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Dynamic Structures and Their Sedimentation Effects in Huangmaohai Estuary, China

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ABSTRACT

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Based on data collected from three cruises of hydrographic survey carried out during 1985–1991 and numerical modelling the present paper provides a brief analysis on the dynamics of Huangmaohai Estuary, emphasizing on the low frequency of flow patterns or circulation. Labeled water parcel trajectories are calculated to reveal the Lagrangian motion. Velocity distribution of the estuary indicates a low energy zone in the mid estuary that acts as a sediment trap. Three large scale dynamic structures are found in the estuary along the North and East Channel which have profound effects on the modern sedimentation. They are from north to south (1) vertical density driven circulation, (2) gorge jet current and (3) horizontal circulation. The effects of estuarine dynamics on the sedimentation process, especially those concerning the river mouth bar, are then discussed.

INTRODUCTION

Huangmaohai Estuary is one of the eight outlets of the Pearl River. It is important for various economic developments of the west Guangdong, China. Several multi-discipline surveys have been carried out since the 1980's. Because its topography is complicated with channels, shoals and tidal flats are situated alternatively and the fresh water discharge is subjected to significant seasonal variations against the unequal semi-diurnal tides. Its dynamic characteristics are not well understood. Modern sedimentation encompasses the entire complex of interrelated physical, chemical and biological processes that bring about the accumulation of sediments. Hydrodynamic analysis that reveals the basic physical process is fundamental to a deeper understanding of the modern morphological and sedimentational processes in an estuary.

Based on field data and numerical modelling techniques, in view of Eulerian and Lagrangian motion, the present research attempts to identify some of the most significant dynamic structures that have profound effects on flow patterns and long term transport of water and sediments. The macro-scale properties of the estuarine dynamics are the main concern. Huangmaohai Estuary is a convection-dominated system. The net displacement of Lagrangian motion is in the same order of magnitude as tidal excursion. Lagrangian residual currents, especially their distribution patterns in the estuary are shown to be responsible to the transport of suspended sediments.

The density-difference-driven residual currents play an important role in Huangmaohai Estuary as in many estuaries in the world. However, in a particular estuary, the local topographical effects may become the dominant process in a certain area. The Kelvin wave is of importance in the Huangmaohai Estuary and in other broad estuaries in South China where long term circulation is a concern.

STUDY AREA

Huangmaohai Estuary is located in the west of Pearl River Delta. Tanjiang River and Hutiaomen River flow in from the north and are the principal sources of fresh water (Figure 1). Geomorphologically, it is a drowned river valley. It is 40 km long and 1.9 km wide in the upper, north end and has maximum width of 34 km near the mouth. The estuary has a surface area of 548 km^2. Two sets of rocky island line up near the mouth in the orientation of ENE-WSW. The estuary is bathymetrically complex. A scoured deep channel extends 20 km from the head towards south which is mainly the result of fresh run-off and strong tidal current in the upper estuary. The North

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Channel is about 300–900 m wide and 12 m deep. Two channels are found in the lower estuary. West and East Channel are separated by Damang Island. In the mid estuary, North Channel and the channels in the south are separated by a broad shoal, or river mouth bar where the water depth is only 2 m which is the major obstacle for navigation. Mean tidal range near the head is 1.24 m. Annual mean fresh water discharge from the two rivers is 1,262 m^3/sec.

TIDAL MODELS

A two dimensional tidal model is applied to simulate the fluid dynamics of the estuary. Since the actual transport of water and suspended sediment is a Lagrangian process, a numerical approach is also incorporated to the 2-D model to simulate the Lagrangian motion.

Governing Equations

The large scale horizontal motion in an estuary can be derived by the shallow water equations:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -g\frac{\partial \zeta}{\partial x} + fv + k\frac{\rho_a W_x |W_x|}{\rho H} - \frac{gu(u^2 + v^2)^{0.5}}{C^2 H} \quad (1)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -g\frac{\partial \zeta}{\partial y} - fu + k\frac{\rho_a W_y |W_y|}{\rho H} - \frac{gv(u^2 + v^2)^{0.5}}{C^2 H} \quad (2)$$

$$\frac{\partial \zeta}{\partial t} + \frac{\partial}{\partial x}(Hu) + \frac{\partial}{\partial y}(Hv) = 0 \quad (3)$$

where

$u(x, y, t)$ is depth-averaged velocity in x direction
$v(x, y, t)$ is depth-averaged velocity in y direction
g is gravitational acceleration
x is horizontal coordinate (south)
y is horizontal coordinate (east)
$H(x, y)$ is water depth, $H = h + \zeta$
$h(x, y)$ is water depth below plane $z = 0$
$\zeta(x, y)$ is water elevation above plane $z = 0$

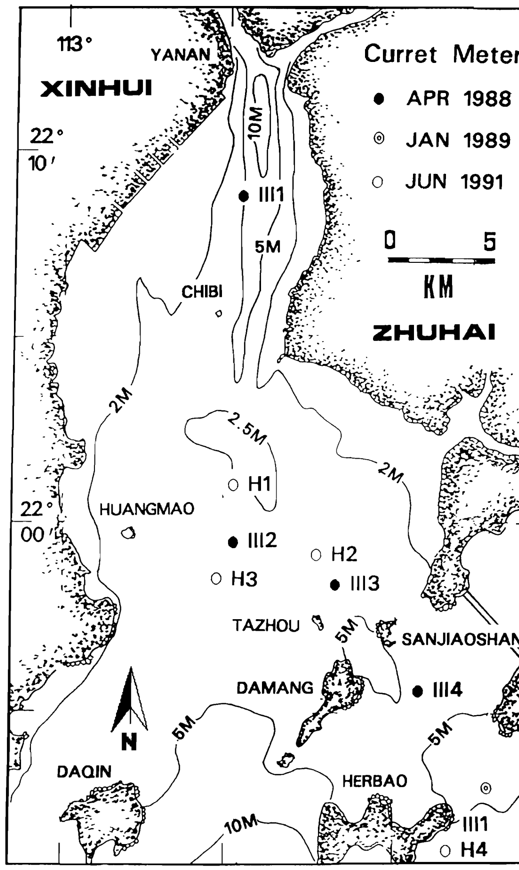

Figure 1. Location map of study area and current meter mooring.

