





Research Article

Study on Vertical Distribution of Sediment Concentration in the Tidal Estuary

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Abstract

The vertical distribution of sediment concentration in estuaries is the core issue of suspended sediment transport. At present, there are many researches on the vertical distribution of sediment concentration in rivers, and a lot of results have been achieved, but that in estuaries is seldom studied. The Yellow River Estuary (YRE) and the Qiantang River Estuary (QRE) are typical tidal estuaries with strong erosion/deposition and high concentration in China. Under the action of alternating tidal flow, the suspended sediment transport shows significant time-varying and non-equilibrium transport characteristics. The vertical distribution of sediment concentration is quite different from that of ordinary rivers. This paper analyzes the vertical distribution of sediment concentration under the action of tidal currents based on the theory of sediment movement and diffusion. Compared with equilibrium sediment transport, the vertical distribution of sediment concentration only differs by one vertical distribution coefficient. Based on the analysis of the measured data, it is found that the vertical distribution of sediment concentration in the YRE and QRE is mostly exponential. Firstly, the multivariate relationship between the vertical distribution coefficient and the sediment saturation and suspension index is established by means of the measured water and sediment data of the QRE. The correlation coefficient R^2 was above 0.64, which has a good correlation. Finally, the established relationship was validated using measured water and sediment data from the YRE, and the results were basically consistent, indicating that the established formula for vertical distribution of sediment concentration is suitable for general tidal estuaries, and has a certain reference value for the simulation of sediment transport in the YRE and QRE.

Keywords

Vertical Distribution of Sediment Concentration, Vertical Distribution Coefficient, Sediment Saturation, Suspended Index, Sediment Carrying Capacity, Yellow River Estuary, Qiantang River Estuary

1. Introduction

The vertical distribution of sediment concentration in estuaries is the core issue of sediment transport. Lots of scholars at home and abroad have studied the vertical distribution of sediment concentration in unidirectional rivers, and many important research results have been achieved. The older

generation of sediment researchers, such as Rouse [1], Qian Ning [2] and Zhang Ruijin [3], have made outstanding contributions to the theory of suspended sediment diffusion under equilibrium sediment transport; Ni obtained the unified formula of vertical distribution of sediment concentration from

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theoretical solution, making most of classic formulas of vertical distribution of sediment concentration of Rouse and other researchers its special cases [4, 5]. However, natural rivers usually show non-equilibrium sediment transport, and the vertical distribution of sediment concentration varies greatly between non-equilibrium and equilibrium sediment transport. Han et al. [6] studied the vertical distribution of sediment concentration in non-equilibrium sediment transport, derived the theoretical solution of the vertical distribution of sediment concentration in non-equilibrium sediment transport, and proposed the calculation method of non-saturation parameters; Zhao et al. [7] reviewed this theoretical research and pointed out the limitations of the calculation method of non-saturation parameters under non-equilibrium sediment transport; Based on the research results of Han [6], Ma et al. [8] simplified the calculation method of parameters such as non-saturation; Hou et al. [9] analyzed the vertical distribution of suspended sediment concentration in the Jingjiang Reach at the downstream of Three Gorges Dam, and discussed the characteristics of unsaturated sediment transport in the reach. Affected by dynamic factors such as reversing tidal current, wave and sediment flocculation, the vertical distribution of sediment concentration in tidal estuaries is relatively complicated. Taking Zhapu water area of Hangzhou Bay as an example, Tang et al. [10] analyzed the vertical structure of suspended sediment concentration using the measured water flow and sediment concentration data, and the results showed that the vertical distribution of sediment concentration basically follows Rouse power function distribution except the short time of flood/ebb slack water; Yang et al. [11] studied the vertical distribution characteristics of sediment concentration under the action of waves and currents on the silty coast through field measured data and wave flume experiment, and established the semi-empirical and semi-theoretical vertical distribution of sediment concentration by using the

sediment diffusion equation; Li et al. [12] improved the Van Rijn formula by theoretical analysis based on the measured data of flow velocity and sediment concentration in nearshore waters and the convenience of engineering application, and validated the formula.

In this paper, based on the previous research results, the vertical distribution of sediment concentration under the action of tidal current was analyzed by the theory of sediment diffusion; Based on this, the relationship between the vertical distribution coefficient of sediment concentration in tidal estuary, sediment saturation and suspension index was firstly established using the measured water and sediment data from the QRE. Then, the established relationship was calibrated using the measured water and sediment data from the YRE.

2. Materials and Method

2.1. Study Area

The QRE is a macro tidal estuary and has a free connection with the East China Sea as shown in Figure 1. It has a funnel shape with its width decreasing from the mouth to upstream. The width of the cross-section located in the mouth from Lucaogang on the north bank to the Waiyou mountain, Zhenhai in Ningbo City on the south bank is 98 km, and narrows to 16.5 km wide at Ganpu, 98 km away from Lucaogang. With fast narrowing, the tidal range is increased by 75% at Ganpu, and the field observed maximum value is 9.15 m. The average flood/ebb velocity during spring tide is about 2.0/1.5 m/s near the mouth, increasing toward Ganpu to 4.2/3.0 m/s. Since the velocity is quite large in the relatively shallow estuary, the flow is of the vertically mixed type. The estuary is known for hosting the famous Qiantang River tidal bore.



