Observations of boundary layer parameters and suspended sediment transport over the intertidal flats of northern Jiangsu, China

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Abstract
A current-turbidity monitoring system (CTMS) was deployed on the intertidal flat at Wanggang, northern Jiangsu during October 16–17, 2000, to measure the tidal current speeds and seawater turbidities at 5 levels above the seabed. Based upon the logarithmic-profile equation, the boundary layer parameters, i.e., \( u_\ast \), \( z_0 \), and \( C_{60} \), were obtained for 247 tidal flow velocity profiles. Around 90% of the profiles were logarithmic according to the critical correlation coefficient. Internal consistency analysis shows that these parameters derived by different methods are consistent with each other. In addition, the height of the bedforms observed is close to the seabed roughness lengths calculated from the velocity profiles, indicating that the boundary layer parameters obtained can reveal the conditions at the sediment-water interface on the intertidal flats. Suspended sediment concentrations were obtained from the 5 CTMS turbidity meters using laboratory and in-situ calibrations. The results show that the in-situ calibrated SSCs have a much higher accuracy than the laboratory calibrated ones. Calculation of suspended sediment fluxes on the intertidal flats, with a magnitude of \( 10^4 \) kg/m per spring tidal cycle, indicates that suspended sediment moves towards the northwest, which is reversal to the transport pattern controlled by the southward Northern Jiangsu Coastal Current in the sub-tidal zone and adjacent shallow waters.

Key words: boundary layer parameter, grain size, sediment transport, intertidal flat, Jiangsu coast

1 Introduction
Intertidal flats are an important habitat for wild life, potential land resources for reclamation, and natural protection of the coastline from erosion. Velocity profiles and boundary layer parameters are critical for the understanding of the sedimentary processes of tidal flats and studies have been undertaken in many estuaries (Ke et al., 1994; Collins et al., 1998; Shi et al., 2000). However, the processes associated with the intertidal flats are generally poorly understood in comparison with sandy beaches and salt-marshes; this situation is partly due to the technical difficulties into undertaking accurate in situ measurements (Dyer, 2000). Rough weather, soft bed surface and complex interactions between physical, biological and chemical factors are responsible for
the difficulties. Thus, it is necessary to use advanced technologies for in-situ measurements. In particular, attention should be paid to the measurements of benthic boundary layer parameters (i.e., roughness length, shear speed and drag coefficient).

The intertidal flats of northern Jiangsu, East China, are sheltered by a wide and unique radial sandbank system, where the tides are characterized by the southern Huanghai Sea (Yellow Sea) rotary tidal waves and the shelf circulation is dominated by the Northern Jiangsu Coastal Current (Yang, 1982; Zhang, 1986; Wang et al., 1999). Previous studies of the region were mainly concentrated on the sedimentary characteristics on large spatial-temporal scales (Yang, 1982; Ren, 1986). Because it is difficult to measure velocity profiles using ordinary current meters within the water column less than 2 m in depth, detailed data sets of tidal current and suspended sediment structures are rare. Further, the coastline here has been prograding towards the sea at a rate of around 50 m/a in response to abundant sediment supply derived from the Changjiang River and coastal erosion of the abandoned Huanghe (Yellow) River Delta (Ren et al., 1984; Li et al., 2001); as a result, the geomorphology and hydrodynamics have changed a lot for the last 20 a. In order to observe the tidal current and suspended sediment structures within the water column over the intertidal flats, a current-turbidity monitoring system (CTMS) with a high frequency sampling rate of up to 0.1 Hz was jointly constructed by Nanjing University and the Nanjing Hydraulic Research Institute, China. In this contribution, we report the performance of the CTMS over the intertidal flats at Wanggang (Dafeng City) located on the northern Jiangsu coast to measure the velocity profiles and the analysis of the data obtained to derive boundary layer parameters.

2 Study area

The intertidal flats on the northern Jiangsu coast are to some extent protected by the radial sandbank system that covers an area of about 20 000 km² (see Fig. 1a). The hydrodynamics over the sandbank system is characterized by two convergent tidal–wave systems, i.e., the East China Sea progressive and the southern Huanghai Sea rotary tidal waves (Huang and Tang, 1982; Wang et al., 1999). Such a condition causes the sediment of the radial sandbanks to move towards the coastline; hence, the tidal flats have been growing rapidly, at a rate of 50 m/a (Yang, 1982; Ren et al., 1984).

