Study on Features of Flow Field in HANGZHOU BAY

Zhaoquan Geng [1], Yongqiang Ni [2], Junzheng Zhu [3] & weihua Geng [4]
(Zhejiang Institute of Hydraulics & Estuary (**ZIHE**), Hangzhou, 310020, P.R. China)

Abstract: Based on analysis and induction of predecessor's study results for flow field of Hangzhou Bay, the field survey data for Hangzhou Bay during the summer and winter have been certificated well by means of the EU-FEM mathematical model. The characteristic of flow field of Hangzhou Bay has been analyzed and studied in respects of the flow path, velocity patterns, isograms of tide level, residual flow and salinity. The study results can be used as an important reference in the plan, development and utilization of Hangzhou Bay.

Key words: Hangzhou Bay (HZB), strong tide estuary, flow path, residual flow, salinity, EU- FEM

1. Introduction

Hangzhou Bay is located center and north of Zhejiang province, south of Shanghai city. The Qiantang River empties to the Bay from west. The East China Sea is in the east of the Bay (Fig.1). HZB is a typical strong tide estuarine bay with horn-shape. HZB is sized of $4800km^2$ area with 85.0km long and from 98.5km to 19.4km wide. The Qiantang river, Chaoe River and Yongjiang River empty to HZB with $444.4\times10^8m^3$ water quantity per year[1]. There is Zhousan Archipelago out-side the Bay. Three important cities, Shanghai, Hangzhou and Ningbo, locate around it. There is lot of big industry by the famous north bank deep channel of HZB. The Andong tide flat is situated in the south bank of the Bay. Having rich resources of port and waterway, reclaiming tide flat, aquatic products, HZB has large value for developing and using. The multi-potentialities of HZB for continuously developing have attracted more and more attention of research institutes, universities, enterprises and institutions. It is very urgent to study the dynamic features of HZB further with cooperation of multi-discipline and multi-unit. Based on analysis and induction of predecessor's study results for flow field of HZB, the field survey data for HZB during the summer of 1981 and winter of 1983 have been certificated well by means of the EU- FEM mathematical model (Fig.2). The characteristic of flow field of HZB has been analyzed and studied in respects of the flow path, velocity patterns, isograms of tide level, residual flow, and salinity. The study results can be used as an important reference in the plan, realignment, development and utilization of HZB. This paper synthesized the analyzing and calculating results.

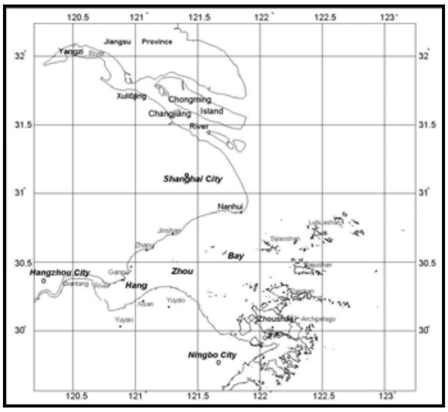


Fig. 1 geography of Hangzhou Bay

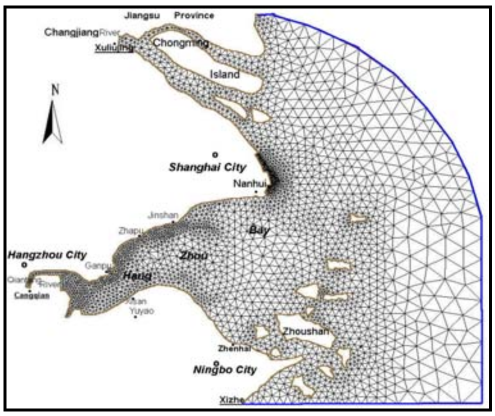


Fig. 2 calculating grids

1, 2,3 Professor, Senior engineer, Senior engineer respectively, Zhejiang Institute of Hydraulics and Estuary , 50 Fengqi East Road, Hangzhou, 310020

4 PHD, Department of Mathematics, Michigan State University, East Lansing, MI, 48823, USA

2. Synopsis of the EU-FEM Models[2]

The vertical averaged two dimension (2-D) water flow equations have been selected as the governing equations.