Figure 1. Sketch of the QRE.

The distribution characteristics of sediment concentration along the QRE are closely related to the hydrodynamic distribution. The section from Cangqian to Cao'e is a high sediment concentration area, with a maximum sediment concentration of $10.0\text{--}50.0\text{ kg/m}^3$ and an average sediment concentration of $3.0\text{--}6.0\text{ kg/m}^3$ during the half month tidal cycle. The sediment concentration in the upstream of Cangqian and downstream of Cao'e gradually decreases.

The bed material at QRE gradually becomes finer from upstream to downstream. More than 90% of the bed material from Wenjiayan to Ganpu is finely sorted silt, the clay particle content is less than 5%~10% and the median particle size d_{50} is $0.025\text{mm--}0.07\text{mm}$. The sediment of Hangzhou Bay downstream of Ganpu is mainly silt and clay, and the median particle size d_{50} is $0.004\text{mm--}0.016\text{mm}$ at the bay mouth, $0.015\text{mm--}0.10\text{mm}$ at the top of the bay. The median particle size of suspended sediment in Hangzhou Bay is $0.004\text{ mm--}0.016\text{ mm}$, which is basically similar to the bed material of the bay mouth, and the particle size gradually coarse from the bay mouth to the bay top. The median particle size of suspended sediment upstream of Ganpu is $0.025\text{ mm--}0.07\text{ mm}$.

2.2. Water and Sediment Monitoring

During the preliminary study of QRE improvement and various water-related projects, a number of on-site hydrological and sediment prototype observations were carried out, and a lot of measured data were accumulated from 2003 to 2020. By sorting and screening the measured data of multiple numbers of observation and multiple stations, the measured water and sediment data of more than 20 observation points from the estuary reach to the coastal reach outside the estuary were selected. These data cover the hydrological year of wet, normal and dry years, typical tides of spring, medium and neap tides, seasonal changes of spring, summer, autumn and winter, and other conditions of QRE. They are fairly representative and can be used as the basic data for the study of vertical distribution of sediment concentration. The location of observation points is shown in Figure 2. The temporal and spatial variation of water and sediment in the QRE can be understood by sorting out and analyzing the flood/ebb flow velocity and variation characteristics of sediment concentration with tide at each observation point.

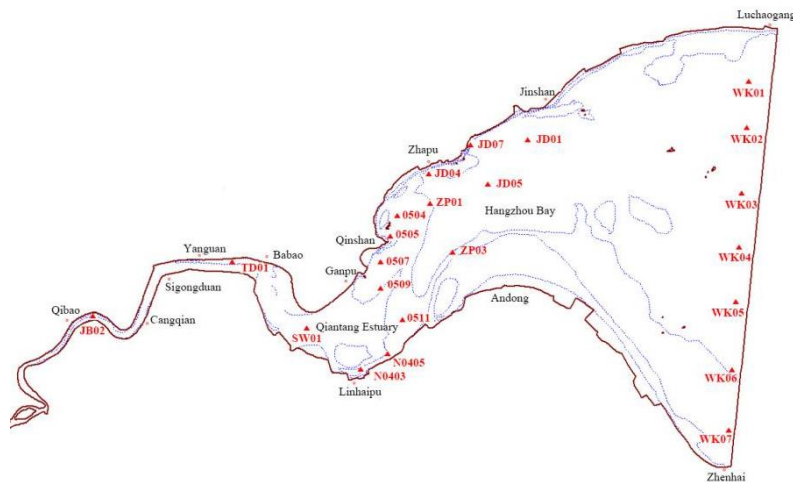


Figure 2. Location and distribution of observation points in the QRE.

2.3. Vertical Distribution of Sediment Concentration in Tidal Estuaries

Sediment transport in tidal estuaries is a reciprocating non-equilibrium sediment transport, which can be described by 3D suspended sediment convection diffusion equation. However, considering that the horizontal flow movement in tidal estuaries is usually characterized by alternating current, and the vertical flow velocity is generally small, the effect of vertical flow velocity on suspended sediment transport can be ignored, and the sediment transport in the flow direction

can be simplified as the vertical 2D convection diffusion equation:

$$\frac{\partial s}{\partial t} + \frac{\partial}{\partial x} \left(us - E_{stx} \frac{\partial s}{\partial x} \right) = \frac{\partial}{\partial z} \left(\omega s + E_{stz} \frac{\partial s}{\partial z} \right) \quad (1)$$

where, s is the sediment concentration; t is the time; u is the flow velocity in the flow direction; E_{stx} , E_{stz} represent the sediment diffusion coefficients in the flow and vertical directions, respectively; x , z represent the coordinates in the flow and vertical directions, respectively; ω is the sediment set-

ting velocity.