The Wanggang tidal flat with a width of 8–11 km and a gradient of 0.01%–0.05% is covered with silt, clayey silt, sandy silt and sand from the upper parts to the lower parts of the intertidal zone (Ren, 1986; Wang and Ke, 1997). This area is meso-tidal with a mean spring tidal range of 3–4 m, and the tides are irregularly semidiurnal in characteristic (Ren et al., 1984). The wind waves are generally weak. Measurements in September 1980 showed that the wave height was 0.15–0.20 m in response to wind speeds of 3.0–4.5 m/s at the water depth of 0.8 m; in addition, the wave height decreases from offshore to landward (Yang, 1982). Typhoons have an impact on the sedimentation of the study area and can form unique storm deposits (Ren et al., 1984).

Early investigations in the 1980s showed that the plants of the upper tidal flats were dominated by Imperata cylindrica var. Major, Suaeda maritima Dumort and Suaeda glauca Bunge, which would be inundated only during spring tides (Ren et al., 1984). However, these plant species are rare in this area at the present time, and have been replaced by flourishing artificially introduced species, such as Spartina anglica C E Hubb.
3 Methods

The CTMS, which is composed of 5 pairs of mini-sized current-turbidity sensors (Fig. 2), has been deployed over the lower tidal flats where there are no vegetations. In addition, a water-pressure sensor made from mono-crystalline silicon was used in the field measurements. It is capable of measuring the water depth in the range of 0~10 m with an accuracy of ±0.01 m. The speed sensor, with a diameter size of 0.05 m, includes 4 paddles and two of them are silver-plated. The use of the silver coating would reflect the luminescence from a source inside this
instrument. The current speed was obtained by counting the paddle's circumgyrates rate on the basis of the photo-electricity principle. The accuracy of the speed sensor is ±0.02 m/s, on the basis of a calibration study in a flume of the Nanjing Hydraulic Research Institute (Cai, 1994). Thus, 5 current meters were deployed within the 2 m water column over the tidal flats and their disturbance to the water body was very small (Wang et al., 2003).

The turbidity meter was designed also by the research team, with the principle similar to a transmissometer (Cai et al., 1999). The luminous flux decays through the seawater due to the water–sediment absorption and scatter, and is given by

\[ F = F_0 \exp(-KNAL) , \]  

where \( F_0 \) and \( F \) are luminous fluxes before and after the light penetrates the seawater body with a thickness of \( L \), respectively; the coefficient, \( K \), is mainly related to light wavelength, sediment diameter and scatter, water temperature and salinity; \( N \) and \( A \) denote the number of particles and the cross-section area of a single particle, respectively. By using A/D transformation, \( F \) can be converted to an electronic signal with the unit of voltage. Hence, the relationship between turbidity and electronic signal can be expressed by

\[ I = I_0 \exp(k_1 - k_2C) , \]  

where \( I_0 \) and \( I \) are electronic signals converted from corresponding \( F_0 \) and \( F \); \( k_1 \) and \( k_2 \) are the coefficients associated with \( K, N, A \) and \( L \). The sensor has a resolution of 0.5 mV and size of 0.04 m.

On the basis of Eq. (2), we have

\[ C = A + B \ln \frac{I}{I_0} , \]  

where \( I_0 \) can be determined before experiments for each turbidity sensor. In the laboratory, water samples with different suspended sediment concentration (SSC) levels (mostly ranging from 0 to 6 g/dm\(^3\)) were produced by mixing fresh water with fine sediments collected from the study area. The linear relationships between \( C \) and \( \ln(I/I_0) \) are profoundly significant for all the turbidity meters (Table 1).

Measurements were performed over the intertidal flats (33°13'04.8"N, 120°48'12.8"E) in the study area (see Fig. 1b) on October 16~17, 2000. The current–turbidity sensors were installed on a pole at 0.10, 0.37, 0.60, 1.00 and 1.60 m above the seabed, respectively. The water-pressure sensor was placed at the surface of the bed. All the sensors were connected to an electronic device which outputs data into a PC at an interval of 20 s (see Fig. 2). During the measurements, water samples were also collected from the 5 depths for the purpose of turbidity-sensor calibration. Furthermore, a ZSX–3 direct-reading current meter was mounted at the height of 0.45 m above the bed. Surficial sediment samples were collected near the observation station. During the measurements, the wind speed was less than or

