Relating accretion and erosion at an exposed tidal wetland to the bottom shear stress of combined current–wave action

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A R T I C L E   I N F O

Article history:
Received 31 December 2010
Received in revised form 2 October 2011
Accepted 4 October 2011
Available online 10 October 2011

Keywords:
Combined current–wave action
Shear stress
Sediment dynamics
Tidal wetland
Mudflat
Salt marsh

A B S T R A C T

Sediment dynamics have an important influence on the morphological evolution of tidal wetlands, which consist of mudflats and salt marshes. To understand the nature of sediment behavior under combined current–wave action at an exposed tidal wetland, we measured the waves, currents, water depths, bed-level changes, and sediment properties at a mudflat–salt marsh transition on the Yangtze Delta, China, during five consecutive tides under onshore winds of ~8 m/s, and calculated the bed shear stresses due to currents (τce), waves (τcw), combined current–wave action (τcw), and the critical shear stress for erosion of the bottom sediment (τcr). The bed shear stresses under combined current–wave action (τcw) were approximately five times higher on the mudflat (up to 1.11 N/m²; average 0.27 N/m²) than on the salt marsh (up to 0.14 N/m²; average 0.06 N/m²). On the mudflat, τcw was larger than the critical erosion shear stress (τcr = 0.103 N/m²) for 70% of the period of submergence, whereas τcw was always lower than τcr at the salt marsh site (τcr = 0.116 N/m²). This result indicates that the sediment dynamics on the mudflat were dominated by erosion, whereas at the salt marsh they were governed by deposition, which is in agreement with the observed bed-level change during the study period (~3.3 mm/tide on the mudflat and 3.0 mm/tide on the salt marsh). A comparison of τcw values calculated using the van Rijn (1993) and Soulsby (1995) models for bed shear stresses under combined current–wave action indicates that both models are applicable to the present case and effectively predict the bottom shear stress under combined current–wave action. Overall, we conclude that τcw in combination with τcr is useful in assessing the hydrodynamic mechanisms that underlie the morphological evolution of exposed tidal wetlands.

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1. Introduction

Tidal wetlands, which generally consist of salt marshes and mudflats, are widely distributed along coastlines worldwide (Eisma, 1998). They provide important ecosystem functions as they filter contaminants, dissipate wave energy, and possess an intrinsic value (Goodwin et al., 2001). In some areas the formation of salt marshes is strongly influenced by peat accumulation (e.g., along the East Coast of the USA), whereas in other areas of the world (e.g., China NW Europe) salt marsh formation is predominantly dependent on sediment deposition (Allen, 2000). Hence, a knowledge of sediment transport is important in understanding the geomorphologic development of salt marshes (Kirwan and Murray, 2007; Temmerman et al., 2007). Sediment dynamics on mudflats can strongly affect the benthic communities that inhabit these areas, and thereby determine the ecological value of the mudflats as feeding grounds for (migratory) birds (Ysebaert et al., 2003). Therefore, an understanding of sediment dynamics is important for managing the biotic value of these ecosystems. However, the dynamics are complicated by strong temporal and spatial variations that are typical of mudflat environments (e.g., O’Brien et al., 2000; Yang et al., 2008). The motion of sediments over tidal wetlands, and in particular over exposed mudflats, is generally driven by a combination of currents and waves (Woodroffe, 2003). Processes of sediment transport under combined current–wave action are therefore the key to understanding the morphological evolution of tidal wetlands. Although many studies have focused on the role of currents on sediment transport and erosion/accretion in intertidal mudflat–salt marsh systems (e.g., French and Spencer, 1993; Bassoullet et al., 2000; Dyer, 2000; Leonard and Reed, 2002; Yang et al., 2007), less is known about sediment behavior under combined current–wave action (Whitehouse and Mitchener, 1998; Wang et al., 2006; Callaghan et al., 2010), possibly due to the difficulties encountered in undertaking integrated observation of waves, currents, and sediment properties. To date, most studies on sedimentary processes associated with combined current–wave action have been based on idealized experiments or

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doi:10.1016/j.geomorph.2011.10.004
numerical modeling (e.g., Davies, 1992; Fredsøe et al., 1999; Cao et al., 2003; Allard et al., 2008) or on observations in near-shore or continental shelf waters (e.g., Drake and Cacchione, 1992; Li and Amos, 1998; Chang and Dickey, 2001; Hu et al., 2009). Consequently, there is a clear need for field studies aimed at understanding sediment motion and erosion/accretion in a macrotidal, highly wave-exposed muddy intertidal mudflat–salt marsh system where currents and waves are expected to strongly interact. The complicated nature of the translation of hydrodynamic measurements to sediment dynamics via bed shear stress due to currents and waves has resulted in a number of alternative mathematical models, including the van Rijn model (van Rijn, 1993) and the Soulsby model (Soulsby, 1995). To our knowledge, these models have not yet been tested side by side, with reference to a macrotidal, highly wave-exposed muddy intertidal mudflat–salt marsh system. Such a comparison would represent a valuable first step towards understanding mud dynamics under the unique conditions of a macrotidal and wave-exposed setting, and would enable an assessment of the applicability of these models in predicting sediment dynamics.

In this study, we aim to extend existing knowledge on sediment behavior under combined current–wave action by measuring waves, currents, sediment properties, and bed-level changes along the mudflat–salt marsh transition of a macrotidal and exposed coast on the Yangtze Delta, China. Our specific objectives are to: (1) quantify the bed shear stress under combined current–wave action ($\tau_{cw}$) using two alternative models, and compare $\tau_{cw}$ with (1a) the bed shear stress generated by currents ($\tau_c$) or waves ($\tau_w$) individually, and with (1b) the critical shear stress for erosion of the bottom sediment ($\tau_{ce}$) and the critical shear stress for the deposition of suspended sediment ($\tau_{cd}$); and (2) examine tidal-cycle-scale erosion and deposition using these shear stresses and compare predicted and observed bed-level change.