$C(x, y)$ is Chezy coefficient
f is Coriolis parameter
ρ, ρ_a are density of sea water and air respectively
k is friction coefficient
W_x, W_y are wind speed in x and y directions.

Boundary conditions:

$$u_r = u_{op}(x, y, t)$$
$$v_r = v_{op}(x, y, t)$$

where u_{op} and v_{op} are velocities in the open boundary. For tide controlled boundary:

$$\Gamma_r = \Gamma_{op}(x, y, t).$$

In the present model, observed tidal boundary was used. For closed boundary,

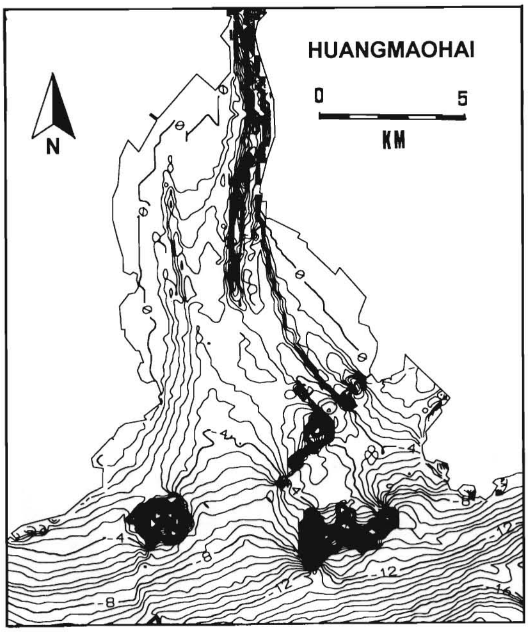

Figure 2. Map of bottom topography.

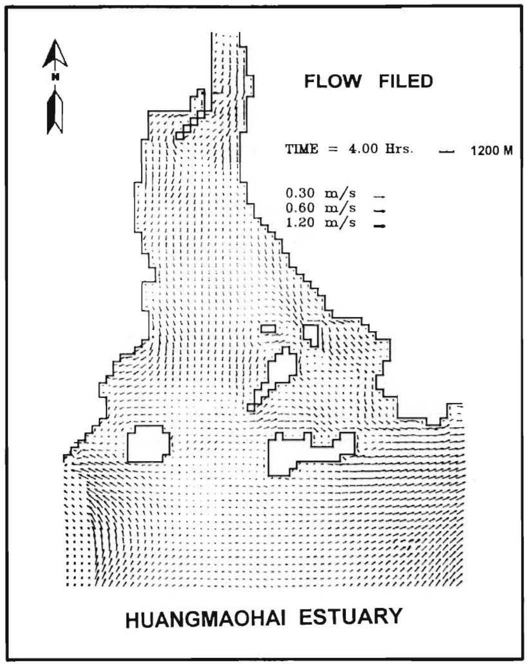

Figure 3. Flow field, flow direction is tangent to the local isobath.

$$(Wn) = 0$$

where W is velocity vector and n is the direction vector normal to the boundary. The area of interest is Huangmaohai Estuary. A North South oriented finite difference schematization was made with grid size $x = y = 600$ m. The shallow-water equations (1) to (3) have been solved by an alternative direction implicit (ADI) finite difference method. Time step of 300 seconds gives enough stability. The model is calibrated so that both calculated tide elevation and current velocities are compared with observed records with fair agreements.

Lagrangian Motion

When the transport of dissolved and suspended matter is of interest, the actual transport is characterized as a convection dominated process which suggests that the transport is Lagrangian motion. The fate of suspended matter should be derived by a Lagrangian mean rather than by an Eulerian mean (CHENG *et al.*, 1986). In order to analyze the Lagrangian motion of labeled water parcel, the Lagrangian velocity components (u_l, v_l) in the x, y directions are defined as the velocity of a water parcel at time t which is released from (x_0, y_0) at time t_0. As time elapses, the position of water parcel can be given by

$$x = x_0 + \eta$$
$$y = y_0 + \xi \tag{4}$$

with the initial conditions that $\eta = \xi = 0$ at time $t = t_0$. Thus the Lagrangian velocity (u_l, v_l) can be expressed in terms of the Eulerian tidal velocity:

$$u_l(x_0, y_0, t) = u(x_0 + \eta, y_0 + \xi, t)$$
$$v_l(x_0, y_0, t) = v(x_0 + \eta, y_0 + \xi, t) \tag{5}$$

where the position of the water parcel is (x_0, y_0) at $t = t_0$. The Lagrangian displacement (η, ξ) can be obtained from integrating the differential equation of a streakline:

$$\frac{d\eta}{u_l} = \frac{d\xi}{v_l} = dt \tag{6}$$

or

$$(\eta, \xi) = \int_t^{t_0+T} [u_l(x_0, y_0, t), v_l(x_0, y_0)]\, dt$$

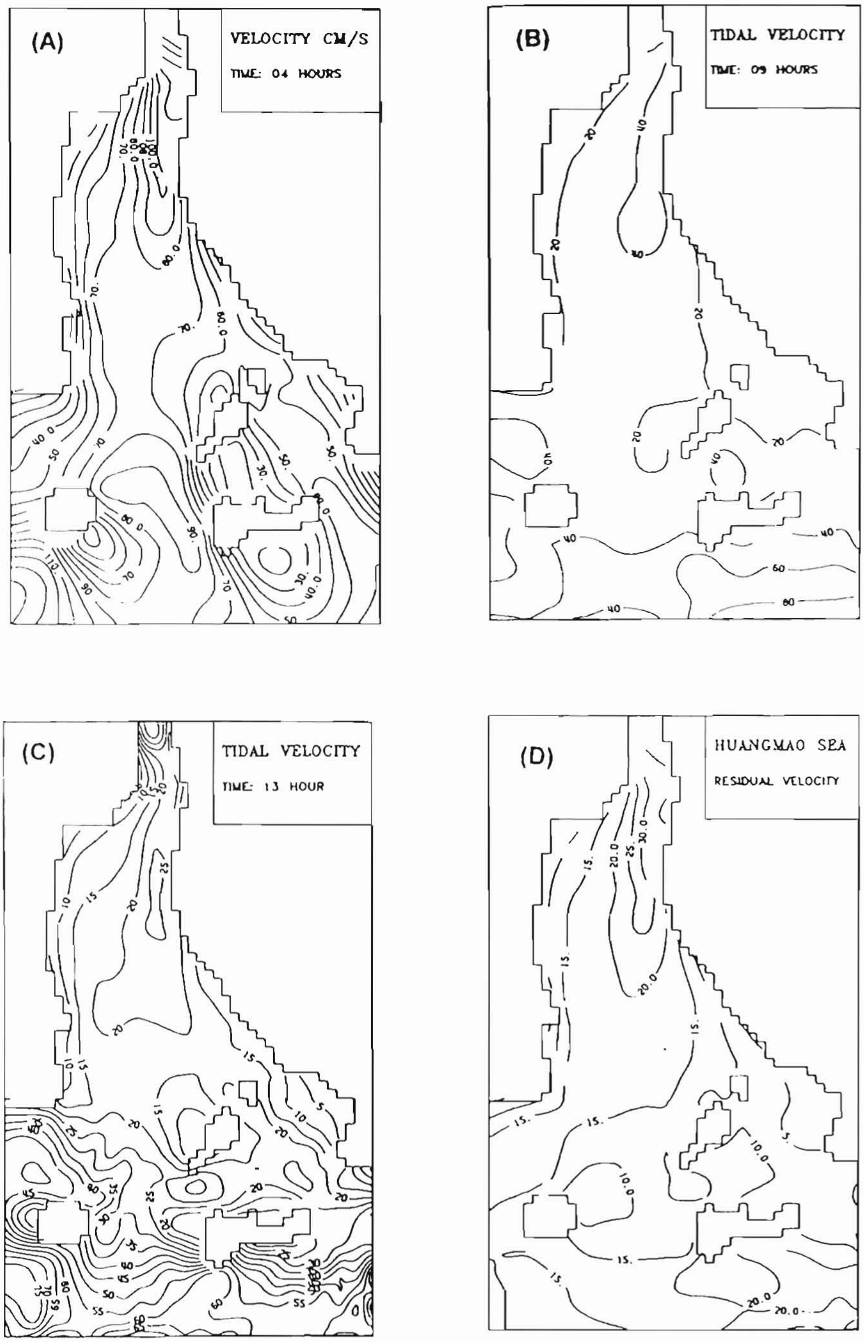

Figure 4. Velocity isogram in different tidal phases. (D) shows the residual velocity.

$$= \int_{t}^{t_0+T} [u(x_0 + \eta, y_0 + \xi, t), \quad v(x_0 + \eta, y_0 + \xi)]\, dt \qquad (7)$$

where T is one or more tidal periods. Eq. (7) is an integral equation of (η, ξ). With appropriate initial and boundary conditions, Eqs. (1) to (7) describe completely the dependent variables (ζ, u, v, u_l, v_l, η, ξ).

TIDAL CURRENT ANALYSIS

Eulerian Velocity Distribution and its Effects on Suspended Sediment Transport

An important property of the tidal current velocity in the estuary is that the tidal current, both magnitude and direction, is mainly controlled by the bathymetry. The direction of the current is tangent to the local isobath (Figures 2 and 3). The spatial distribution of current velocity based on the three cruises of hydrographic survey and the verified 2-D model indicate the existence of a low energy (velocity) zone in the mid-estuary, which coincides with the river mouth bar, or mid shoal. Figure 4A–D shows the current velocity in different phases in a tidal cycle. Shown in Figure 4D is the isogram of Eulerian residual current. The maximum ebb current exceeds 110 cm/sec in the North Channel and 90 cm/sec in the lower estuary while it is less than 60 cm/sec in the mid-estuary. During most of the time in a tidal cycle, current velocity over the mid-bar is substantially lower than that in both upper and lower estuary. The decrease of current velocity significantly affects the transport rate of suspended sediment and sedimentation process. According to BAGNOLD (1966) the suspended load discharge q_s expressed as dry weight per unit time and width is given by:

$$\frac{\gamma_s - \gamma}{\gamma} q_s = 0.01\tau_0 \frac{U^2}{\omega} \qquad (8)$$

where γ_s and γ are specific weights of sediment and water respectively, τ_0 is unit tractive force exerted by the flow on the bed, U is average flow velocity over the water column, ω is settling velocity. When flow carrying sediment from both river and the sea slows down in the mid estuary, the sediment transport capacity decreases rapidly which in turn may cause suspended sediment to accumulate in the water column over the mid shoal. Satellite picture, hydrographic survey and 2-D model indicate that a high sediment concentration zone exists in the mid estuary during flood season. This low energy zone acts as a sediment trap for both suspended and bed load from inland and marine sources.

Lagrangian Motion

The verified 2-D numerical model is used as the based-line flow field and the movement of marked water parcels can be calculated from Eq. (7). Shown in Figure 5 are the labeled water parcel trajectories computed in a Lagrangian sense over a period of diurnal and semi-diurnal tides. Lagrangian net displacement in Huangmaohai Estuary is smaller than tidal excursion as required but it is large enough to be the same order of magnitude as tidal excursion. As a comparison, the Lagrangian net displacement is one order of magnitude smaller than tidal excursion in a semi-enclosed estuary with little fresh water (CHENG *et al.,* 1986). This indicates the strong effects of fresh water run-off on the tidal current and sediment transport. Note that the tidal excursion of marked water parcels initiating from both upper and lower estuary is substantially greater than that from the mid-estuary. Note also that the water parcels initiate from either upper or lower North Channel, they end closely in the mid-estuary over the river mouth bar. This unique Lagrangian motion reveals the effects of flow dynamics on the sedimentation process. The small Lagrangian current velocity during the turning of tides is favored for sediment deposition. Water parcels or suspended sediment initiating from the lower estuary are carried to deep water by the strong West Guangdong nearshore drift. Figure 5 shows that the marked water parcels starting from the upper East Channel do not discharge to sea through lower East Channel, instead, after passing the gorge, turns to the west, joins the West Channel and causes serious siltation between Damang and Hebao island.

DYNAMIC STRUCTURES AND SEDIMENTATION

Based on hydrological survey, remote sensing images and the numerical model, three large scale dynamic structures are found in the estuary along the North and East Channels which have a profound effect on the sedimentation.