Table 1. Calibrations for the CTMS turbidity meters in the laboratory (\( n \) denotes the number of measurement for a sample with different SSC levels, and \( z \) is the height above the seabed where the sensor is placed)

<table>
<thead>
<tr>
<th>No.</th>
<th>Calibration equation</th>
<th>( r )</th>
<th>( n )</th>
<th>SSC(g/dm(^3))</th>
<th>( z/m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( C=8.62-17.26\ln(I/I_0) )</td>
<td>0.99</td>
<td>17</td>
<td>0-8</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>( C=6.61-13.14\ln(I/I_0) )</td>
<td>0.98</td>
<td>13</td>
<td>0-6</td>
<td>0.37</td>
</tr>
<tr>
<td>3</td>
<td>( C=11.22-18.37\ln(I/I_0) )</td>
<td>0.99</td>
<td>12</td>
<td>0-6</td>
<td>0.60</td>
</tr>
<tr>
<td>4</td>
<td>( C=8.22-13.07\ln(I/I_0) )</td>
<td>0.99</td>
<td>15</td>
<td>0-6</td>
<td>1.00</td>
</tr>
<tr>
<td>5</td>
<td>( C=8.03-11.95\ln(I/I_0) )</td>
<td>0.98</td>
<td>12</td>
<td>0-6</td>
<td>1.60</td>
</tr>
</tbody>
</table>
equal to 5 m/s, and the wave height was less than or equal to 0.2–0.3 m.

4 Results

4.1 Current speed data and boundary layer parameters

The tidal current speeds measured by the CTMS sensor 0.37 m above the bed are generally in agreement with those recorded by the direct-reading current meter 0.45 m above the seabed (Fig. 3). A small difference between these two data sets may result from the difference in their deployment locations.

![Graph](image)

**Fig. 3.** Relationship between tidal current speeds measured by the ZSX-3 direct-reading current meter \( u_{ex} \) 0.45 m above the bed and the CTMS speed sensor 0.37 m above the bed \( u_{y} \).

The speed sensor 1.0 m above the bed did not work properly during the measurements due to a deployment problem. Thus, only current speeds measured over the other 4 heights (i.e., 0.1, 0.37, 0.6 and 1.6 m above the bed) were averaged in 1 min and used for the analysis. The data sets during the ebb and a complete tidal cycle have been processed and shown in Fig. 4. The bed at the deployment site was exposed for more than 5 h and inundated for about 6.3 h during the complete tidal cycle, with a maximum water depth of 2.17 m during high water (HW). The observed peak current speeds were 0.59 m/s during the flood phase (3.1 h before HW) and 0.88 m/s (57 min after HW) during the ebb phase. The slack water occurred 1.5 h before HW and lasted for about 20 min, when the rate of water depth change was almost 0, and the current speeds were about or smaller than 0.10 m/s. The slack period did not occur at the HW because the tidal waves over the study area are not purely standing waves; they contain a component of progressive waves (Wang et al., 1999).

However, measurements at a similar position (lower intertidal flat) on September 13–14, 1980, showed that the tidal currents were almost symmetrical with slight flood domination (Yang, 1982; Ren et al., 1984). Both flood and ebb durations were about 2.5 h, with peak current speeds of 0.5 m/s; the slack water persisted for more than 40 min. The changes of hydrodynamics in the study area may result from the decrease in the width of tidal flats due to the reclamation in the recent two decades. Another possible cause may be related to the fact that our measurement station is close to the Wanggang Channel which is dominated by the ebb current and strongly influenced by the freshwater river flow from the land.

The universal logarithmic velocity distribution is expressed by von Karman–Prandtl equation (Dyer, 1986)

\[
\frac{u_s}{u_*} = \frac{1}{\kappa} \ln \frac{z}{z_0},
\]

where \( u_s \) and \( u_* \) are the current speed (m/s) at height \( z \) above the seabed and the bed-shear speed (m/s), respectively; \( \kappa \) is the von Karman constant and taken as 0.4 for seawater; \( z \) and \( z_0 \) are the height (m) above the bed and the bed-roughness length (m), respectively. Based on Eq. (4), current speeds \( u_{y} \) of the 4 layers obtained by the CTMS were regressed against log-height, In
Fig. 4. Time-series of current speeds, simultaneously measured at various heights above the seabed by using the CTMS on October 16−17, 2000. $u_{10}$ is the current speed 0.1 m above the bed; $u_{0.37}$, 0.37 m above the bed; $u_{0.6}$, 0.6 m above the bed; and $u_{1.6}$, 1.6 m above the bed. “S” denotes slack water period.