2. Study area

Field measurements were conducted on an exposed mudflat–salt marsh transition on Eastern Chongming Island, Yangtze Estuary (Fig. 1). Site Mu (mudflat) was located 340 m seaward from the marsh edge (0.2 m above the mean sea level), and site Ma (salt marsh) was located 250 m landward from the marsh edge (0.7 m above mean sea level) (Fig. 1c–d). Site Ma was located in the Scirpus marriquet vegetation (0.4–0.6 m in height, ~3 mm in stem diameter and 70%–80% in projective coverage), which occupies the lowest 0.5 km of the marsh (3 km in width).

The tidal wetland in eastern Chongming faces the East China Sea, with a maximum width of 7–8 km. The tides in the Yangtze Estuary are irregularly semidiurnal. At the Sheshan gauging station, 20 km east of the studied tidal wetland (Fig. 1b), the average tidal range is 2.5 m, reaching up to 3.5–4.0 m during normal spring tides; the highest recorded tidal range is 4.64 m and the highest recorded water level is 2.9 m above mean sea level (GSII, 1996). Upon the subtidal slope, the peak current velocity is ~2 m/s during spring tides. Overall, the current velocity decreases landward from the subtidal area to the supratidal salt marsh, with the peak near-bed flow velocity being ~0.5 m/s in front of the marsh edge (Yang et al., 2008).

Wind speed over the Yangtze Estuary is highly variable, with multi-year averages of 3.5–4.5 m/s and a maximum recorded speed of 36 m/s (GSII, 1996). During the field observations of this study,
the wind direction ranged from 29° to 107°, and the wind speed ranged from 6.5 to 8.1 m/s at Sheshan (Appendix Fig. 1). At the delta front (~7 m below mean sea level), the mean and maximum wave heights are 1.0 and 6.2 m, respectively, based on multi-year records (GSII, 1996). Given the abundant supply of fine-grained sediment from the Yangtze River, the tidal wetland in Eastern Chongming has rapidly prograded in recent centuries (Yang et al., 2005). However, the rate of progradation has shown a marked decrease in the past two decades, linked to dam construction upon the Yangtze (Yang et al., 2006). At present (2006–2010), accretion still occurs on the salt marsh (average rate of ~5 cm/yr), whereas erosion is found on the mudflat of the present transect (Yang et al., 2011). The surface sediment of the tidal wetland in Eastern Chongming is typically very fine sand (63–125 μm) in the lower flat, coarse silt (32–63 μm) in the upper flat, and medium silt (16–32 μm) and fine silt (8–16 μm) on the salt marsh (Yang et al., 2008).

3. Methods

3.1. Field measurements

We measured waves and currents at site Mu during five consecutive tides between spring and neap tides on September 22–24, 2009, and at site Ma during a tide on September 22, 2009. At the same time, bottom and suspended sediments were sampled. Although our measurements consisted of a limited number of tidal cycles, the dataset enables us to address our study aims because (i) the wind conditions generated significant waves and (ii) the predominant current conditions were captured within the single tidal cycles.

Waves and water depths were measured using self-logging sensors (SBE 26plus SEAGAUGE, Sea-Bird Electronics Inc., USA) that were programmed to measure the mean water depth every 10 min. Within the same 10-minute interval, waves were determined by 4 Hz pressure measurements over a 256-second period, giving 1024 measurements per burst. With a characteristic significant wave period of ca. 2 s, each burst contains more than 100 waves for determination of the wave height and wave period. The wave sensors were mounted horizontally on the sea bed, with the pressure sensors being located 0.15 m above the sediment surface. All of the water depth data have been corrected for this 0.15 m offset so that all the presented data give the height from the sediment surface. To test the consistency between instruments, we placed the three sensors at the same site (spaced at ~1 m) on the mudflat, and found that they recorded equal water depths and wave heights that differed by <3%.

Currents were measured using a self-logging Pulse-Coherent Acoustic Doppler Profiler (PC-ADP, the SonTek, USA) and Acoustic Doppler Profilers-XR (ADP-XR). The PC-ADP was fixed on a tripod with its sensor probe facing downward at a height of 65 cm above the sediment surface. The ADP-XR was mounted on the sea bed with its sensor probe facing upward at a height of 15 cm above the sediment surface. It measured velocities at five layers from 20 cm above the probe (i.e., 35 cm from the bed) to the water surface.

The latitude, longitude and elevation of the observation sites and the topographic profile through the experimental sites were determined using a Real Time Kinematic Global Position System (Ashtech, USA). The double-rods method (Yang et al., 2003) was employed to determine the bed-level changes during September 22–25, 2009. The bed level was determined during low water, giving the time-integrated bed-level changes over a flooding period. To avoid mutual interference between the instruments, the rods (25 mm diameter) were placed at least 3 m away from the instruments, with 1 m between the rods. Sediments were sampled using a tube-shaped sampler with a diameter of 36 mm. Suspended sediments were sampled using a 600 ml bottle, with its mouth facing upward at a height of 15 cm above the seabed, fastened on a tripod before the flood; the bottle was recovered after the ebb.

3.2. Data processing and samples analysis

Processing of the data from the self-logging wave and tide sensors (including pressure correction), PC-ADP and ADP-XR was conducted using the software provided by the respective manufacturers. In the laboratory, samples of wet bottom sediment were weighed and oven dried at a temperature of 50 °C until the weight was stable (~48 h). The ratio of water weight (i.e., the difference between the wet and dry weights) to dry weight of the sediment was defined as water content (Taki, 2001). The sediment grain size was measured using a LS13320 Laser Particle Size Analyzer (Coulter Inc., USA). Note that all the sediment samples were deflocculated before analysis by the Coulter counter, avoiding the measurement of any larger flocs that may have been in suspension.