$$\frac{\partial z}{\partial t}+\frac{\partial (Hu)}{\partial x}+\frac{\partial (Hv)}{\partial y}=0 \qquad (2.1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial z}{\partial x}-fv-\frac{W_x}{H}+gu\frac{\sqrt{u^2+v^2}}{C_z^2 H} \qquad (2.2)$$
$$=\frac{\partial}{\partial x}(\varepsilon_x\frac{\partial u}{\partial x})+\frac{\partial}{\partial y}(\varepsilon_y\frac{\partial u}{\partial y})$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial z}{\partial y}+fu-\frac{W_y}{H}+gv\frac{\sqrt{u^2+v^2}}{C_z^2 H} \qquad (2.3)$$
$$=\frac{\partial}{\partial x}(\varepsilon_x\frac{\partial v}{\partial x})+\frac{\partial}{\partial y}(\varepsilon_y\frac{\partial v}{\partial y})$$

With the initial conditions:

Z (x, y, 0) = Z* (with "*" means given)

u (x, y, 0) = v(x, y, 0) = 0

and the boundary conditions:

Z (x, y, t) = Z*(x, y, t) on the open boundary

and V_n (x, y, t) = 0, on the close boundary.

In which, z is the tidal level (m), u and v is the depth averaged velocity component in the x and y direction respectively (m/s), H is the water depth (m), H = Z - Z_o, Z (x, y, t) and Z_o (x, y, t) is the water surface level and the bottom elevation respectively, f = 2 ω sin φ, ω is the angular velocity of the earth, φ is the geographical latitude, g is the acceleration of gravity, Cz is Chezy's coefficient, εx and εy are turbulant viscosity coefficient in the x and y directions respectively, wx and wy is the wind strath component in the x and y direction respectively.

Equation (2.1) governs the continuity of water flow. Equation (2.2) and (2.3) governs the motion convergence on x and y direction respectively.

The Explicit Upstream Finite Element Method (EU-FEM) scheme has been chosen in this model. The Galeking residual method has been used in equation (2.1)~(2.3) after the partial integral for turbulent terms. The different schemes are upstream scheme for advective terms, foreword different scheme for time derivate.

Let inner conduct $(u, v)=\int_\Omega uv\,d\Omega$ and $\frac{\partial q}{\partial t}=\dot{q}$ .Use forward different scheme $\dot{q}=(q^{n+1}-q^n)/\Delta t$. Where, Δt is the time step(s), n is its number. Thus,

$$(\dot{z},\bar{\phi}_j)+(\frac{\partial(\hat{H}u)^n}{\partial x}+\frac{\partial(\hat{H}v)^n}{\partial y},\hat{\phi}_j)=0 \qquad (2.4)$$

$$(\dot{u},\bar{\phi}_j)+(u_j^n\frac{\partial u_j^n}{\partial x}\bigg|_{T_x^j}+v_j^n\frac{\partial u_j^n}{\partial y}\bigg|_{T_y^j},\hat{\phi}_j)+(g\frac{\partial z^{n+1}}{\partial x},\hat{\phi}_j)+(\overline{\frac{g(\sqrt{u^2+v^2}\cdot u)^n}{C_z^2H^{n+1}}},\bar{\phi}_j)$$

$$-(\overline{fv_j^n},\bar{\phi}_j)-(\frac{\overline{W_x}}{H^{n+1}},\bar{\phi}_j)+\frac{\partial}{\partial x}(\varepsilon_x\frac{\partial\hat{u}^n}{\partial x},\frac{\partial\hat{\varphi}_j}{\partial x})+\frac{\partial}{\partial y}(\varepsilon_y\frac{\partial\hat{u}^n}{\partial y},\frac{\partial\hat{\varphi}_j}{\partial y})=0 \qquad (2.5)$$

$$(\dot{v},\bar{\phi}_j)+(u_j^n\frac{\partial v_j^n}{\partial x}\bigg|_{T_x^j}+v_j^n\frac{\partial v_j^n}{\partial y}\bigg|_{T_y^j},\hat{\phi}_j)+(g\frac{\partial z^{n+1}}{\partial y},\hat{\phi}_j)+(\overline{\frac{g(\sqrt{u^2+v^2}\cdot v)^n}{C_z^2H^{n+1}}},\bar{\phi}_j)$$

$$+(\overline{fu_j^n}, \overline{\phi}_j) - (\frac{\overline{W_y}}{H^{n+1}}, \overline{\phi}_j) + \frac{\partial}{\partial x}(\varepsilon_x \frac{\partial \hat{v}^n}{\partial x}, \frac{\partial \hat{\phi}_j}{\partial x}) + \frac{\partial}{\partial y}(\varepsilon_y \frac{\partial \hat{v}^n}{\partial y}, \frac{\partial \hat{\phi}_j}{\partial y}) = 0 \qquad (2.6)$$

In which， $\left.\frac{\partial u}{\partial x}\right|_{T_x^j}$ indicates that $\frac{\partial u}{\partial x}$ is taken on the upstream element T_x^j， and etc. Let the general variation： $\hat{q} = q_j \hat{\phi}_j$； $\overline{q} = q_j \overline{\phi_j}$.