$z$, above the bed. At the confidence level of 90% for the 4 pairs of data, the critical correlation coefficient ($r$) should be 0.9 (Collins et al., 1998). Totally, 247 current profiles were tested by this method and 225 of these profiles, i.e., 91% of the total, were identified to be logarithmic and were used to calculate the apparent boundary layer parameters associated with the intertidal flats (see Table 2). Subsequently, the internal consistency analysis developed by Collins et al. (1998) was adopted to estimate the boundary layer parameters, i.e., $u_*$, $z_0$ and $C_{60}$. It should be noted that $C_{60}$ was defined in a similar method to that of the drag coefficient $C_{100}$ (i.e., $C_{60}=u_*^2/u_{60}^2$) (Dyer, 1986).

The relationship between the derived $u_*$ and the observed $u_{60}$, i.e.,

$$u_* = au_{60} + b$$

must satisfy a number of conditions to meet the requirements of the von Karman–Prandtl equation (Collins et al., 1998). First, the linear correlation between $u_*$ and $u_{60}$ should be significant. Because the correlation coefficient, $r = 0.83$, is above the critical coefficient 0.18 for 225 data points.

Table 2. “Apparent” boundary layer parameters derived from the 225 current speed profiles measured over the intertidal flats in Wanggang, northern Jiangsu during October 16−17, 2000

<table>
<thead>
<tr>
<th>Characteristic value</th>
<th>$z_0$/m</th>
<th>$u_*/$m·s$^{-1}$</th>
<th>$C_{60}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>0.001 0</td>
<td>0.006 8</td>
<td>0.004 3</td>
</tr>
<tr>
<td>Maximum</td>
<td>0.052 7</td>
<td>0.082 4</td>
<td>0.038 6</td>
</tr>
<tr>
<td>Mean</td>
<td>0.019 8</td>
<td>0.038 7</td>
<td>0.016 3</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.012 6</td>
<td>0.014 8</td>
<td>0.007 6</td>
</tr>
</tbody>
</table>
pairs at the confidence level of 99% (see Fig. 5), this condition is satisfied. Second, the regression line intercept should be small. In the present study, we have obtained that $b=0.0021$, which is sufficiently small. Third, the parameter $z_0$ calculated from the equation

$$a = \frac{k}{\ln \frac{z}{z_0}}$$  \hspace{1cm} (6)

should be consistent with the value derived on the basis of Eq. (4). In this study, we have derived the following: $a=0.1138$, $z=0.6$ m, and therefore $z_0=0.0179$ m; this $z_0$ value is indeed close to the value 0.0198 m obtained on the basis of Eq. (4). Finally, there should be consistency between the $C_{50}$ values according to the formula $C_{50}=a^2$ and regression analysis. We have obtained $C_{50}=0.0130$, which is similar to the value listed in Table 1 (i.e., 0.0163). Hence, the internal consistency is confirmed by the results obtained.

The ripples over the seabed surface have a height of 1~2 cm at the measurement station. Ripples with heights of 4~5 cm have been found at a neighbouring site; this observation may imply that larger ripples exist at the measured station during the inundation period but they are not observed when the tidal flat is exposed. On the other hand, the calculated roughness length $z_0$ ranged between 0.01 and 0.05 m (see Table 2), representing the magnitude of small-scale bedforms over the intertidal flats. However, this does not necessarily mean that the bed roughness length should be exactly the same as the ripple size; the roughness length is also related to the surficial sediment grain size (Dyer, 1986). Both the roughness length ($z_0$) and the drag coefficient ($C_{d0}$) are inversely proportional to the reference velocity ($u_{*0}$) when the current speeds exceed 0.3 m/s (see Fig. 6). When the current speeds are smaller than 0.3 m/s, the correlation is much poorer. Such a phenomenon could be attributed to the following factors.

1. As the current speed increases, the size of turbulent eddies also increase in the flow. Larger eddies resulting from higher speeds will
not be able to penetrate into the bed as closely as the smaller eddies do. Hence, when the speed and eddy size increase, the length between the top of the bedforms and the typical level at which the current speed diminishes \( z_e \) will decrease (Vincent and Harvey, 1976).