3.3. Calculation of shear stresses

3.3.1. Bed shear stress under combined current–wave action ($\tau_{cw}$)

According to linear wave theory, the peak value of the orbital excursion ($A_0$) and velocity ($U_0$) at the edge of the wave boundary layer can be expressed as follows:

$$\bar{A}_0 = \frac{H}{2 \sinh(kh)}$$

$$\bar{U}_0 = \omega \bar{A}_0 = \frac{\pi H}{T \sinh(kh)}$$

where $\omega = 2n/T$ is the angular velocity $(s^{-1})$, $k = 2n/L$ is the wave number $(m^{-1})$, $H$ is the wave height $m$, $L$ is the wave length $m$, $T$ is the wave period $s$, $h$ is the water depth $m$, $\bar{A}_0$ is the peak value of the orbital excursion, and $\bar{U}_0$ is the wave orbital velocity $(m/s)$.

In the van Rijn (1993) model, the bed shear stress due to waves ($\tau_w$, $N/m^2$) is calculated as follows:

$$\tau_w = 0.25 \rho_w u_{rms}^2$$

where $\rho_w$ is the seawater density (measured to be 1030 kg/m$^3$), $u_{rms}$ is the rough bed friction factor (calculated to be 0.01–0.11 at the present study sites). Utilizing the equivalent bed roughness, we have $k_e = 25 \eta^2/\lambda$ where $\eta$ is the ripple height and $\lambda$ is the ripple wavelength (Davies and Thorne, 2005). $H_s$ is significant wave height $(m)$ for the calculation of $\bar{U}_0$ in Eq. (2).

In the Soulsby (1995) model, $\tau_w$ is calculated as follows:

$$\tau_w = 0.5 \rho_w u_{rms}^2$$

where $H$ is $H_{rms} = H_s/\sqrt{2}$ for the calculation of $\bar{U}_0$ in Eq. (2).

To calculate the shear velocity $(u_*$, $m/s$; Eq. (5)), the velocity data were fitted to logarithmic velocity profiles using linear regression by the least-squares method. Bed shear stress due to currents ($\tau_c$, $N/m^2$) was subsequently calculated according to Eq. (6) (Whitehouse et al., 2000), as follows:

$$\frac{u_c(Z)}{u_*} = \frac{1}{k} \ln \left( \frac{Z}{Z_0} \right)$$

$$\tau_c = \rho_w u_{rms}^2$$

where $u_c(Z)$ is the current velocity at height $z$ above the bed, $k$ is the Von Karman’s constant ($\approx 0.4$), and $z_0$ is the bed roughness amplitude (within the range ~0 to 1.88 cm, following Whitehouse et al., 2000) for ripples at our study sites.
The time-averaged and cycle-mean bed shear stress due to currents and waves (τcw, N/m²) was calculated using the van Rijn (1993) model (Eq. (7)) and the Soulsby (1995) model (Eq. (8)).

The van Rijn (1993) model is expressed as follows:

\[ \tau_{cw} = \alpha_s \tau_c + \tau_{w-vanRijn} \]  

(7)

where \( \alpha_s = \frac{\ln(30/k_s)^2}{-1 + \ln(30/k_s)^2} \), \( k_s \) is the apparent bed roughness, and \( k_b \) is the bed roughness. In this study, we assumed \( k_b = k_s \), following van Rijn (1993) who stated that this equality holds when the ratio of the peak orbital velocity to depth-averaged velocity is 1 (i.e., \( \alpha_s = 1 \)). In Eq. (7), \( \tau_c \) is positive when the wave direction is the same as the current direction, but is negative when the wave direction is opposite to the current direction (van Rijn, 1993). In this study, \( \tau_c \) was typically positive during the flood phase and negative during the ebb phase.

The Soulsby (1995) model is expressed as follows:

\[ \tau_{cw} = \frac{1}{1 + 1.2 \left( \frac{\tau_{w-Soulsby}}{\tau_c + \tau_{w-Soulsby}} \right)^{1.21}} \]  

(8)

3.3.2. Critical shear stress for the erosion of bottom sediment (τce)

Because the bottom sediment in the study area was mainly fine grained (i.e., the median grain size (d50) at sites Mu and Ma was 22.5 and 14.7 μm, respectively), we determined the critical shear stress for the erosion of bottom sediment (τce, N/m²) using Eq. (9), which is suitable for cohesive sediments (Taki, 2001):

\[ \tau_{ce} = 0.05 + \beta_s \frac{1}{(\pi/6)(1 + sW)^{1/3} - 1}^2 \]  

(9)

where \( \beta \) is a dimensionless coefficient, \( s \) is the specific weight of the particle \((s = \rho_c/\rho_w - 1)\), \( \rho_c \) is the sediment particle density (= 2650 kg/m³), \( \rho_w \) is the seawater density (measured to be 1030 kg/m³), and \( W \) is the water content. Based on Taki’s (2001) experimental data, \( \beta = 0.3 \) when the grain size of the bottom sediment is less than several tens of microns and the water content of the bottom sediment is relatively high, which is in agreement with the present sediments.

3.3.3. Critical shear stress for the deposition of suspended sediment (τsd)

Based on the experimental results of Lum Borg (2005), the critical shear stress for the deposition of suspended sediment (τsd, N/m²) ranges from 0.01 to 0.1 N/m² and is typically around 0.05 N/m² for mixtures of fine-grained mineral particles. These values were employed in the present study because the suspended sediment in the study area originates from the Yangtze River (catchment area of 1.8 × 10⁶ km²) and is composed of a range of mineral particles (Yang et al., 2002).