Vertical Density Driven Circulation

Vertical density driven circulation, or non-tidal gravitational circulation in some estuarine literature, is the vertical circulation in an average sense over one or more tidal periods. The circulation is driven by the variation of horizontal pressure along the depth between the baroclinic and barotropic components. The horizontal pressure gradient at any depth z in an estuary is

$$\frac{\partial p}{\partial x} = g \int_{-\zeta}^{z} \frac{\partial \rho}{\partial x} dz - g\rho_s \frac{\partial \zeta}{\partial x} \qquad (9)$$

where ρ_s is the density at the sea surface. In stratified conditions, the integral term increases with depth so that the contribution of the surface slope is gradually compensated. Flows induced by the first, density, part of Eq. (9) are called baroclinic flows, and those due to the sea surface gradient are barotropic flows. When the first term exceeds the second term after a certain depth, the water flows up estuary with lighter fresh water flows down to the sea in the upper layer. At the toe of the density circulation near the bottom, the up-stream flow meets the down-stream flow, which is often called the 'null point' where serious siltation occurs. The density circulation is mainly affected by estuarine bathymetry, river discharge, coastal water body and winds. The develop of the circulation is most sensitive to fresh water run-off. During the flood season, the river discharge can turn the entire estuary to brackish water. The isohaline of 15‰ is pushed down to the south of Hebao and Daqin Island near the mouth. The 30‰ isohaline can reach Yanan near the head of estuary in low water season. When the limit of salt water moves down in flood season the distance of salt water intrusion increases due to the strong stratification. Shown in Figure 6a–c are the velocity profiles in a complete tidal cycle measured in low water season in April, 1988. The up-stream flow near the bottom can be found in station III1 (Figure 6a) moored near the head of the estuary. Figure 6b and c show that the depth (thickness) occupied by the up-stream flows increases from starting at 0.8 height at station I to 0.7 height at station III2, and finally 0.3 height at station III3. The up-stream net current velocity near bottom is 5–10 cm/sec. Shown in Figure 7a and b are velocity profiles measured in flood season (June, 1991). The seaward flow controls the entire North Channel; the toe of the density circulation is situated between stations H1 and H2 over the mid shoal. In most of the time, Yamen Estuary is partially mixed. Weak stratification occurs in the high water season. The ebb-flood asymmetry exists in all observations. On flood, the baroclinic pressure

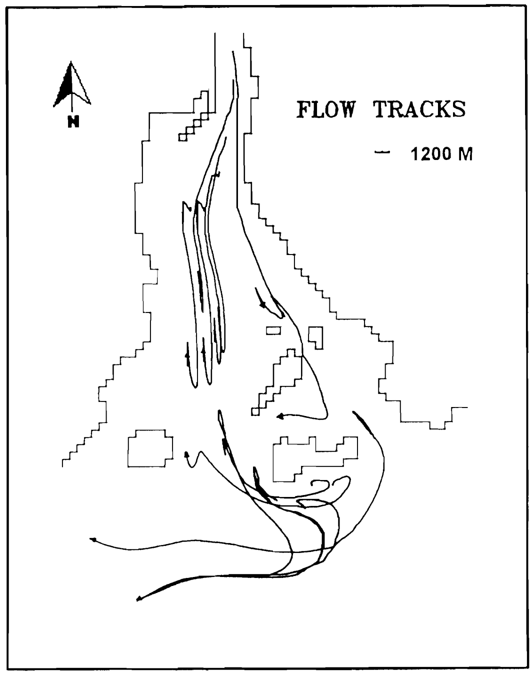

Figure 5. Labelled water parcel trajectories in a tidal cycle indicate a convection-dominated system.

gradient is in the same direction as the barotropic gradient and enhances it at depth. This tends to reduce the shear stress in the water column by enhancing the landward flow near the bed, and the shear is relatively concentrated near the bottom. This is shown clearly in all the observed velocity profiles. On ebb, the baroclinic pressure gradient is in the opposite direction as the barotropic gradient and reduces it at depth. The result is substantial shear (Figure 7a). Stratification is then increased and boundary shear stress is reduced on ebb relative to the neutral value. The ebb-flood asymmetry has important consequences for sediment transport (WU, 1989). Most aspects of the ebb-flood asymmetry discussed here have been confirmed in other systems, *e.g.*, the Fraser River Estuary (GEYER, 1988) and the Dawamish (PARTCH and SMITH, 1978).

The vertical circulation in the East Channel is strongly disturbed by a jet current system near the narrow gorge between Sanjiaoshan and Damang Island. To the south of the gorge, a horizontal circulation develops in the Cross-sea where the vertical circulation disappears. Shown in Fig-