To explore the vertical distribution pattern of sediment concentration in water body, Eq. (1) was integrated vertically to obtain:

$$E_{stz} \frac{\partial s}{\partial z} + \omega s = q_s \quad (2)$$

Where, q_s is the source item, its expression is as follows:

$$q_s = \underbrace{\int_a^z \frac{\partial s}{\partial t} dz}_1 + \underbrace{\int_a^z \frac{\partial}{\partial x} \left(us - E_{stx} \frac{\partial s}{\partial x} \right) dz}_2 + \underbrace{\left(E_{stz} \frac{\partial s}{\partial z} + \omega s \right) \Big|_a}_3 \quad (3)$$

On the right of equal sign in the above equation, item 1 is the vertical integration of time derivative item of sediment concentration, item 2 is the vertical integration of space derivative item of the convection-diffusion of suspended sediment in the flow direction, and item 3 is the net exchange item of sediment near the bottom. The three items have some influence on the vertical distribution of sediment concentration, which is different from the vertical distribution of sediment concentration under equilibrium condition. The turbulent diffusion equation under non-equilibrium sediment transport is expressed as:

$$\frac{ds}{dz} + \frac{\omega s}{E_{stz}} = \frac{q_s}{E_{stz}} = \delta_s \quad (4)$$

where, δ_s is the source item.

The source item δ_s of the sediment diffusion equation during non-equilibrium sediment transport is not equal to 0, and there are no mature results and data about δ_s at present. As a first-order approximation of Eq. (2), item 1 and item 2 reflected in the source item δ_s can be expressed as a function related to the net exchange item of sediment near the bottom. In this way, δ_s actually reflects the contribution of net flux of sediment near the bottom to the adjustment of vertical distribution of sediment concentration, and its value is related to suspension index (ω/ku_*), saturation degree of sediment transport (s_*/s), etc. Referring to the method used by Han et al. [6] in studying the vertical distribution of sediment concentration under non-equilibrium sediment transport, the following equation can be obtained:

$$\delta_s = \frac{\omega s}{E_{stz}} f\left(\frac{s_*}{s}, \frac{\omega}{ku_*}\right) \quad (4)$$

where, s is the average vertical sediment concentration; s_* is the average vertical sediment carrying capacity; $f(\bullet)$ is a function; k is the Karman constant; u_* is the friction velocity.

By substituting Eq. (4) into Eq. (3), the following equation can be obtained:

$$\frac{ds}{dz} = -\frac{\omega s}{E_{stz}} \left(1 - f\left(\frac{s_*}{s}, \frac{\omega}{ku_*}\right) \right) = -\frac{\omega sc}{E_{stz}} \quad (5)$$

where, $c = 1 - f(s_*/s, \omega/ku_*)$ is the correction coefficient for vertical distribution of sediment concentration under non-equilibrium sediment transport (referred to as “distribution coefficient”). When $c=1$, the sediment transport by water flow is in equilibrium, and the erosion and deposition of the riverbed are balanced; When $c<1$, the sediment transport by water flow is in a supersaturated state, and the riverbed is deposited; When $c>1$, the sediment transport by water flow is in an unsaturated state, and the riverbed is eroded.

If the vertical diffusion coefficient of sediment is $E_{stz} = ku_*H/6$, the vertical distribution index formula of sediment concentration under non-equilibrium sediment transport can be obtained by integrating Eq. (5):

$$\left. \begin{aligned} s &= s_a e^{-\beta \eta} \\ \beta &= 6c\omega/ku_* \end{aligned} \right\} \quad (6)$$

where, s_a is the sediment concentration near the bottom; $\eta = z/H$ is the relative water depth; H is the water depth.

Compared with the vertical distribution formula of sediment concentration (Calinski distribution) under equilibrium sediment transport, Eq. (6) only differed by one vertical distribution coefficient c . The vertical distribution coefficient was determined by multivariate fitting of the measured water and sediment data from the QRE, and the vertical distribution law of sediment concentration was discussed. The relationship between the ratio of sediment concentration near the bottom to average vertical sediment concentration and β was obtained through vertical integration of the formula of sediment concentration.

3. Results

3.1. Exponential Distribution of Sediment Concentration

The vertical distribution exponential formula (6) of sediment concentration was employed to statistically analyze the stratified sediment concentration at different times of maximum flood, flood slack, maximum ebb, ebb slack (1.0H, 0.8H, 0.6H, 0.4H, 0.2H, 0.05H) at each observation point in Figure 2. Figure 3 shows the vertical distribution of sediment concentration at representative observation points in the QRE at representative times.