4. Results

4.1. Wave characteristics and current velocity

The maximum water depth at high tide ranged from 0.94 to 1.71 m at site Mu and was 1.21 m during the only tide (Tide 1) measured at site Ma (Fig. 2a). The burst-based significant wave height ranged from 0 to 0.76 m during the five tides at site Mu and from 0 to 0.19 m during Tide 1 at site Ma (Fig. 2a); the burst-based significant wave period ranged from 0.66 to 5.47 s at site Mu and from 0.79 to 3.42 s at site Ma (Appendix Table 1). At both sites and during all tides, the wave height was strongly positively correlated with water depth (r = 0.96–0.99; Fig. 3a), i.e., the wave height tended to be largest at high tide (Fig. 2a). The ratio of significant wave height to water depth ranged from 0.04 to 0.34 at Mu, and from 0.04 to 0.17 at Ma (Appendix Table 1). As the wind-induced generation of waves did not vary significantly in time (i.e., the wind speed ranged from 7.6 to 8.0 m/s with onshore directions ranging from 35° to 100°; Appendix Fig. 1); the positive relation between wave height and water depth (Fig. 3a) reflects changes in bed friction with water depth and the flat geomorphology of the study area.

At site Mu, the instantaneous near-bed current velocity ranged from 0.03 to 0.73 m/s (average, 0.28 m/s; Fig. 2b). During Tide 1, the near-bed current velocity was much lower at site Ma (0.03–0.15 m/s; average, 0.09 m/s) than that at site Mu (0.04–0.50 m/s; average, 0.30 m/s). Typically, the flood period was shorter than the ebb period, and the flood current velocity was higher than the ebb current velocity, showing tidal asymmetry (Fig. 2b). On average, the ratio of flood to ebb period was 0.69, and the ratio of flood current velocity to ebb current velocity was 1.2. The current direction was clockwise rotational. It tended to be southwestward (onshore) at early flood, to be alongshore at the high tide, and to be eastward or southeastward (offshore) at late ebb. During the incoming tide, the current reaches a maximum in the onshore direction. During high water, a maximum value is found due to alongshore currents, and at ebb a maximum is reached due to dewatering in the offshore direction.

4.2. Shear stresses

4.2.1. Bed shear stress due to currents (τc) and waves (τw)

The bed shear stress due to currents (τc) ranged from −0.87 N/m² (average, 0.21 N/m²) at site Mu during the five tides. During Tide 1, the τc was an order of magnitude lower at site Ma (−0.04 N/m²; average, 0.02 N/m²) than at site Mu (0.003–0.44 N/m²; average, 0.19 N/m²) (Fig. 2c; Table 1). The difference in τc between Ma and Mu was much smaller than the difference in τc. The intertidal pattern of τcw was similar to that of the water depth and wave height (Fig. 2a, c). That is, τcw tended to be higher at high tides. τcw exponentially increased with water depth (∆ = 0.74; Fig. 3b).

Because τc is a function of currents (Eq. (6)), it shows similar behavior to near-bed current velocity (Fig. 2b-c). At high water depth, the waves are higher but do not penetrate deep into the water column, meaning they are not strongly influenced by the bed. In contrast, at times of shallower water depth, the waves are less high but the water depth is sufficiently limited for the waves to be strongly influenced by the bed. This means that understanding the relation between water depth and wave height (Fig. 3) is useful.

4.2.2. Bed shear stress due to combined wave–currents (τcw)

Based on the two models described above (Eq. (7) and (8)), the calculated bed shear stress due to combined current–wave action (τcw) ranged from 0.01 to 1.11 N/m² (average, 0.27 N/m²) at site Mu during the five tides. The high value of τcw compared with τw and τc clearly shows the importance of combining τc and τw into a single parameter. During Tide 1, the τcw was again much lower at site Ma (0.016–0.140 N/m²; average, 0.058 N/m²) than at site Mu (0.035–0.555 N/m²; average, 0.285 N/m²) (Fig. 2d; Table 1). On average, similar values of τcw were obtained from the Soulsby model (τcw = 0.238 N/m²) and the van Rijn model (τcw = 0.242 N/m²) (Fig. 2d; Table 1). However, individual τcw values differed between the two models (Fig. 2d). The τcw (van Rijn model) followed more the pattern of the calculated τw, whereas the τcw (Soulsby model) followed more the pattern of the τc (Fig. 2c–d). τcw (van Rijn model) was significantly higher at the flood phase than at the ebb phase. Although τcw (Soulsby model) was overall higher at the flood phase than at the ebb phase, its difference between flood and ebb phases was less
significant than the \( \tau_{cw} \) (van Rijn model) (Fig. 2d). \( \tau_{cw} \) (van Rijn model) was higher than \( \tau_{cw} \) (Soulsby model) at typical flood phases when both the directions of currents and waves are onshore, and was lower than \( \tau_{cw} \) (Soulsby model) at typical ebb phases when the directions of currents and waves are opposite. In other cases, \( \tau_{cw} \) (van Rijn model) could be either higher or lower than \( \tau_{cw} \) (Soulsby model) (Fig. 4). The implications of these findings for erosion and deposition are considered in Section 4.3.

4.2.3. Sediment properties and the critical shear stress for sediment erosion (\( \tau_{ce} \))

The bottom sediment in the study area was composed of natural mineral particles with an approximate density (\( \rho_s \)) of 2650 kg/m\(^3\). The median grain size was measured to be 22.5 \( \mu \)m at site Mu and 14.7 \( \mu \)m at site Ma. The water content of bottom sediment was 46\% at site Mu and 36\% at site Ma. These data indicate a value of 0.3 for \( \beta \) in Eq. (9) and \( \tau_{ce} \) values of 0.103 N/m\(^2\) for the mudflat and 0.116 N/m\(^2\) for the marsh. \( \tau_{cd} \) critical shear stress for deposition of suspended sediment (based on Lumborg, 2005).