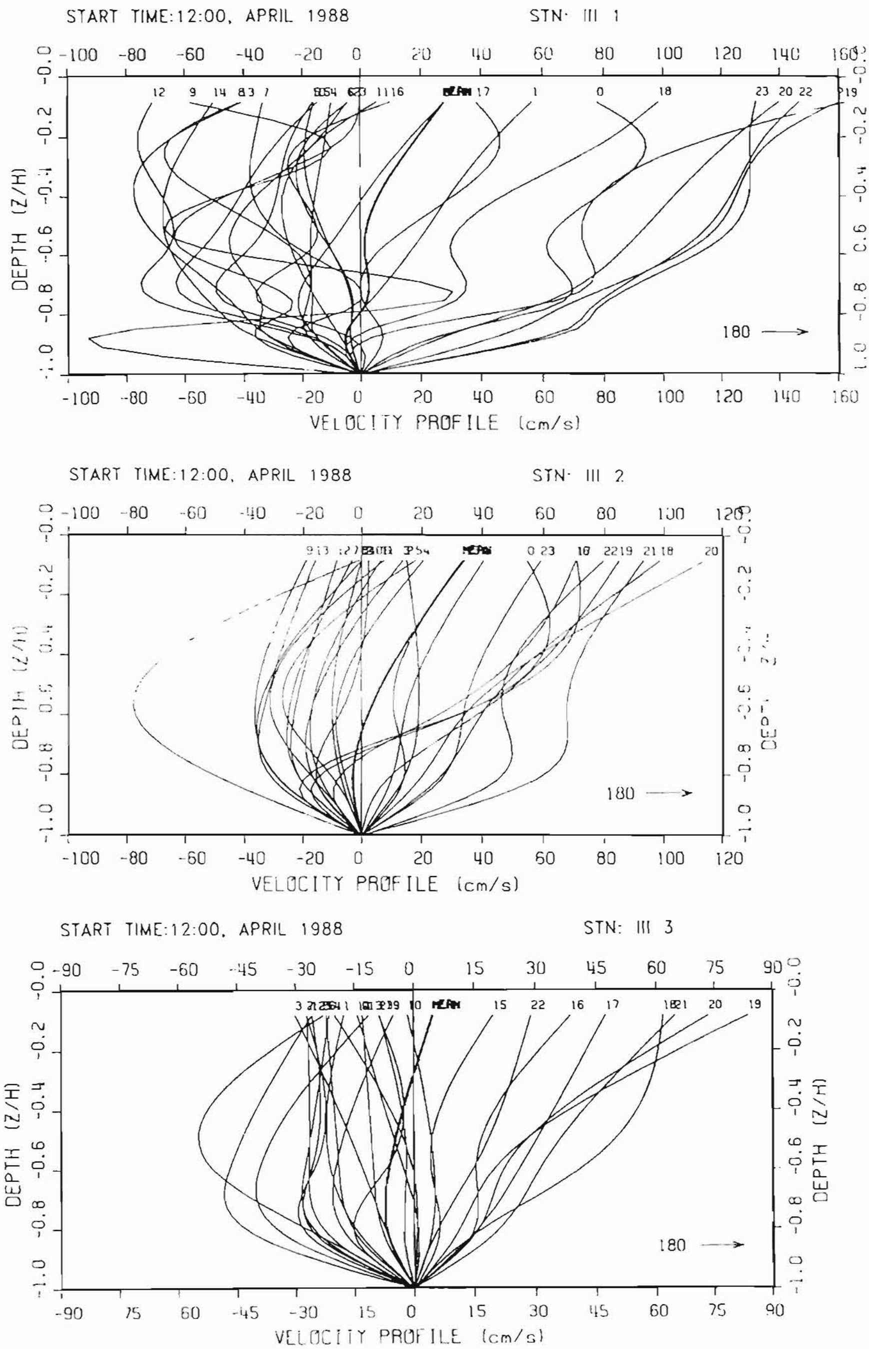

Figure 6. Velocity profiles measured in April 1988 at station (a) III1 (b) III2 and (c) III3. The gross line represents the tidally mean velocity.

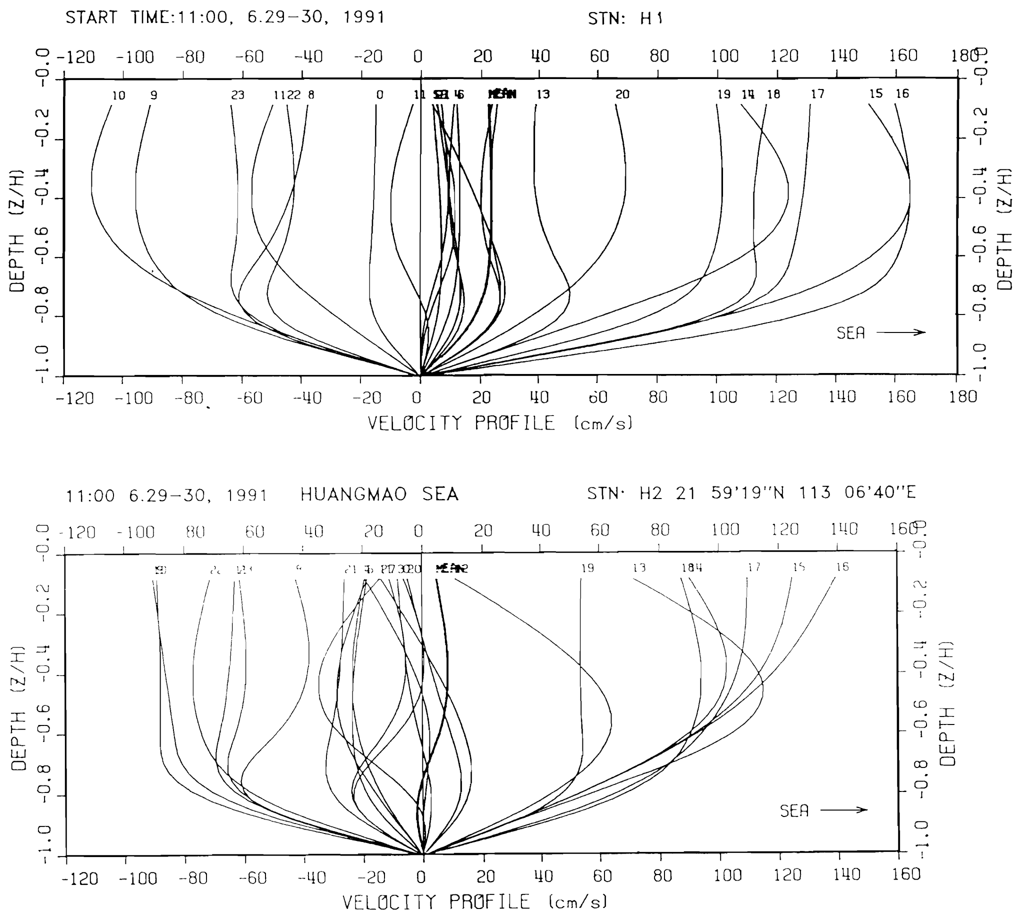

Figure 7. Velocity profiles measured in June, 1991 at station (a) H1 and (b) H2. The gross line represents the tidally mean velocity.

ure 8 are velocity structures in the lower estuary. They show a complicated combination of surface and bottom Ekman flows, density flow and gradient flow which differ from the structure of the density dominated flow in the upper and mid estuary. The existence and variations of the density driven circulation have strong effects on sedimentation. In low water season, mixing is strong and the 'null point' is moving back and forth within the North Channel. Sediment supply from both the river and sea is low and erosion takes place in the river mouth bar (Wu, 1991). Severe siltation occurs in flood season when the river carries a great amount of sediment to the estuary and at the mean time when the 'null point' that serves as a sediment trap is right over the mid shoal.