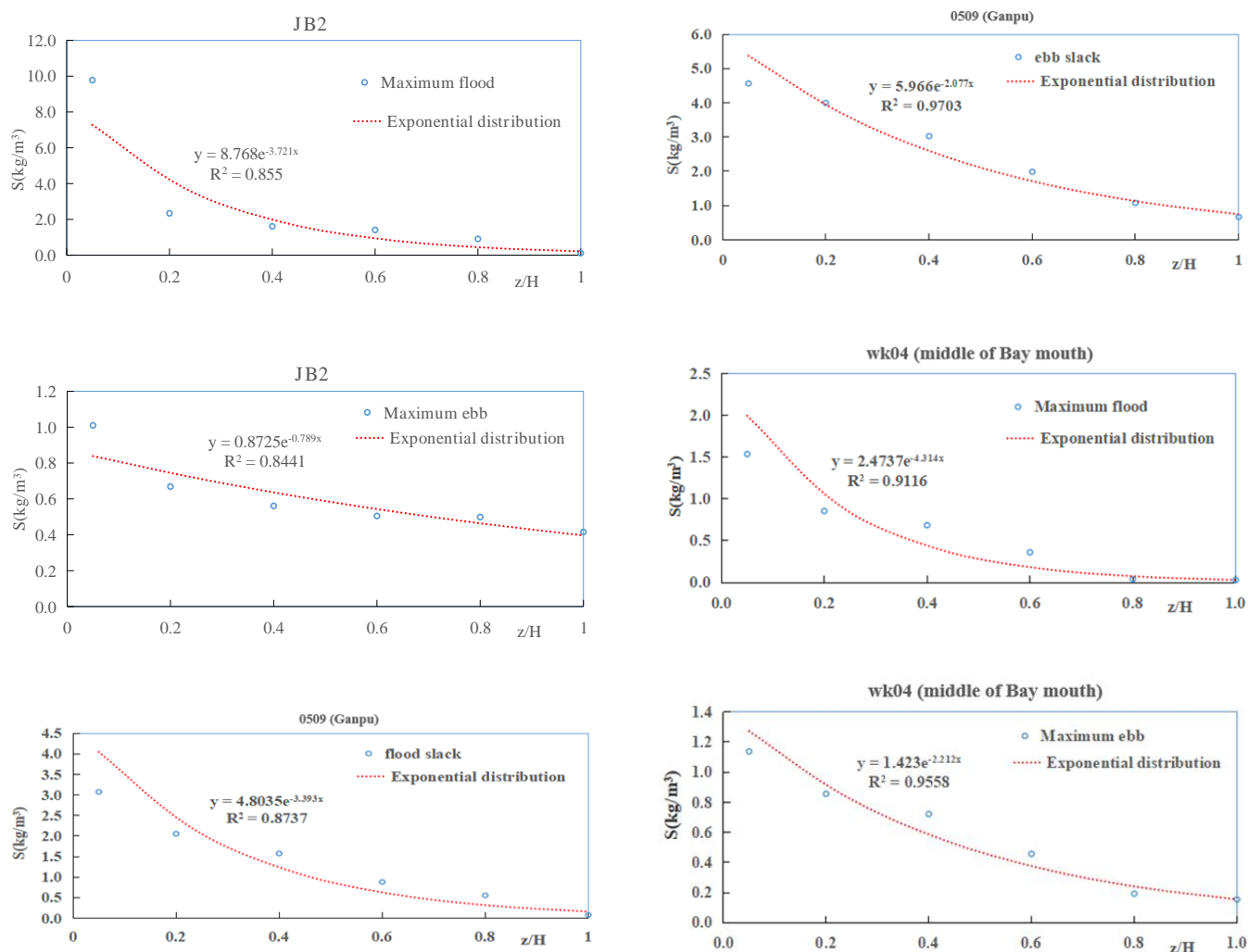


Figure 3. Fitting relationship of vertical distribution of sediment concentration in the QRE.

Table 1. Characteristic parameters of vertical distribution in QRE.

item		JB2	0509	JD03	ZP03	JD01	wk01	wk04	wk06
s_a	A*	8.77	15.5	3.85	2.59	2.77	2.98	2.47	0.49
	B*	0.41	4.80	1.42	14.7	3.75	0.55	7.27	5.44
	C*	0.87	9.30	2.25	0.74	3.04	1.55	1.42	4.74
	D*	0.64	5.97	4.29	2.30	2.01	4.62	2.32	0.53
β	A	3.72	3.92	1.61	1.91	1.29	3.18	4.31	0.67
	B	1.63	3.39	1.6	3.17	1.27	1.16	4.04	2.56
	C	0.78	1.41	0.67	2.44	1.78	1.62	2.21	2.69
	D	1.57	2.08	1.92	1.45	1.62	2.5	3.04	2.21

* A: moment of Maximum flood; B: moment of Flood slack; C: moment of Maximum ebb; D: moment of Ebb slack.

From Figure 3, it is found that the vertical distribution of sediment concentration at each observation point basically

follows the exponential distribution law, and most of the correlation coefficients R^2 are in the range of 0.83~0.98, indicating a good correlation. Thus, the vertical distribution coefficient c of sediment concentration can be determined through multiple regression by fitting exponent β and corresponding suspension index (ω/ku_*).