(2) When the surficial sediment is entrained due to high current speeds (e.g., greater than 0.3 m/s), the bed roughness will be reduced (Cheng et al., 1998). In the Mississippi River, von Rijn (1993) found that the effective bed roughness length would decrease significantly with increasing velocities because the bedforms become more rounded or are washed out at high velocities.

(3) During the slack water before HW, the current speed is so small (<0.1 m/s) that eddies may not exist near the bed. Further, the high speed during the middle flood would make the bed smoother. Thus, the roughness length will be small at slack water time (Fig. 6).

4.2 In-situ calibration for turbidity meters

The grain size was measured using a Cilas 940 L laser particle analyzer for the suspended sediment samples collected at different water depths at the CTMS deployment site during October 16–17, 2000 (see Fig. 7). The mean grain size of suspended sediment is highly uniform and concentrates in the range of 6.4–7.9 \( \phi \).

The turbidities at the 5 heights were calibrated using 23 in-situ collected water samples at the corresponding depths. The correlation is significant at the 99% confidence level (with the critical correlation coefficient being 0.52). The calibration equation shown in Fig. 8 was used to estimate the SSC.

A comparison between in-situ and laboratory calibration shown in Fig. 9 suggests that the in-situ calibration is better than the laboratory calibration: the latter underestimates the SSCs. It also shows that 50% of the SSC data sets have a relative error of less than 30% by using the in-situ calibrated equation, but only 20% of the data sets satisfy this condition by using the laboratory calibrated equation. The in-situ environment, e.g., the suspended sediment characteristic, water temperature and salinity, may have a significant influence on the turbidity measurement of the CTMS sensors.

The SSCs were estimated by the in-situ calibration equation for the heights of 0.10, 0.37, 0.60, 1.00 and 1.60 m above the bed (see Fig. 10). Several SSC peak values are
present in the tidal cycle. During the early flood, early ebb (shortly after HW) and middle ebb, SSCs were found to be high, i.e., greater than 3 g/dm³. However, at the slack water before HW the SSC was low (<1 g/dm³) due to the settling of suspended sediment when the current velocity was less than 0.1 m/s. In addition, a thin layer of seawater (less than 5 cm) was observed to remain on the intertidal flats due to the topographic conditions, which could not be drained off before the subsequent flood tide. These water masses were highly clear since most of the suspended sediment was settled onto the bed.

4.3 Suspended sediment flux

Using the current speeds and SSCs at the 4 heights above the bed, the suspended sediment flux within the water column has been estimated. The fluxes during the flood and ebb are $11.2 \times 10^3$ and $7.75 \times 10^3$ kg/m with the directions of $293^\circ$ and $348^\circ$, respectively. Thus,
the net suspended sediment transport is directed towards the northwest (324°) with a magnitude of $14.7 \times 10^3$ kg/m per tidal cycle. This is consistent with the residual current pattern of this area obtained by Ren (1986) and Zhang (1990). It should be noted that the suspended sediment in the sub-tidal zone and adjacent waters moves southward because of the North-
ern Jiangsu Coastal Current that flows from the north to the south. Therefore, although there is a long-term trend for the sediment to be transported from the old Huanghe River mouth towards the southern coastal areas, the direction of suspended sediment movement in some places over the intertidal flats may be reversed. Previous studies show that the sediment deposition varies in seasons (Yang, 1982), and the present study may provide a sediment transport pattern in autumn.

5 Summary and conclusions

A CTMS system has been utilized to measure the current speed and turbidity at several heights above the seabed over the Wanggang intertidal flats, northern Jiangsu. The result shows that this area is ebb-dominated, different from the observations made two decades ago. The boundary layer parameters are derived for a large number of velocity profiles by regression analysis on the basis of the logarithmic Karman–Prandtl equation. About 91% of the profiles have high correlation coefficients that are significant at the 90% confidence level. Furthermore, these parameters are also calculated using other methods, indicating an internal consistency between the data sets. The estimated bed roughness length is comparable to the height of ripples present over the flat surface.

Calibrated equations are derived for the CTMS turbidity meters by using laboratory and in-situ calibrations. The results show that the latter has a smaller relative error for measurements. The SSCs calculated by the in-situ calibration equation for different water depths show that SSC peaks occur during the early flood, early ebb and middle ebb. The derived net suspended sediment flux has a magnitude of 10^4 kg/m per spring tidal cycle, directed towards the northwest; this pattern is different from the overall sediment movement in the offshore areas of the region, indicating localized effects.

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