Three special techniques are used in the models. The first is to use the FEM of lumped mass type, which can make the scheme explicit and without matrix operator. The second is to use the upstream technique for the advective terms and to consider the turbulent viscosity terms. The last is that the Hu or Hv in the equation of continuity considered as one variable, moreover, the H in the equation of tidal motion is taken H^{n+1} (is not H^n). These three techniques make the scheme more stable and more useful. This model possesses one order approach precision.

3. Characteristics of tide and flow path in HZB

3.1 Characteristics of tide

After transmitted into the East China Sea, the tide wave, which originated from the Western Pacific Ocean, will continue toward the Huang Ocean with its major parts and advance to Changjiang River Estuary and the HZB with its minor part, except some power consuming during the transmission process. When the tide wave arrives at HZB, affected by the horn-shaped bay, by the shallow water and the bottom friction function, it turns from the traveling wave to standing wave with obviously phenomenon of day tide.

Table 3-1 the tide characteristics

Station Name / Items	Ganpu	Zapu	Jinshan
High tidal level (m)	7.56	6.54	5.98
Occurred date	1997.8.19	1997.8.9	1997.8.19
Low tidal level (m)	-3.36	-3.01	-2.37
Occurred date	1951.8.22	1930.9.24	1969.4.5
Maximum tidal range (m)	9.93	8.57	7.34
Occurred date	1951.8.20	1962.8.2	1989.10.16
Average high tidal level (m)	4.05	3.52	3.16
Average low tidal level (m)	-1.56	-1.12	-0.80
Average tidal range (m)	6.61	5.65	4.93
Average flood period (h: m)	5:25	5:27	5:28
Average ebb period (h: m)	7:00	6:58	6:57
Statistic period	1951-1999	1930-1999	1952-1998

In general, HZB belongs to the shallow irregular half-day tide area and the statistics of the tide character in the three major tidal level stations are listed in Table 3-1. From the table, we can learn that in HZB, from Bay mouth to the Bay bottom, the tidal range and the high tidal level continuously raised while the low tidal level continuously depressed and the flood period decreased while the ebb period increased.

3.2 The Features of Flow Path

According to the analysis for the transmission direction of the tide power of the M_2 branch tide in HZB, combined with the accumulated testing results of the numerical simulation for different range in HZB (Figure 2), The sketch map of the flood and ebb current path in the HZB have been showed in Figure 3. The tide power in this area comes from the Southeast. Zhoushan Archipelago impedes the transmission of the tide power towards the Bay. The tide wave enters the HZB through the five water channels among islands from Zhenhai to Zhoushan, Zhoushan to Daishan, Daishan to Dajushan, Dajushan to Sijiaoshan and Sijiaoshan to Luhuashan. The three channels in north, which have relatively wider offing and deeper water, are the main channels for the tide power to enter the HZB. These three floods current converge at the frontline from Tanxu to Jinshan. The two flood currents in south converge in the Wangpanshan nearby. The major parts of the entered tide wave converge at the sea area between Jinshan and Wangpanshan, affected by the landscape of the horn-shaped HZB, and then the tide wave is driven toward Southwest. The ebb current direction in this area is basically reverse with the flood current. The ebb current originates from the Qiantang River Estuary, advances from west to east, after passes the Andong section, most of it flows toward north east. A small part of it advances toward East first, then along the deep channel of the north bank of the HZB, flows toward northeast to the Bay mouth, upon arriving the South coastal of Shanghai, it turns East, finally flows toward Southeast coerced by the ebb current from the ChangJiang River. In general, the major flood current leans to north while the major ebb current leans to South. There is a "∝" shaped flow path at the Bay bottom nearby.