Table 1 shows the parameters such as near-bottom sediment concentration (s_b) and index (β) obtained by fitting the vertical distribution of sediment concentration at observation points. From Table 1, it is shown that the sediment concentration near the bottom varies in different reaches and at different times of flood/ebb. The near-bottom sediment concentration (JB02, 0509) in the estuary reach is greater than that in the Hangzhou Bay waters (JD03, ZP03, JD01, wk01, wk04, wk06), and the near-bottom sediment concentration is relatively large at the maximum flood and ebb of the estuary reach and at the flood and ebb slack of Hangzhou Bay, which reflects the response of near-bottom sediment concentration to hydrodynamics and sediment characteristics. The strong turbulence of tidal bore in the QRE has a great influence on the incipient motion and suspension of sediment concentration near the bottom, and the fine cohesive sediment of Hangzhou Bay waters affects the deposition of suspended sediment greatly.

3.2. Vertical Distribution Coefficient (c)

To determine the vertical distribution coefficient c and establish a multivariate correlation between c and suspension index (ω/ku_*), sediment saturation (s_*/s), the key is to determine the sediment carrying capacity of tidal current, sediment settling velocity and friction velocity of tidal estuaries. The sediment settling velocity was calculated by the formula considering sediment flocculation [13]. The friction velocity was estimated by the Manning formula, and the Manning coefficient varied according to the flood/ebb and different reaches. Regarding the sediment carrying capacity of tidal current in the QRE, a large number of measured water and sediment data were adopted in this paper, the maximum and minimum sediment concentrations in the tidal cycle were selected as the sediment carrying capacity according to the concept of time varying sediment carrying capacity proposed by Sun [14], and the corresponding velocity, water depth and gradation of sediment grain were used as the water and sediment conditions. On this basis, the following logarithmic sediment carrying capacity formula of tidal current in the QRE was established [15], and the correlation coefficient R^2 was above 0.64, indicating a good correlation. The sediment carrying capacity of tidal current was calculated by Eq. (7), and the sediment saturation can be obtained by its ratio to the vertical average sediment concentration.

$$s_* = k \lg \left(\frac{u^3}{bgh\omega} \right) \quad (7)$$

where, k and b are empirical coefficients, which are obtained

by fitting local measured data. The coefficients obtained by fitting in this paper are $k=4.5$ and $b=5.75$ [16].

Figure 4 shows the multivariate correlation between the exponential vertical distribution coefficient c and the suspension index (ω/ku_*), sediment saturation (s_*/s), as shown in Eq. (8), and the correlation coefficient R^2 was about 0.64. Under the same sediment saturation, the vertical distribution coefficient decreased with the increase of suspension index. Conversely, under the same suspension index, the greater the sediment unsaturation, the greater the vertical distribution coefficient c , and the smaller the vice versa.

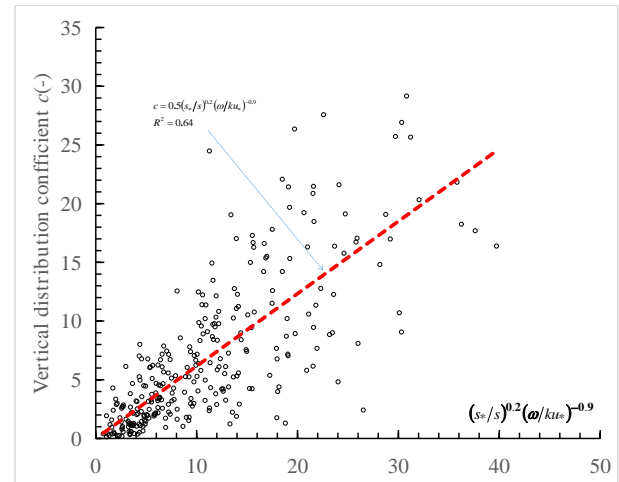


Figure 4. Correlation between vertical distribution coefficient and suspended index, sediment saturation.

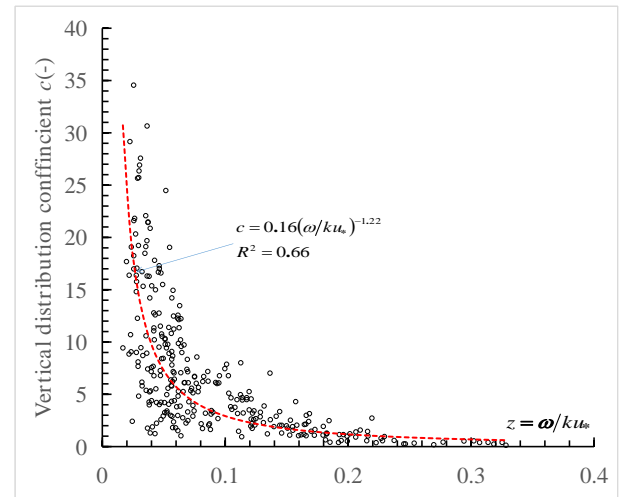


Figure 5. Correlation between vertical distribution coefficient and suspended index.

In addition, we further analyzed the single factor relationship between the vertical distribution coefficient c and the suspension index, as shown in Eq. (9) and Figure 5. The correlation coefficient R^2 was around 0.66, and the vertical distribution coefficient decreased with the increase of suspension index.