At site Mu, each tide contained phases of \( \tau_{cw} > \tau_{ce} \) (net erosion) and \( \tau_{cw} < \tau_{cd} \) (net deposition). On average, the duration of \( \tau_{cw} > \tau_{ce} \) was more than 70\% of the period of tidal submergence, whereas the duration of \( \tau_{cw} < \tau_{cd} \) was less than 20\% (Fig. 2d; Table 2). Specifically, when using the Soulsby (1995) model, the duration of \( \tau_{cw} \) (Soulsby model) > \( \tau_{ce} \) (net erosion phase) was more than 66\% of the period of submergence, whereas the duration of \( \tau_{cw} \)
5. Discussion

5.1. Values of $r_{ce}$ and $r_{cd}$

The critical shear stress for erosion, $r_{ce}$, is determined by the properties of the bottom sediment, and can therefore vary significantly over space and time (Gust and Morris, 1989; Schüinemann and Kühl, 1993; Houwing, 1999; Milburn and Krishnappan, 2003; Lumborg, 2005). From the literature, the $r_{ce}$ value of mudflats can range from 0.1 to 0.6 N/m$^2$ (Widdows et al., 1998; Christie et al., 1999; Andersen et al., 2007; Wang et al., 2008; Wang, 2009). The values of $r_{ce}$ in the present study (0.103 N/m$^2$ for the mudflat site and 0.116 N/m$^2$ for the salt marsh site) are low compared with many other mudflats (e.g., Christie et al., 1999; Andersen et al., 2007), probably because the bottom sediments of the present study were relatively recently deposited due to the high rate of progradation (~300 m/yr) in Eastern Chongming (Yang et al., 2001). As a consequence of the low $r_{ce}$ values, the bottom sediment has been less compacted and its water content is high because of frequent submergence beneath tidal water. Examples of $r_{ce}$<0.2 N/m$^2$ have also been reported for the mudflats in the Ems/Dollard estuary, the Netherlands ($r_{ce}$=0.1 N/m$^2$ on average for soft deposits; Kornman, 1998), for the Skeffling mudflats in the Humber estuary, UK ($r_{ce}$=0.18 N/m$^2$; Table 1 in Houwing, 1999), and for mudflats in Luoyuan Bay, Southeastern China ($r_{ce}$=0.11–0.15 N/m$^2$; Wang, 2009). In the present study, the value of $r_{ce}$ was slightly higher at the salt marsh site than at the mudflat site, probably because the higher elevation of the marsh site and its more frequent exposure to air resulted in a lower water content of the bottom sediment, although transpiration by marsh vegetation may also be partly responsible for dewatering at this site.

### Table 1

Statistics of bed shear stress due to currents ($\tau_c$), waves ($\tau_w$), and combined current–wave action ($\tau_{cw}$).

<table>
<thead>
<tr>
<th>Tides</th>
<th>$\tau_c$ (N/m$^2$)</th>
<th>$\tau_w$ (N/m$^2$)</th>
<th>$\tau_{cw}$ (N/m$^2$) based on Soulsby (1995) model</th>
<th>$\tau_{cw}$ (N/m$^2$) based on van Rijn (1993) model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Mean</td>
<td>Std</td>
</tr>
<tr>
<td>Tide 1 (mudflat)</td>
<td>0.003</td>
<td>0.440</td>
<td>0.191</td>
<td>0.162</td>
</tr>
<tr>
<td>Tide 2 (mudflat)</td>
<td>0.008</td>
<td>0.872</td>
<td>0.244</td>
<td>0.191</td>
</tr>
<tr>
<td>Tide 3 (mudflat)</td>
<td>0.015</td>
<td>0.747</td>
<td>0.340</td>
<td>0.206</td>
</tr>
<tr>
<td>Tide 4 (mudflat)</td>
<td>0.003</td>
<td>0.090</td>
<td>0.102</td>
<td>0.140</td>
</tr>
<tr>
<td>Tide 5 (mudflat)</td>
<td>0.001</td>
<td>0.722</td>
<td>0.165</td>
<td>0.178</td>
</tr>
<tr>
<td>Tide 1 (marsh)</td>
<td>0.002</td>
<td>0.042</td>
<td>0.020</td>
<td>0.010</td>
</tr>
</tbody>
</table>
The concept of a critical shear stress for deposition, $\tau_{cd}$, has been widely utilized in studies of sediment dynamics (e.g., Krone, 1962; Dyer, 1986; Christie et al., 1999; van der Ham and Winterwerp, 2001; Lumborg, 2005; and references therein). For simplicity, a deposition threshold of $\tau_{cd}=\tau_{ce}$ has been used in some studies (e.g., Christie et al., 1999), but a deposition threshold of $\tau_{cd}>\tau_{ce}$ is more generally employed (e.g., Christie et al., 1999; Milburn and Krishnappan, 2003; Lumborg, 2005; Andersen et al., 2007). The $\tau_{cd}$ value of single particles depends not only on the water temperature, turbulence, salinity and suspended sediment concentration, but also on the size, density and shape of the grains themselves (Partheniades, 1965). In other words, $\tau_{cd}$ differs between grains, as well as spatially and temporally. Hence, $\tau_{cd}$ could theoretically be considered a range rather than as a single value. For example, in laboratory experiments, $\tau_{cd}$ was found to be 0.088 N/m² for mud (median size = -20 µm) and 0.12–0.32 N/m² for sand of various grain sizes (Milburn and Krishnappan, 2003). From a mudflat on the Danish Wadden Sea, $\tau_{cd}$ was found to be 0.1 N/m², which is much lower than the local $\tau_{ce}$ value of 0.24 N/m² (Andersen et al., 2007). Along the western coast of the Baltic Sea, a similar low $\tau_{cd}$ range of 0.01–0.1 N/m² was employed (e.g., Lumborg, 2005; and references therein). The $\tau_{cd}$ value for coarse grains) differs between grains, ranging from 0.01 to 0.1 N/m² (average, 0.05 N/m²).

