A preliminary study on seasonal variations of sediment concentrations in the inner Qiantang Estuary

Dongfeng Xie¹³, Junbao Huang¹², Jiang Bo¹, Ruohua Li¹, Ziwen Tang¹ and Haiyan Lu¹

¹Zhejiang Institute of Hydraulics and Estuary, Hangzhou, China; ²Ocean College, Zhejiang University, Zhoushan 316021, China
³Email: dongfeng.xie@hotmail.com

Abstract. The Qiantang Estuary is characterized by high suspended sediment concentrations, due to the world-famous tidal bore. In this study, continuous sediment concentrations have been observed in the inner Qiantang Estuary in April, June, September and November of 2018, by fixing an OBS on a floating platform. The results show that SSC have both tidally and seasonal variations, in particular influenced by the tidal bore. In summer and autumn the tidal ranges were relatively large and the time series of SSC were spike-similar. In spring and winter the tidal ranges were relatively smaller and the time series of SSC were similar to a sine/cosine curve. SSC is largest in autumn, followed by summer and winter, and smallest in spring. SSCs in the summer and autumn correlate positively with tidal range but the correlations in spring and winter are less insignificant. SSC depends mainly on the tidal range given the tidal range is large enough. Under relatively smaller tidal range, the relative importance of other factors such as river discharge, bed level changes and winds, etc., on the sediment concentrations would be increased.

1. Introduction
Suspended sediment concentration (SSC) is one of the key factors for water environment in coast and estuaries[1,2]. It is an important indicator of sediment transport, bed erosion/deposition. It is also important for feeding and breeding of a variety of species and thus of great ecological importance.

Many estuaries in China are composed of fine clay and silt which is mainly from the Yellow River and Changjiang River, with long-term averaged sediment discharges used to be approximately 1.1 and 0.48 billion t/y, respectively[3]. Meanwhile tidal ranges from the seaside are usually larger, resulting in strong tidal currents. Consequently, the estuaries are characterized by high sediment concentrations. From the viewpoint of coastal management, it is of major importance to under the sediment concentration evolutions.

The Qiantang Estuary is the largest macro-tidal estuary of the Zhejiang Province, China. It is a funnel shaped estuary with the width at the mouth up to about 100 km and narrows gradually landward to be several kilometers (Figure 1). The annually-averaged tidal range at Ganpu is up to 6.0 m[4]. When tides propagate landward further, it deformed drastically and finally evolves into the world-famous Qiantang bore at the Qibao-Yanguan reach. In recent years, many field works, numerical and physical models have been carried out to study the formation, propagation and turbulence characteristics of the tidal bore[5-7]. It has been recognized that the tidally variations of SSC in the Qiantang Estuary depend on the strength of the tides[8-9]. Most observations were carried out at the Yanguan reach where the tidal bore is most spectacular[10-11], but field work in the further landward
is still limited. Moreover, few attentions have been paid on the SSC variations over a longer timescale, namely seasonal cycle, probably because of the lack of field data.

In this study, based on a series of continuous SSC data in the four seasons of 2018 in the inner Qiantang Estuary, we attempt to analyze seasonal variations of the SSC and deepen our understanding on the underlying physical mechanisms.

2. Methodology

In April, June, September and November of 2018, field works were carried out to observe the sediment concentration in the Qibao reach (Figure 1). An optical backscatter sensor (OBS) was
distributed in the main channel where water depth is about 5 m below the mean seal level. In the Qiantang Estuary, water level and tidal current change drastically at the bore arrival. Hence it is dangerous to carry out the field work on a boat. In this study, the OBS was fixed at a floating planform and the SSC can be recorded automatically. The Qiantang Estuary is a vertically well-mixed estuary and the sediment concentrations at the middle vertical layers are basically equivalent to the depth-averaged sediment concentration[4,10]. Hence the detector of OBS was set at about 0.5H, in which H is the water depth (Figure 2). In each month, the observation periods were 30 days and the record interval was half an hour. A longer field work is difficult due to the instrument maintenance.

During all the observations, no extreme events, e.g. river floods, storm surges, etc., occurred. Thus the recorded data can represent the normal hydrographic conditions.

The OBS data were calibrated against discrete water samples, with the correlation coefficient being 0.99. A detailed description of the methods for water sampling and analysis in laboratory can be found in Xie et al[10]. Meanwhile, the synchronous water level data at the Qibao tidal gauging station were collected, in order to link the SSC variations to hydrodynamic conditions.