Jet Current

The narrow scoured trough in the upper East Channel between Damang and Sanjiaoshan Island (Figure 1) has played an important role in the sedimentation process. The gorge is approximately 1,500 m wide. The water depth exceeds 5 m in the trough and decreases to 2–3 m to both sides of the gorge which separates the mid shoal in the East Channel into two parts. The seaward and landward changes in the water depth are considered to be the response to an efflux system or, simply, the deceleration flows. Tidal current velocity exceeds 1.0 m/sec in the upper layer and 0.8 m/sec in the lower layer in station III3 near the gorge and decreases rapidly in both directions. Shown in Figure 9 are the gradual changes of tidal

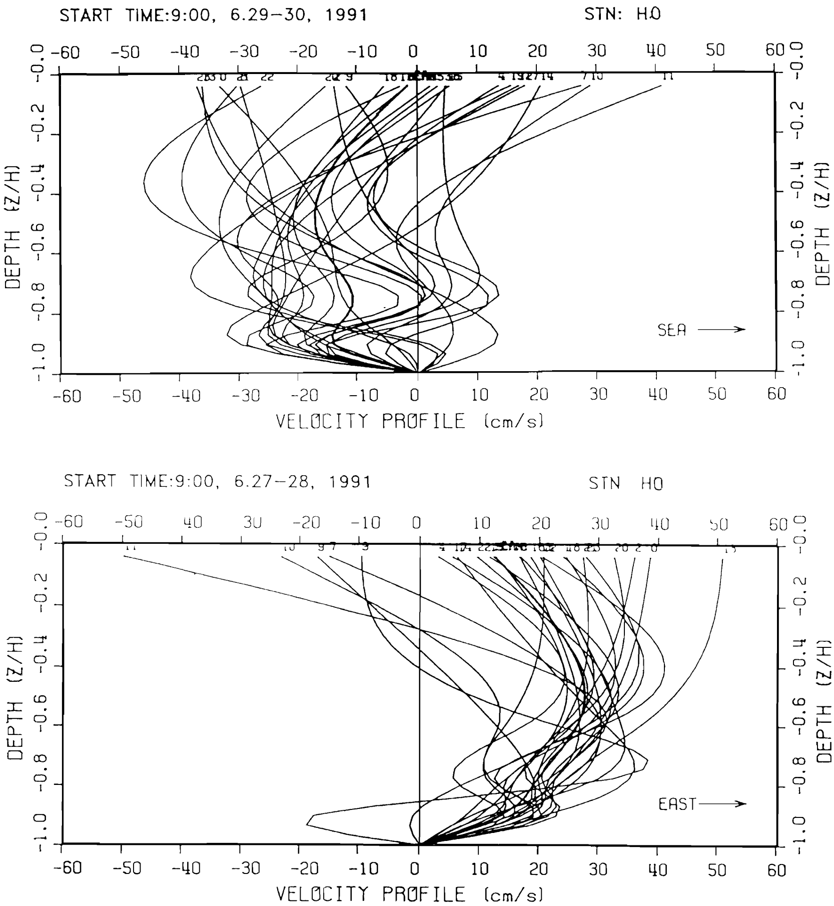

Figure 8. Velocity profiles measured in April 1991 at station H0, (a) north component and (b) east component. The gross line is the tidally mean velocity.

current velocities calculated from the 2-D model which decreases with the increase of the distance from the gorge. The stability of the interface between the upper fresh water layer and salt water below depends on the value of the densimetric Froude number F_i given by

$$F_i = \frac{U}{\sqrt{\gamma g h}} \quad (10)$$

where U is the velocity of the upper layer, g is the acceleration of gravity, h is the flow depth of the upper layer and γ the density ratio

$$\gamma = (\rho_l - \rho_u)/\rho_l \quad (11)$$

where ρ_l and ρ_u are the density of lower and upper layers respectively. Observations taken near the gorge indicate that the values of F_i range from 2–8, the maximum reaches 8–40 during the low water season in the winter. F_i ranges from 0.4 to 2.0 during the flood season when buoyancy increases. The distance from the top of the shoal in the north to the gorge is approximately 8 km and this distance is 4 km in the south. Studies point out that the distance from the top of a depositional shoal to the jet mouth is about 4–6 times the width of the jet. This shows reasonably close agreement with our observation. Based on observations (station II 3 in January, 1989, station V4 in July, 1989) taken near the gorge, the Eulerian residual current is directed upstream in all depths. The efflux system has restrained and actually replaced the

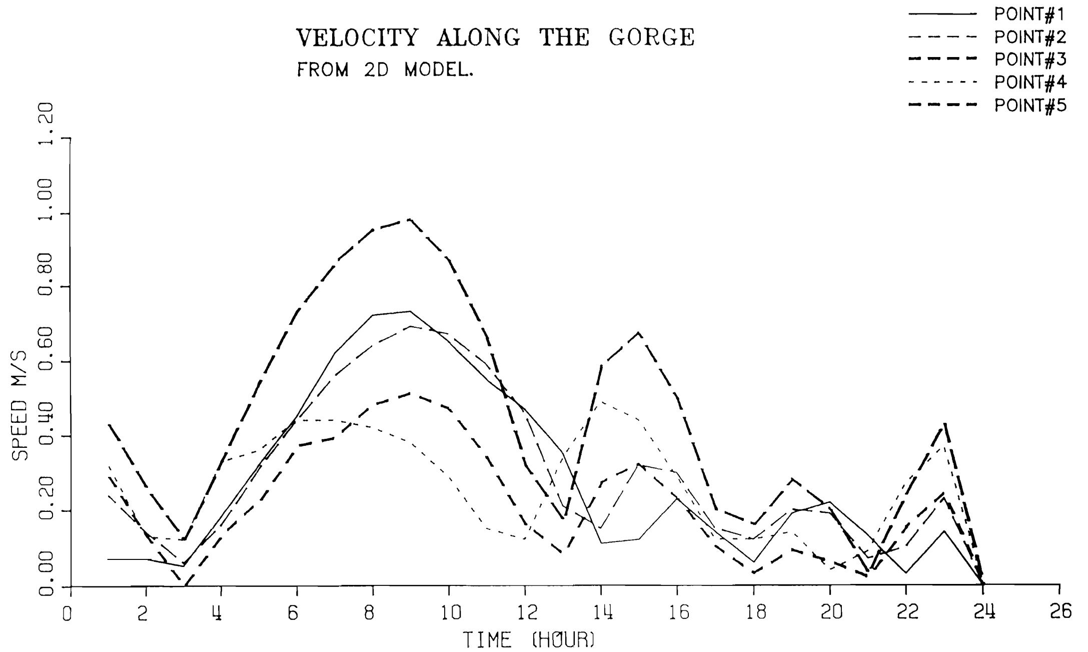

Figure 9. Jet current velocity variation. Point #1 to #5 line up along the East Channel from north to south. Point #3 is located in the middle of the gorge, the distance between each calculated point is approximately 800 m.

