/s).

(2) Once coupled with the south-westward WG current, the nearshore currents pass the entrance uni-directionally. Therefore, the location and area of the circulation cells are relatively stable compared to the pure tidal current condition. During the flood process, only one circulation cell develops inside the harbor basins with maximum speed of 0.1~0.2m/s; but during the ebb process, two circulation cells form simultaneously at the harbor entrance, and one of them locates directly at the center of approach channel, and its maximum speed could reach 0.4~0.5m/s.

Based on the above analysis, under the impact of different current movement patterns, the feature of entrance circulation cells have significant differences including their location, shape, and speed. Under the impact of the WG current, the maximum channel cross-flow speed becomes larger and so is the circulation speed. Especially, because the radius of circulation cell at the entrance under the action of WG current is less than 250 m (Fig. 14), the large ship is very likely to encounter opposite forces at its bow and stern, and that may bring in additional navigation risk.

To sum up, according to the modeling results, the WG current plays an important role on the development of both channel cross-flow and the entrance circulation for West Guangdong sea harbor; and it indicates that when designing the harbor layout, the WG current must be carefully studied.

Conclusions

By applying methodologies of field measurement data analysis and numerical simulations, the distribution characteristics of the WG current and its impact on a typical sea harbor were studied. Base on the results, some conclusions are made as follows:

(1) The WG current is a unique oceanic current in the nearshore area of West Guangdong coast, China. It flows to south-west with significant seasonal variation and superposes on the astronomic tidal currents, forming a complex nearshore current movement system. Through analysis from the in-situ survey datasets, the speed of WG current gradually increases to offshore with a maximum value of 0.3 m/s.

(2) The direct process-oriented modeling system coupling the tidal current and oceanic current is hard to achieve especially for the case study. By developing the concept of behavior-oriented modeling, we incorporated the impact of oceanic current by adding flow flux sources at the model inner boundary. The validation results indicate this method successfully describes the nearshore current movement characteristics in the vicinity of the harbor.

(3) The simulation results show that under the tidal-WG current coupling condition, the westward cross-flow speed in the approach channel is significantly increased, and a strong circulation cell occurs inside the harbor entrance, which may bring opposite forces to the bow and stern of the ships when they navigate into the harbor. As a result, the WG current could bring in additional risk of the ship navigation safety. Therefore, special attentions must be taken into account when designing the harbor layout at the WG coastal area.

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