3. Application of the methodology on real case study

3.1. Tidal bore impact on SSC variations

The Qibao reach is located at the inner estuary, about 150 km from the mouth. The estuary is dominated by semi-diurnal tides, with a period of around 12.5 hours. The tidal waves are seriously deformed when the incoming tides propagate landwards. Namely, the rising tides shorten and the falling tides lengthen. The averaged flood duration at Qibao tidal gauging station was only about 1.5 hours whereas the averaged ebb duration was more than 10 hours. At the bore arrival (herein the bore arrival is judged in term of water depth temporal gradient), the water level rose drastically and then gradually fell down in 1~2 hours (Figure 3). Accordingly the SSC in the inner Qiantang Estuary shows significant tidal cyclic variations. SSC was larger during flood tides, the peak SSCs appeared after the passage of the tidal bore, and smaller during ebb tides, consistent with previous studies in the Yanguan reach[5,6,10]. On the other hand, SSC in the inner reach was smaller than that of the Yanguan reach where SSC of more than 20 kg/m$^3$ was recorded after the bore passage[4, 12]. This is because when the tidal bore propagates landward, its energy is dissipated gradually. Current velocity in the Qibao reach is normally in the order of 1~2 m/s, much smaller than the Yanguan reach which is usually larger than 3 m/s[7].

Furthermore, the larger tidal range was, the higher the SSC was. For example, in the summer and autumn, the tidal range during spring tides were about 2 m and the peak of the SSC after the bore passage was about 6 kg/m$^3$. Then, the SSC decreased fast. As a result, the time series of the SSC was a spike-like line. In the spring, the tidal range at Qibao was relatively smaller, with the maximum around 1 m. Accordingly the peak SSC was only about 0.4 kg/m$^3$. The variations of the SSC were relatively gentle and the time series of SSC was similar to a sine/cosine curve.

In winter, the tidal range was within 0.5 m, comparable with that in spring. However, the SSC was a little large than in spring, with the peak being about 1.0 kg/m$^3$. This is probably caused by two reasons. Firstly, the N-NW wind waves in winter are stronger than the other three seasons[4,13], which can enhance the turbulent mixing of sediment and water volume[10,14]. Secondly, the SSC in the lower estuary is much higher in winter than in other seasons[9,15], which can increase the SSC at Qibao when transported upstream.
3.2. Seasonal variations of SSC

Figure 4 shows the frequency of the half-hourly SSC data in the four seasons. Table 1 lists the SSCs of representative frequencies. Overall SSC was largest in autumn and smallest in spring. The SSC in summer was larger than in winter. Mean SSCs in the four seasons were orderly 0.11, 0.38, 0.76 and 0.25 kg/m$^3$, respectively.

Figure 4. Cumulative frequency curves of SSCs in spring, summer, autumn and winter of 2018.
### Table 1. Statistic values of SSC of representative frequencies.

| Season  | Mean | 10% | 10% | 50% | 75% | 90% |
|---------|------|-----|-----|-----|-----|-----|
| Spring  | 0.11 | 0.27| 0.27| 0.12| 0.06| 0.03|
| Summer  | 0.38 | 0.85| 0.85| 0.34| 0.14| 0.08|
| Autumn  | 0.76 | 1.65| 1.65| 0.58| 0.22| 0.04|
| Winter  | 0.25 | 0.52| 0.52| 0.21| 0.09| 0.03|

### Figure 5. The relationships between averaged SSC over flood/ebb tides and tidal ranges at Qibao in the summer and autumn (a) and the spring and winter (b) of 2018.

To quantify the seasonal differences of SSC variations, herein relationships between the tidal range and the averaged SSCs over flood/ebb tides in the four seasons are built up (Figure 5). It is turned out that in the summer and autumn SSCs correlate positively with tidal range, with the correlation coefficient being 0.76 and 0.82, similar to previous studies in the lower Qiantang Estuary[9, 12]. It can be seen in Figure 5 that the positive relationship is more significant under relatively larger tidal ranges. In spring and winter, although the SSCs also show increasing trends with the increase tidal ranges, the points are much more scattered and such relationships appear to be less significant. The results imply that the SSC depends mainly on the tidal range if the tidal range is large enough; however if the tidal range is relatively small, the relative importance of other factors such as river discharge, bed level changes and winds on the sediment concentration would be increased.