5.2. Intertidal phases of erosion and deposition determined by comparison between $\tau_{cow}$, $\tau_{ce}$ and $\tau_{cd}$

Some previous studies identified erosion and deposition based on a single critical shear stress of sediment in combination with bed shear stress (e.g., Christie et al., 1999); whereas others employed separate critical shear stresses for erosion and for deposition (e.g., Cancino and Ramiro, 1999; Lumborg, 2005; Andersen et al., 2007; and references therein). Although there is evidence that sediment is continuously deposited and resuspended (e.g., Sanford and Halka, 1993), it is assumed in most models, following Einstein (1950), that deposition occurs when the bed shear stress is lower than a critical value for deposition, whereas erosion occurs when the bed shear stress is higher than a minimum value for erosion (Cancino and Ramiro, 1999).

In the present study, we define net erosion (i.e., the net erosion phase) as the duration of $\tau_{cw}>\tau_{ce}$ and net deposition phase as the duration of $\tau_{cw}<\tau_{ce}$ and define a no net change phase as the duration of $\tau_{cw}>\tau_{ce}>\tau_{cd}$. For the first case, the larger the value of $\tau_{cw}$ and the longer the duration of $\tau_{cw}>\tau_{ce}$, the greater the erosion. For the second case, the lower the value of $\tau_{cw}$ and the longer the duration of $\tau_{cw}<\tau_{cd}$, the greater the deposition. As shown in Fig. 2d and Table 2, at site Mu, $\tau_{cw}$ is larger than $\tau_{ce}$ (0.103 N/m²) for most of the submergence time, suggesting that the mudflat experienced erosion during most of the submerged periods. Because the size of the near-bed suspended particles of the present study ranged from >63 µm (very fine sand) at site Mu or >32 µm (coarse silt) at site Ma to <4 µm at both sites (Fig. 5), we believe that $\tau_{cd}$ differed between grains, ranging from 0.01 ($\tau_{cd-min}$ for fine grains) to 0.1 ($\tau_{cd-max}$ for coarse grains) N/m² (see Lumborg, 2005). That is, when $\tau_{cw}<0.1$ N/m², coarse

![Fig. 4](image-url) - Plot of $\tau_{cw}$ (van Rijn model) against $\tau_{ce}$ (Soulsby model). Typical ebb phase means offshore ebb currents and onshore waves are normal in magnitude; typical flood phase means onshore flood currents and offshore waves are normal in magnitude; other cases include slack water at high tide, opposite directions of currents and waves in flood stage and consistent directions of currents and waves in ebb stage, etc.

![Fig. 5](image-url) - Size distribution of suspended sediment at a height of 15 cm above sediment surface in the mudflat (a) and in the salt marsh (b), on September 22–24, 2009, Eastern Chongming Island, Yangtze Estuary. Median: the median grain size.

<table>
<thead>
<tr>
<th>Tides</th>
<th>For $\tau_{cw}$ based on Soulsby (1995) model</th>
<th>For $\tau_{cw}$ based on van Rijn (1993) model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\tau_{cw}&gt;\tau_{ce}$</td>
<td>$\tau_{cw}&lt;0.05$ N/m²</td>
</tr>
<tr>
<td></td>
<td>Duration (%)</td>
<td>N/m²</td>
</tr>
<tr>
<td>Tide 1 (mudflat)</td>
<td>230</td>
<td>73</td>
</tr>
<tr>
<td>Tide 2 (mudflat)</td>
<td>220</td>
<td>81</td>
</tr>
<tr>
<td>Tide 3 (mudflat)</td>
<td>330</td>
<td>94</td>
</tr>
<tr>
<td>Tide 4 (mudflat)</td>
<td>80</td>
<td>33</td>
</tr>
<tr>
<td>Tide 5 (mudflat)</td>
<td>180</td>
<td>53</td>
</tr>
<tr>
<td>Tide 1 (marsh)</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 3
Changes in bed level based on double-rods method.

<table>
<thead>
<tr>
<th>Date (time)</th>
<th>Height of rods (mm)*</th>
<th>Average change in bed level per day (mm)</th>
<th>Number of tides</th>
<th>Average change in bed level per tide/total changes during the 6 tides (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mudflat (site Mu)</td>
<td>Salt marsh (site Ma)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Point 1</td>
<td>Point 2</td>
<td>Point 3</td>
<td>Average</td>
</tr>
<tr>
<td>Sep. 22 (10:00)</td>
<td>360</td>
<td>370</td>
<td>380</td>
<td>370</td>
</tr>
<tr>
<td>Sep. 23 (10:00)</td>
<td>347</td>
<td>378</td>
<td>413</td>
<td>379</td>
</tr>
<tr>
<td>Sep. 24 (11:00)</td>
<td>373</td>
<td>384</td>
<td>394</td>
<td>384</td>
</tr>
<tr>
<td>Sep. 25 (11:00)</td>
<td>372</td>
<td>389</td>
<td>409</td>
<td>390</td>
</tr>
</tbody>
</table>

* At each point, a thin aluminium bar was put onto the two rods, and the vertical distance between the sediment surface and the bar was surveyed. ‘−’ means erosion.

suspension, the lower the \( \tau_{cw} \) value, the more that fine grains are also deposited. When \( \tau_{cw} \) decreased to less than 0.05 \( (\tau_{cd-ave}) \) N/m\(^2\), most of the grains larger than the median grain size would have been deposited. Because the \( \tau_{ce} (0.103 \text{ N/m}^2) \) at site Mu was equal to \( \tau_{cd-max} (0.1 \text{ N/m}^2) \), we expect that there is always an exchange of sediment between the water column and the seabed. At site Ma, \( \tau_{cw} \) was not only less than \( \tau_{ce} (0.116 \text{ N/m}^2) \) but also less than \( \tau_{cd-max} (0.1 \text{ N/m}^2) \) (Fig. 2d), suggesting that deposition of more than the coarsest sediment fractions occurred for all the submergence time and that there was no phase of erosion.