When $c=10$, the corresponding suspension index Z was 0.034;
When $c=1$, the corresponding suspension index Z was 0.223;
When $c=0.5$, the corresponding suspension index Z was 0.393.

$$c = 0.5(s_*/s)^{0.2}(\omega/ku_*)^{-0.9} \quad (8)$$

$$c = 0.16(\omega/ku_*)^{-1.22} \quad (9)$$

3.3. Calibration of Vertical Distribution of Sediment Concentration

To verify the rationality of the vertical distribution formula for sediment concentration in tidal estuaries established above, hydrological and sediment measurement data from the YRE and its surrounding waters were used to calibrate formulas (6), (8) to (9). The YRE is a world-renowned estuary with abundant sediment and weak tides. From 1950 to 1979, the average annual flow rate at Lijin Station was 42.8 billion m^3 , with an average annual sediment concentration of 18.3 kg/m^3 and a sediment discharge of 1.118 billion tons into the sea. The annual runoff and sediment discharge during the flood season accounted for 62% and 85%, respectively. In the past 50 years, due to the influence of human activities in the river basin, the inflow of water and sediment from the estuary has been continuously reduced, reaching 28.86 billion m^3 and 0.638 billion tons respectively for many years [17]. Most of the waters in the Yellow River Delta are characterized by irregular semi diurnal tides, with an average tidal range of 0.75~1.77m. The tidal current near the mouth of the river are reciprocating, while the waters outside the mouth are mostly rotational. The maximum surface flow velocity is mostly below 1.2m/s. We selected the measured water and sediment data from the YRE in August 2017 to verify the vertical distribution of sediment concentration. The location of observation points are shown in Figure 6.

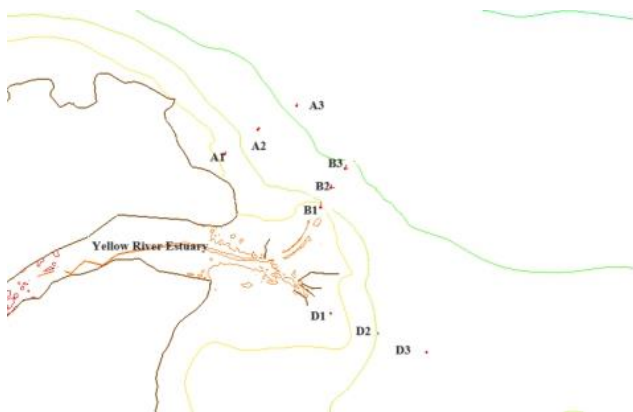
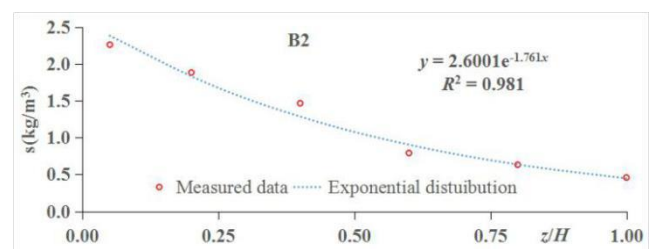
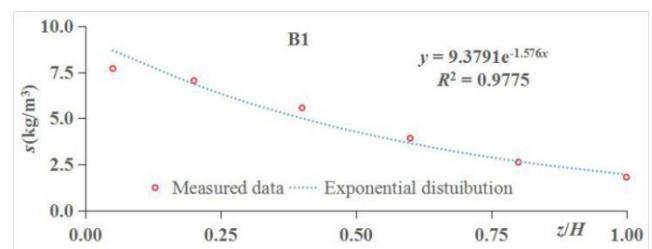
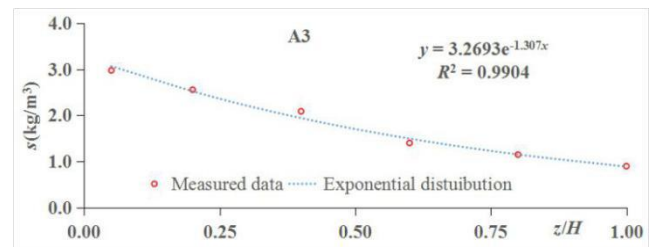
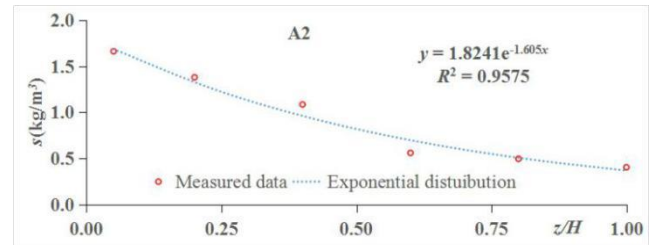
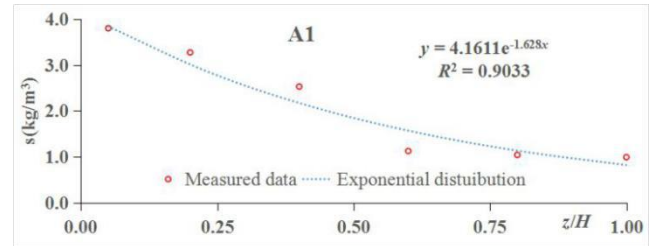


Figure 6. Location of observation points in the YRE.