Previous studies have revealed that sediment concentrations in the outer Changjiang Estuary and the Hangzhou Bay also changes seasonally[16-18]. In winter SSCs in the Hangzhou Bay and the outer Changjiang Estuary are about two times of those in summer[9, 18]. However, this study shows in the inner Qiantang Estuary, SSC in winter was smaller than that in summer. This can be explained by the effect of wind waves on tidal flats. In the Changjiang Estuary and Hangzhou Bay, there exist extensive tidal flats. In winter a large amount of surficial sediments on the flats can be resuspended by wind waves and dispersed southerly into the Hangzhou Bay. In the inner Qiantang Estuary, most tidal flats have been reclaimed in the last decades for the aims of flood defense and resource development[4]. Thus, the sediments that can be resuspended by wind waves are limited.

### 4. Conclusions

This study deepens our understanding the inter-tidal and seasonal suspended sediment transport variations in the inner Qiantang Estuary. The results are also of practical significances on estuarine management. The findings are summarized below:

1. In summer and autumn when the tidal range was relatively large, the time series of SSC is spike-similar whereas in spring and winter when the tidal ranges were relatively smaller, the time series of SSC is similar to a sine/cosine curve.
(2) SSC in the inner estuary shows obvious differences among various seasons. The largest occurred in autumn, and the smallest occurred in spring. The mean SSCs in the four seasons were orderly 0.11, 0.38, 0.76 and 0.25 kg/m$^3$, respectively. Such a seasonal distribution is obviously different from the lower estuary.

(3) Quantitative relationships between averaged SSC over flood/ebb tides and tidal ranges have been built up. SSC depends mainly on the tidal range given the tidal range is large enough but the role of other factors such as river discharge, bed level changes and winds on the sediment concentration would be increased if the tidal range is relatively small.

Acknowledgement
This research was supported by the National Natural Science Foundation of China (No. 41676085), the Zhejiang Provincial Natural Science Foundation of China (No. LY16D060004) and the Special Project of Zhejiang Scientific Research Institute (Study on the evolution and estuarine planform of Hangzhou Bay).

References
[1] Dyer K 1986 Coastal and estuarine sediment dynamics John Wiley
[2] Perillo G 1995 Geomorphology and sedimentology of estuaries Elsevier Science
[3] Milliman J, Syvitski J 1992 Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers Journal of Geology 100
[4] Han Z, Dai Z, Li G 2003 Regulation and exploitation of Qiantang Estuary China Water Power Press
[5] Pan C, Mao X, Geng Z 2007 Numerical modeling of the tidal bore on the Qiantang River China Journal of Hydraulic Engineering 133 2
[6] Lin B 2008 Characteristics of tidal bore in Qiantang river Ocean Press
[7] Xie D, Pan C, Lu B, Ye X 2012 A study on the hydrodynamic characteristics of the tidal bore on the Qiantang estuary based on field data Chinese Journal of Hydrodynamics 27 5
[8] Pan C, Huang W 2010 Numerical modeling of suspended sediment transport in Qiantang River: an estuary affected by tidal bore Journal of Coastal Research 26 6
[9] Xie D, Pan C, Wu X, Gao S, Wang Z 2017 The variations of sediment transport patterns in the outer Changjiang Estuary and Hangzhou Bay over the last 30 years Journal of Geophysical Research Oceans 122
[10] Xie D, Pan C 2013 A preliminary study of the turbulence features of the tidal bore in the Qiantang River China Journal of Hydrodynamics 25 6
[11] Tu J, Fan D 2017 Flow and turbulence structure in a hypertidal estuary with the world’s biggest tidal bore Journal of Geophysical Research Oceans 122
[12] Xie D, Pan C, Gao S, Wang Z 2018 Morphodynamics of the Qiantang Estuary, China: Controls of river flood events and tidal bores Marine Geology 406
[13] ECCHC (Editorial Committee for Chinese Harbors and Embayments) 1992 Chinese Harbours and Embayments PartV China Ocean Press
[14] Chanson H 2012 Tidal bores-theory and observation World Scientific
[15] Chen J, Liu C, Zhang C, Walker H 1990 Geomorphological development and sedimentation in Qiantang Estuary and Hangzhou Bay Journal of Coastal Research 6 3
[16] Yang Y, Zhang M, Li Y, Wang Z 2015 The variations of suspended sediment concentration in Yangtze River Estuary Journal of Hydrodynamics 27
[17] Li P, Yang S, Milliman J, Xu K, Qin W, Wu C, Chen Y, Shi B 2012 Spatial, temporal, and human-induced variations in suspended sediment concentration in the surface waters of the Yangtze Estuary and adjacent coastal areas Estuaries and Coasts 35
[18] Dai Z, Chu A, Li W, Li J, Wu H 2013 Has suspended sediment concentration near the mouth bar of the Yangtze (Changjiang) Estuary been declining in recent years? Journal of Coastal Research 29