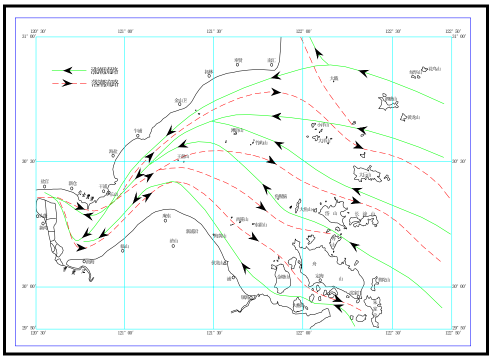


Fig. 3 sketch of paths of tide in HZB

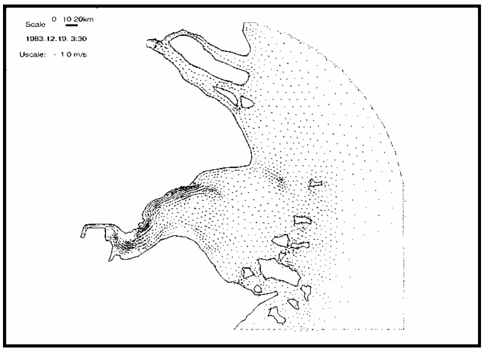


Fig. 4 calculating ebb curent patterns

3.3 The features of flow velocity and direction in HZB

The main power, which sustains the flow fields of HZB, comes from the tide wave originated from the East China Sea and transmitted from Southeast and East. The runoff of Changjiang River and Qiantang River (including Chaoe River) also has some contributions[3]. The runoff of Changjiang River has obvious effect on Zhapu downstream HZB and its flow fields at the north, while the runoff of Qiantang River has some relationship with the Zapu upstream HZB. The landscape and topography under water have great restriction to the flow fields. The flow fields is very complex in the Bay, because of HZB has hone-shaped plain, Zhoushan Archipelago is outside the Bay mouth. With the narrowness of the Bay width from mouth to bottom and the uplift of the topography underwater, the transform of the tide wave in shallow area increase, which creates the world-famous Qiantang bore at the top of the Bay. According to the distribution of the flow velocity (Figure 4), in general, the flow fields in HZB change with regularity from east to west and the flow velocity continuously increases from downstream to upstream.

HZB is a typical strong tide sea area with higher velocity. The flood velocity is 1.85～2.79m/s and the ebb velocity is 1.44～2.35m/s during spring tide period; The flood velocity is 1.37～2.05m/s and the ebb velocity is 1.25～2.19m/s during middle tide period; The flood velocity is 1.02～1.54m/s and the ebb velocity is 0.9～1.53m/s during neap tide period. After analyzing the isograms sketch of the rate of maximum velocity between flood and ebb, it is known that the flood flow is dominant in the north sea area of Wanpansan and the ebb flow is dominant in the south sea area of Wanpansan. The averaged direction of flood flow is 220° ～270° and the averaged direction of ebb flow is 46° ～88° . The average angle of the direction between flood and ebb is 180° approximately.

4. The behavior of residual flow in HZB

The residual flow is very important for analyzing pollutant transportation, sediment movement, and the distribution of temperature and salinity. After verifying the flow fields in HZB, we further calculate the residual flow fields. Figure 5 presents

Euler residual flow fields with comprehensive tidal statistics with the result, which lasts 20 tidal circulations. The average velocity of residual flow in HZB is about 20cm/s. The residual flow points northeastern and a little eastern, which is similar with the trend of the north bank, symbolizing the path through which the runoff of Qiantang River enters the Bay. Near the north bank, the residual flow walks toward the west, and it looks like a close-to-bank branch from the Changjiang River. Near the mouth of the Bay, the residual flow in the north points southeast while the residual flow in the South points South, which shows that the flowing directions of the runoff comes from Changjiang River after emptying to HZB. At the Mouth of Changjiang River, Qiantang River, and Caoe River, there is large residual flow, which is created by the runoff. The residual flow in northeast of HZB points at west by south, symbolizing that there is part of water from the Changjiang River entering the HZB. What we want to emphasize is the difficulty in residual flow analysis. The residual flow not only is affected by the power of season runoff, but also has relationship with the underwater topography, Cariole's force, and the non-linear facts in the shallow tidal wave. Futhermore, excluding the cycle facts of the flood current and ebb current, it has the relationship with the spring tide, middle tide and neap tide. When the tidal wave enters the Bay and the Mouth, transformed by shallow water, the waveform and the period of flood and ebb current become more asymmetrical and the function of non-linear facts shows much dramatic.