To analyze the vertical distribution characteristics of sediment concentration under the influence of tidal currents in the YRE, representative measurement points such as A1, A2, A3,

B1, B2, and D2 were selected to analyze the water depth, flow velocity, and stratified sediment concentration at different times. Figure 7 shows the vertical distribution of sediment concentration at representative measurement points and its exponential fitting relationship. From the graph, it can be seen that similar to the QRE, the vertical distribution of sediment concentration in the YRE and its surrounding waters basically follows an exponential relationship, with a fitted correlation R^2 of 0.84~0.99, indicating a very good correlation.



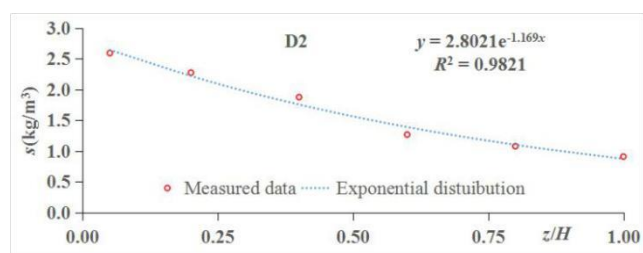


Figure 7. Fitting relationship of vertical distribution of sediment concentration in the YRE.

Table 2 presents the vertical average sediment concentration (s), bottom sediment concentration (s_a), fitting index (β_m), fitting correlation coefficient (R^2), suspension index (ω/ku_*), sediment concentration vertical distribution coefficient (c), and the index (β_c) calculated using formula (6) at three measurement sections near the YRE, including A (left side of the YRE), B (the YRE), and D (right side of the YRE).

From the Table 2, it can be seen that the average vertical sediment concentration and bottom sediment concentration of the YRE section (B) and its right section (D) are higher than those of the left section, reflecting the transport and diffusion characteristics of sediment entering the sea under the unique mechanism of runoff and tidal current. Further comparison between the calculated and measured values of the vertical distribution index of sediment concentration (β) shows that 67% of the data have a calculation error of less than 30%, and 87% have a calculation error of less than 50%. This indicates that the previously established formula for the vertical distribution of sediment concentration in tidal estuaries is also applicable to the YRE and the surrounding waters, and has a certain degree of universality.

Table 2. Characteristic parameters of vertical distribution in YRE.

points	S	S_a	β_m	R^2	ω/ku_*	c	β_c
A1	2.12	4.16	1.62	0.90	0.36	0.56	1.20
A1	0.83	1.21	0.81	0.99	0.39	0.50	1.18
A2	0.93	1.82	1.61	0.96	0.29	0.73	1.26
A3	1.84	3.27	1.31	0.99	0.17	1.40	1.41
A3	0.79	1.67	1.79	0.97	0.15	1.62	1.45
B1	4.77	9.38	1.58	0.98	0.17	1.39	1.42
B1	1.35	2.93	1.90	0.98	0.18	1.32	1.43
B2	3.55	8.40	2.16	0.98	0.10	2.63	1.58
B2	1.25	2.60	1.76	0.98	0.24	0.92	1.31
B3	1.22	2.69	1.91	0.98	0.10	2.50	1.57
B3	0.35	0.53	0.90	0.91	0.29	0.72	1.26
D2	1.66	2.80	1.17	0.98	0.18	1.30	1.39

points	S	S_a	β_m	R^2	ω/ku_*	c	β_c
D2	0.74	1.53	1.78	0.92	0.34	0.59	1.21
D3	2.99	9.39	3.59	0.84	0.28	0.74	1.26

4. Discussion

Under the action of reciprocating currents in tidal estuaries, the sediment in the riverbed is in a non-equilibrium sediment transport state of suspended and sinking. In this paper, the three-dimensional non-equilibrium sediment transport equation under the action of unsteady currents is simplified into a two-dimensional non-equilibrium transport equation in a profile, and a first-order approximate expression for the distribution of sediment concentration under non-equilibrium conditions is derived. This reflects the influence of riverbed erosion/sedimentation on the vertical distribution of sediment concentration under the action of currents, and the key is how to determine the vertical distribution coefficient c . Han et al. [6] conducted meaningful work on this. In order to obtain the calculation expression of c , he introduced the bottom sediment concentration and sediment carrying capacity under the vertical equilibrium distribution of average sediment concentration, and the bottom sediment carrying capacity under the vertical distribution of sediment carrying capacity. The bottom sediment concentration was weighted, and based on this, the implicit expressions of the sediment vertical distribution coefficient c and the three parameters of sediment suspension index, sediment saturation, and weighting coefficient were derived. The calculation process was relatively complex. Ma et al. [7] later made improvements to this by reducing the parameters to two. The author of this article found that the vertical distribution of sediment concentration in the QRE and the YRE follows an exponential distribution formula (6) under the action of reciprocating currents at the estuary. Compared with the exponential distribution at equilibrium, the indices of the two are different. Therefore, a correlation relationship between the vertical distribution c and single or multiple factors such as hydrodynamics and sediment saturation was established. Compared with the results of Han and Ma [6, 8], the calculation was relatively simple, and the actual water and sediment data at the YRE were used for verification, and the calculation accuracy was basically satisfactory. But these works still need further correction. Firstly, consider the influence of vertical differences in sediment settling velocity on the vertical distribution of sediment concentration; The second is to further explore the relationship between bottom sediment concentration and water and sediment conditions, and establish a vertical distribution formula for absolute sediment concentration.