5.3. Comparing measured erosion and deposition with values of \( \tau_{cw} \), \( \tau_{ce} \) and \( \tau_{cd} \)

Although it is scientifically relevant to relate intertidal bed-level changes to the temporal changes in the values of \( \tau_{cw} \), \( \tau_{ce} \) and \( \tau_{cd} \) that determine the phases of inferred erosion and deposition, the application of this approach has generally been unsatisfactory or unsuccessful (e.g., Christie et al., 1999). One of the reasons for this lack of success is the difficulty in obtaining accurate bed-level changes at a high temporal resolution, due to the unclear interface between the water column and sediment bottom. This is especially the case for highly turbid conditions in which fluid mud may be present. Hence, the comparison of measured bed-level changes with stress (\( \tau_{cw} \), \( \tau_{ce} \), and \( \tau_{cd} \)) inferred erosion and deposition at the temporal scale of tidal cycles is an important method in examining short-term sediment dynamic processes. For example, in the Skeffling mudflats of the Humber Estuary (UK), a net deposition of 2 mm was found during a calm tidal cycle (wind speed 2–6 m/s) when \( \tau_{cw} \) ranged from 0 to 0.7 N/m\(^2\) and the duration of \( \tau_{cw} > \tau_{ce} \) dominated the period of tidal submergence, and a net erosion of 60 mm was observed during a stormy tidal cycle (wind speed 10–25 m/s) when \( \tau_{cw} \) increased to 2.4 N/m\(^2\) and the duration of \( \tau_{cw} > \tau_{ce} \) dominated the period of tidal submergence (Christie et al., 1999).

In the present study (wind speed ~8 m/s; Appendix Fig. 1), the mudflat site Mu experienced on average 3.3 mm of net erosion per tide during the observation period (Table 3), when \( \tau_{cw} \) ranged from 0 to 1.1 N/m\(^2\) (van Rijn model); 0 to 0.91 N/m\(^2\) for the Soulsby model (Table 1) and the duration of \( \tau_{cw} > \tau_{ce} \) was on average 73% (van Rijn model); 67% for the Soulsby model) of the period of tidal submergence (Table 2). Therefore, the present case is intermediate between the calm and stormy examples from the Skeffling mudflats (Christie et al., 1999). At the salt marsh site Ma, we observed an average net deposition of 3 mm per tide. As with the Skeffling mudflats (Christie et al., 1999), the net erosion/deposition determined in the present study, predicted by comparing \( \tau_{cw} \) with critical shear stresses, was in agreement with the observed bed-level changes. Although this comparison is qualitative in that we lacked the data needed to calculate sediment flux and erosion/deposition rates, the results support the contention that \( \tau_{cw} \) in comparison with the critical shear stresses of the sediment is a useful approach in examining intertidal sediment dynamics.

It is unreasonable to expect that the erosion/deposition rates at sites Mu and Ma during the observation period are typical of the long-term geomorphologic evolution of the region, as they correspond to an annual erosion of 2.3 m at site Mu and an annual deposition of 2.1 m at site Ma, which is unrealistic (Yang et al., 2011). In fact, Yang et al. (2003, 2008) reported frequent alternations of erosion and deposition on the tidal flats of the Yangtze Delta, and the deposition rate in the salt marsh is highly variable over the year, being higher during spring tides and stormy weather than during neap tides and calm weather (Yang et al., 2003, 2008). Our field campaign to estimate shear stresses was undertaken during the transition period from spring to neap tides, but with onshore wind speeds that were two times higher than the annual average (Appendix Fig. 1; G3ill, 1996). Hence, the wave component in the hydrodynamics during the observation period was stronger than the annual average, indicating that more sediment was transported into the salt marsh during this period than is typically observed.

5.4. Applicability of the Soulsby and van Rijn models in predicting \( \tau_{cw} \) in exposed tidal wetlands

In exposed tidal wetlands, both waves and currents play an important role in sediment dynamics, indicating the necessity to consider the combined wave–current action. The values of \( \tau_{cw} \) derived from the Soulsby and van Rijn models are consistent with the combined current–wave action in the present study area, because: (1) the net erosion/deposition trends obtained by comparing \( \tau_{cw} \) and \( \tau_{ce} \) of both models differ greatly in cases where \( \tau_{cw} \) and \( \tau_{ce} \) are in agreement with the results of bed-level measurements; (2) for both models the average \( \tau_{cw} \) is significantly larger than \( \tau_{ce} \) or \( \tau_{cd} \); and (3) \( \tau_{cw} \) and the durations of \( \tau_{cw} > \tau_{ce} \) and \( \tau_{cw} < \tau_{cd} \) are largely similar between the models. For example, during the five tides, \( \tau_{cw} \) at the mudflat site (n=153) averaged 0.268 N/m\(^2\) (Soulsby model) or 0.269 N/m\(^2\) (van Rijn model) (Table 1), and the average duration percentages of \( \tau_{cw} > \tau_{ce} \) and \( \tau_{cw} < \tau_{cd} \) are 65% and 11% (Soulsby model) or 72% and 10% (van Rijn model) (Table 2), respectively.