density driven circulation near the gorge as a dominant dynamic process. The gorge efflux system is sedimentologically significant. The deposition of the shoal to the north of the gorge is the result of density circulation acting as a sediment trap and the deceleration of the jet flows as well. The shoal to the south of the gorge is mainly the result of the efflux system. Since the jet system is physically stable, the shoals in both sides of the gorge have not shown significant changes since at least the 1930's based on the navigation charts published from 1861 to the present. As a comparison, the shoal in the West Channel has experienced significant seaward migration in the same period. The inner slope of the shoal has been scoured and the isobath of 5 m migrated 40 m per year seaward in the last 40 years (YANG, 1992), at the mean time the outer slope advanced 36 m/yr to the sea (Figure 10).

Horizontal Circulation

Observations and the 2-D model reveal a horizontal circulation in the Cross-sea in the lower estuary. It is a residual circulation. Water flows in from East Outlet between Gaolan and Hebao Island. One branch flows north passing through the Damang Gorge; the main stream turns west and joins the West Channel. The mean velocity in the Cross-sea ranges 5–15 cm/sec and reaches 20 cm/sec outside the East Outlet. Kelvin wave, topography, and the West Guangdong drift all have their contribution to the development of the circulation. The mechanism of this circulation is not yet completely clear. Kelvin wave is the balance between Coriolis force and the horizontal gradient when tidal waves enter an estuary. Water elevation and velocity under the Kelvin wave are given by:

$$\zeta = R_0 e^{f/c} \mathrm{COS}\left(\sigma t - \frac{a}{c}x\right)$$

$$U = \frac{g}{c} R_0 e^{f/c} \mathrm{COS}\left(\sigma t - \frac{a}{c}x\right) \quad (12)$$

where c is the phase celerity of the tidal wave, σ is angular frequency of the tidal waves, f the Coriolis parameter and R_0 the amplitude of the tidal wave. Under the Kelvin wave, both tidal range and current velocity in the eastern part are greater than that in the western part. A counterclockwise

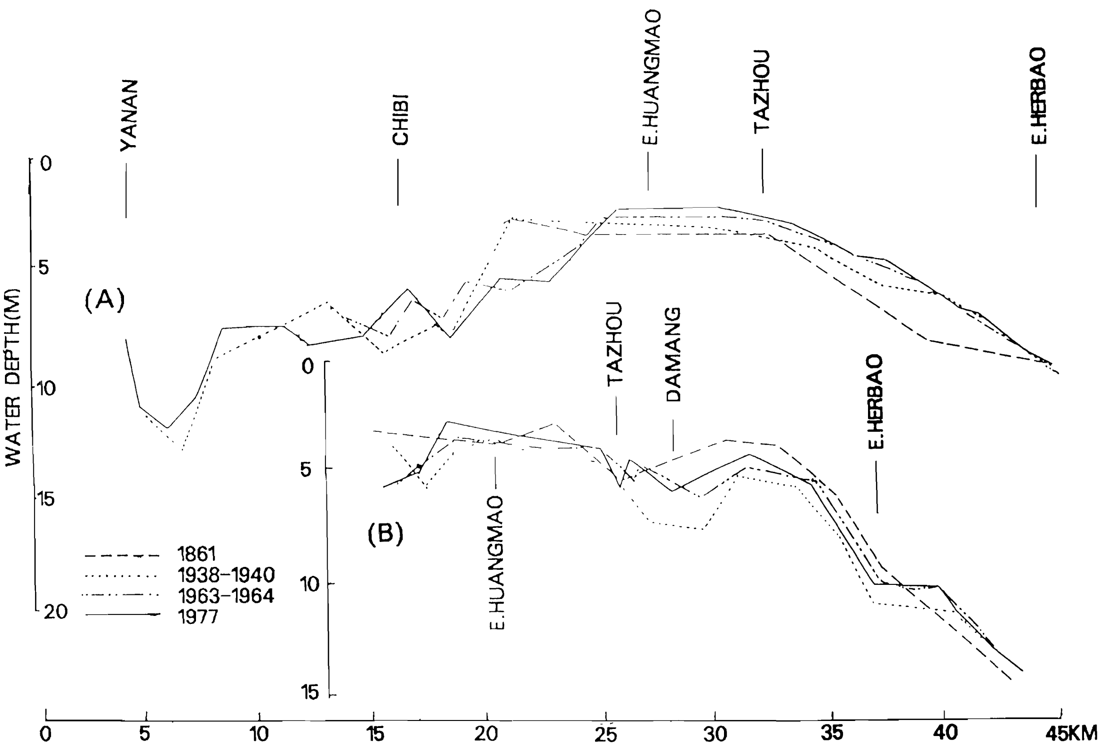

Figure 10. Bottom profiles of the (a) West Channel and (b) East Channel.

horizontal circulation is then prone to develop. Yuedong nearshore drift flows from ENE to WSW along the coast. It can be considered as a geostrophic flow which is the result of the dynamic balance between the Coriolis force and the water elevation gradient with the high water along the coast. When the drift reaches the estuary, the gradient no longer exists and the drift flows in the estuary through the East Outlet. The residual circulation has certain effects on the water and sediment transport in the lower estuary. The upstream residual flow restrains the sediment entering the sea through East Outlet. Since the shelf water with low levels of suspended sediment flows in, it is favored for the East Outlet to maintain a deep channel free from serious siltation.