In summary, there are still many issues worth exploring regarding the vertical distribution of sediment concentration in tidal estuaries. In the future, it is necessary to further study the comparison between equilibrium and non-equilibrium

sediment transport states through flume experiments, construct expressions for relevant physical parameters, and test measured data to enrich the basic theory of sediment movement under hydrodynamic action.

5. Conclusions

Based on the theory of non-equilibrium sediment transport and measured data of water and sediment in the YRE and QRE, the vertical distribution of sediment concentration in tidal estuaries was studied. The main conclusions are as follows:

- 1) Based on the diffusion theory of sediment movement, the vertical distribution characteristics of sediment concentration in tidal estuaries were analyzed. Compared with the vertical distribution formula of sediment concentration under equilibrium sediment transport, it only differs by one vertical distribution coefficient c . This coefficient reflects the sediment transport state of tidal current. When $c < 1$, the sediment transport by tidal current is in a supersaturated state, and the riverbed is deposited; When $c = 1$, the sediment transport by tidal current is in equilibrium, and the erosion and deposition of the riverbed are balanced; When $c > 1$, the sediment transport by tidal current is in an unsaturated state, and the riverbed is eroded.
- 2) Through the analysis of the measured water and sediment data in the QRE and YRE, it is revealed that the vertical distribution of sediment concentration in the estuary basically follows the exponential distribution law, and the multivariate relationship between the vertical distribution coefficient and the suspended index, sediment saturation, as well as the single factor relationship with suspension index were established. The correlation coefficient R^2 was above 0.64. Based on this, the calculation formula of vertical distribution of sediment concentration in tidal estuaries was constructed.
- 3) The established relationship was validated using measured water and sediment data from the YRE, and the results shows that 67% of the data have a calculation error of less than 30%, and 87% have a calculation error of less than 50%. This indicates that the previously established formula for the vertical distribution of sediment concentration in tidal estuaries is also basically applicable to the YRE and the surrounding waters, and has a certain degree of universality.

However, it should be pointed out that there are many factors that affect the vertical distribution of sediment concentration in tidal estuaries, such as wind waves, density currents, etc. This article only studied the distribution law of sediment concentration under the action of reciprocating currents. In the future, more detailed measurement data of water and sediment should be collected, combined with flume experiments to further explore the characteristics of sediment concentration vertical distribution under equilibri-

um and non-equilibrium sediment transport conditions, establish expressions for relevant physical parameters, and deepen research results.

Abbreviations

YRE	Yellow River Estuary
QRE	Qiantang River Estuary

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Author Contributions

Yingbiao Shi: Conceptualization, Resources, Methodology, Project administration, Writing- review & editing

Wenlong Cheng: Conceptualization, Formal Analysis, Investigation, Writing-original draft

Kun He: Conceptualization, Data curation, validation, visualization

Jun Zhang: Conceptualization, Formal Analysis, Investigation

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Data Availability Statement

The data is available from the corresponding author upon reasonable request.

The data supporting the outcome of this research work has been reported in this manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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Biography



Yingbiao Shi is a Professor-level Senior Engineer and Assistant Chief Engineer in Zhejiang Institute of Hydraulics & Estuary (ZIHE). From 1985–1989 and 1991–1993, he completed his undergraduate and Master's degree studies in the Department of River Sediment Engineering, Wuhan

Hydraulic and Electric Engineering University, and he obtained a Ph. D. in Energy and Environmental Protection from Zhejiang University in China in 2022. From 1989 to now, he has worked in ZIHE. He is mainly engaged in scientific research on estuary sediment and estuary regulation. His research directions are numerical simulation of estuary sediment, riverbed evolution, water environment and ecology, etc. He developed 1D and 2D movable bed mathematical models of material transport; 2D coupled mathematical model of water flow, sediment transport and riverbed deformation, which have been well applied in flood and salinity prediction in the Qiantang River Estuary.

Research Field

Yingbiao Shi: sediment transport, mathematical model, riverbed evolution, water environment, estuary and coastal engineering, disaster prevention and reduction.

Wenlong Cheng: computational water and sediment dynamics, estuary and coastal engineering, water environment, water conservancy, fluvial process.

Kun He: physics model test, tidal bore dynamics, mathematical model, estuary and coastal engineering, wave model test.

Jun Zhang: ports and waterways, wave model test, sediment transport, estuary and coastal engineering, mechanics of fluids.