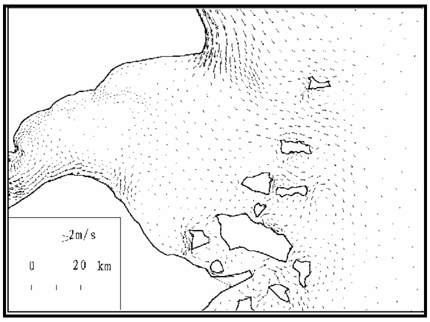
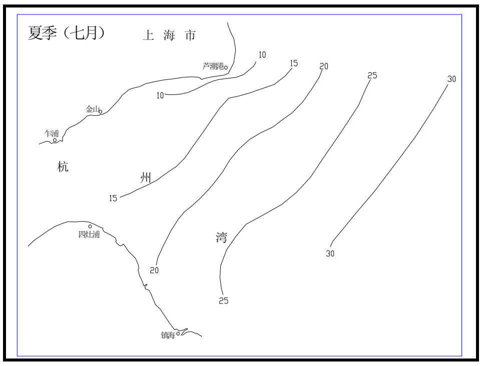


Fig. 5 patterns of residual flow of HZB

5. The behavior of the salinity in HZB

Salinity is relatively conservative hydrographic factor and its change and distribution is restricted by ocean flow and runoff of river. The low salinity water near the bank created by water flow has great impact to the alongshore water[4]. According to analysis from the survey data during 1981 to 1983, in the sea area from HZB to Zhoushan Archipelago, the isohaline is distributed like a snake from northeast to southwest (Figure 6). In space distribution, the isohaline is toward the internal Bay at the south of HZB, toward the external Bay at the middle part of the HZB, and a little toward the internal Bay at the north of the middle part of the HZB. In time distribution, the annual salinity change of the water at the estuarial is decided by the annual change of the runoff. The flood season and typhoon season, which creates two low salinity periods, affects the salinity in Qiangtang Estuary[5]. However, the salinity in the HZB is less affected by the runoff, therefore it changed by the annual period. The daily change of the salinity is decided by the tides. In the north sea area of Zhejinag, the Qiangtang Estuary is on the west while the Estuary of Changjiang River is on the north. Therefore the salinity gradient is the largest. The isohaline above Ganpu is nearly south~north while it is southwest to northeast beyond the west of Ganpu. In figure 7, we draw the calculating isograms of salinity distribution in the HZB plain in summer. From this figure, it can be seen that the isohaline of 10‰,15‰, 20‰, 25‰ and 30‰ are very similar with the survey data.



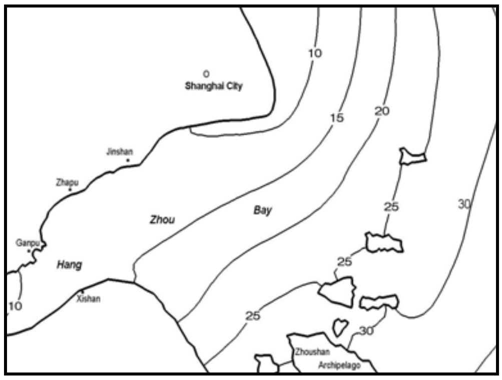


Fig. 6 salinity distribution of HZB surveyed Summer

Fig. 7 salinity distribution of HZB calculated Summer

In the calculating area the maximum salinity grads zone occurs in the east and southeast area of Nanhuizui, near which the freshwaters of Changjiang River meet outer seawaters. It is obvious that the salinity in HZB is affecting by the runoff of Changjiang. The salinity in HZB is uniform in vertical because of the strong tide and rapid flow in HZB. The salinity distribution in HZB belongs to well mix type.

6. Conclusions

Based on predecessor’s study results for Hangzhou Bay, the flow path, velocity patterns, isograms of tide level, residual flow, and salinity of the Bay have been calculated by means of the EU-FEM mathematical model.

(1) It leads to the shallow irregular half-day tide in Hangzhou Bay, that affected by the horn-shaped, by the uplift of the topography underwater and the bottom friction function of the Bay.

(2) The flow fields in Hangzhou Bay change with regularity from east to west and the flow velocity continuously increases from downstream to upstream. The flood flow is dominant in the north sea area of the Bay and the ebb flow is dominant in the south sea area of the Bay.

(3) Affected by the tide from out sea and by the runoff from three Rivers, the salinity distribution in Hangzhou Bay changes with time (season) and space (up/down-stream, north and south).

References

1. Compile Committee of History of China Bay,《History of China Bay》(Vol. 5: Bays in Shanghai and north of Zhejiang province), pp.1-87, Ocean Publishing house, 1992.
2. Zhaoquan Geng and Yongqiang Ni, Application of an Explicit Upstream FEM in Estuary study, China Ocean Engineering 1999, V01.13, N0.3.
3. Li Sengdu and Hu Hui, Study of Flow Field in HZB, Ocean and limnology, 1987(1), pp.28-37
4. Mao Hanli, The Basic characteristics of temperature and Salinity in HZB, Ocean and limnology, 1965.
5. Su Jilan and Wang Kanshan, The Frontface of HZB and its Materials transportation, Ocean Journal, 1990