NATURAL DEPOSITIONAL RATE AND CHANNEL REDEPOSITION

The main source of suspended sediment in the estuary is from the fresh water which counts for 77% of the total suspended sediment input to the estuary (Yang, 1992). Sediment input from the marine side mainly comes from Modaomen and Jitimen, also outlets of the Pearl River located to the east of Huangmaohai Estuary. Based on the measurement of navigation charts from 1937 to 1977, the average depositional rate of the bay is 1.28 cm/yr. There are three zones with high depositional rate: the mid-shoal, the western marginal shoal and eastern marginal shoal. Since large-scale reclamation projects have been carried out in both the eastern and western marginal shoals, the maximum natural depositional rate occurred in the mid-shoal which reaches 4.0 cm/yr. Negative depositional rate occurred in both the North Channel and the Lower estuary. The high depositional zone in the mid-estuary is coincident in position with the low energy zone.

In October 1990 a testing navigation channel was opened in the mid-shoal connecting the North Channel and the East Channel. The total length of the artificial channel is 7.5 Km, the bottom width is 60 m, the bottom elevation is 4.0 m, and average dredged depth is 1.14 m. Echo sounding was taken in a regular base to monitor the rede-

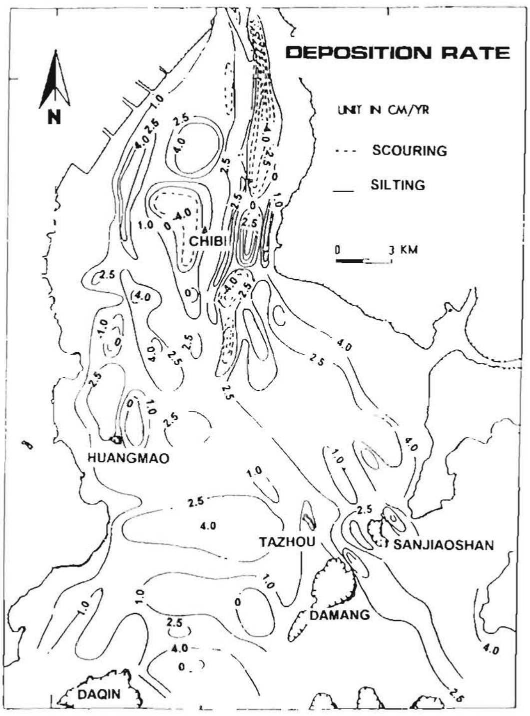

Figure 11. Isogram of depositional rate in the estuary, data collected from 1938 to 1977 (modified from YANG, 1992).

position. Figure 12 shows the echo sounding longitudinal profile of the channel. The survey indicates that severe deposition occurred during river floods and storm surges. Slight scouring took place in low water season in winter. The redepositing rate is more than 60 cm/yr. It is no surprise that the artificial channel was completely refilled in less than two hydrographic years during which no maintenance dredging occurred. The low energy zone and null point deposition mechanism have profound effects on the sedimentation.

CONCLUSIONS

(1) Observations and the 2-D numerical model reveal a low energy (velocity) zone in the mid estuary that acts as a sediment trap for suspended and bed load from both inland and marine sources.

(2) Labeled water parcel trajectories calculated over a complete tidal cycle reveal some of the important features of the Lagrangian motion. The net Lagrangian displacement is in the same order as tidal excursion, which indicates the seaward flow is a dominant process in Huangmaohai Estuary.

(3) Three large scale dynamic structures which have substantial effects on sedimentation are found in the estuary along the North and East

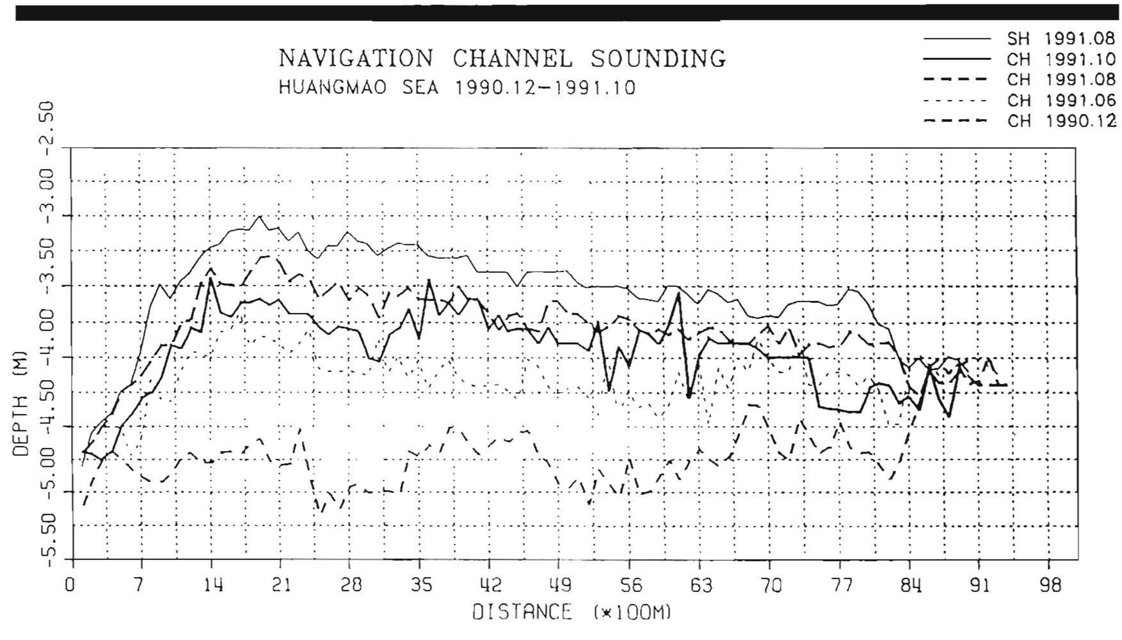

Figure 12. Repeat echo sounding of the testing channel profiles. SH—shoulder of the channel. CH—channel bottom.

Channels. (a) Density driven circulation migrates from the head of estuary in dry season to mid estuary where it causes serious siltation in flood season. (b) Near the gorge between Damang and Sanjiaoshan Island, the efflux system becomes a dominant dynamic feature in the East Channel. This system is physically stable; the shoals in both sides of the gorge have not shown significant changes since at least the 1930's. (c) The horizontal circulation in the lower estuary is considered the result of the combination effects of Kelvin wave, topography and West Guangdong drift. The upstream residual flow restrains the sediment entering the sea through East Outlet and directs the flow to the pass between Damang and Hebao Island.

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