The value of \( \tau_{cw} \) shows a large difference in the case that \( \tau_{cw} \) obtained by both models differ greatly in cases when \( \tau_{cw} \) is significantly higher than \( \tau_{ce} \) (Fig. 2c–d). For example, at site Mu at 14:30 on September 22 (ebb stage during Tide 1), \( \tau_{cw} = 0.30, \tau_{ce} = 0.041, \tau_{cw} \) (van Rijn model) = 0.28, and \( \tau_{cw} \) (Soulsby model) = 0.082 N/m\(^2\) (Fig. 2c–d). That is, \( \tau_{cw} \) (van Rijn model) was more than three times higher than \( \tau_{cw} \) (Soulsby model). Although we cannot assess which model is more accurate, our results indicate that the van Rijn model is more accurate in describing the wave dynamics than the Soulsby model (Fig. 2c–d). From a practical viewpoint, the Soulsby model is easier to use because of the smaller number of input parameters. The relative merits and accuracies of the two models require further studies.

6. Summary and conclusions

We aimed to enhance the current understanding of sediment motion and erosion/accretion in a macrotidal, highly wave-exposed muddy intertidal mudflat–salt marsh system, by comparing the sediment dynamics predicted by the van Rijn (1993) and Soulsby (1995) models.
models against measurements made in the Yangtze Delta. Observations at the mudflat site Mu (340 m seaward from the marsh edge and 0.2 m above mean sea level) during five consecutive tidal cycles from spring to neap tides showed that the water depth ranged from 0 to 1.7 m, the significant wave height from ~0 to 0.76 m (onshore wind speed of ~8 m/s, twice the multi-year average), the near-bed current velocity from ~0 to 0.73 m/s, the bed shear stress due to waves ($\tau_w$) from ~0 to 0.49 N/m$^2$ (average, 0.20 N/m$^2$), the bed shear stress due to currents ($\tau_c$) from ~0 to 0.87 N/m$^2$ (average, 0.21 N/m$^2$), and the bed shear stress due to combined wave–currents ($\tau_{cw}$) from ~0 to 1.11 N/m$^2$ (average, 0.27 N/m$^2$). These data show that at a macrotidal, highly wave-exposed muddy intertidal mudflat–salt marsh system such as the Yangtze Delta, waves and currents may be equally important in terms of sediment dynamics on the mudflats. $\tau_{cw}$ was typically higher in the flood stage than in the ebb stage, suggesting landward sediment transport. At site Mu, the median grain size and water content of the bottom sediment were measured to be 23 $\mu$m and 46%, respectively, which gives a critical shear stress for erosion ($\tau_{ce}$) of 0.103 N/m$^2$. For each tidal cycle, the duration of $\tau_{cw} > \tau_{ce}$ was longer than the duration of $\tau_{cw} < \tau_{cd}$ (critical shear stress for the deposition of suspended sediment). On average, the duration of $\tau_{cw} > \tau_{ce}$ was more than 70% of the period of submergence, whereas the duration of $\tau_{cw} < \tau_{cd}$ was less than 20% of this period. These findings suggest, at least qualitatively, that intertidal sediment dynamics were dominated by erosion. This inference is supported by measurements of bed-level change, which showed an average net erosion of 3.3 mm per tide.

In comparison, observations at the S. mariqueter salt marsh site Ma (250 m landward from the marsh edge and 0.7 m above mean sea level) showed subdued hydrodynamics and a slightly higher $\tau_{ce}$ (0.116 N/m$^2$). At site Ma, $\tau_{cw}$ ranged from ~0 to 0.14 N/m$^2$ (average, 0.06 N/m$^2$), indicating sediment deposition during tidal submergence. In agreement with this inference, measurements of bed-level change at the site gave an average deposition rate of 3 mm per tide. The great difference in sediment dynamics between mudflat and salt marsh is attributed mainly to the presence of vegetation, although elevation and landward distance may also be relevant factors.

The Soulsby (1995) and van Rijn (1993) models generally gave similar average $\tau_{cw}$ values and durations of $\tau_{cw} > \tau_{ce}$ and $\tau_{cw} < \tau_{cd}$. However, in the case that $\tau_w$ is significantly higher than $\tau_c$, the two models yield strongly different values of $\tau_{cw}$. We conclude that it is necessary to employ $\tau_{cw}$ in place of $\tau_c$ and $\tau_w$ in studies of sediment dynamics in exposed intertidal wetlands, and that further work is needed to assess the performances of the Soulsby and van Rijn models in such cases.

**Acknowledgments**

This study was funded by the Natural Science Foundation of China (41071014) and the Ministry of Science and Technology of China (2010CB951202, 2008DBB90240) and the Committee of Science and Technology of Shanghai. We acknowledge the THESEUS project for supporting SKLEC and NIOO for research on the use of salt marshes as a coastal defense. We thank S. te Slaa, Y. Wang, C. S. Wu, C. Li, and J. Zhao for their assistance in the field, A. J. Wang for providing useful materials, and P. Li for providing wind datasets from weather and tide gauging stations. Special thanks are extended to B. C. Van Prooijen and D. S. van Maren for their comments and suggestions, which helped to improve the manuscript. Two anonymous reviewers are thanked for their helpful comments and suggestions. We also thank Prof. Andrew Plater, Editor-in-Chief, for granting us the opportunity to submit a revised manuscript.

**Appendix A**

**Appendix Table 1**

Statistics of near-bed current velocity, wave height, wave period and the ratio of wave height to water depth during submergence of five tidal cycles.

<table>
<thead>
<tr>
<th>Tides</th>
<th>Near-bed current velocity (m/s)</th>
<th>Wave height (m)</th>
<th>Wave period (s)</th>
<th>Ratio of wave height to water depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max</td>
<td>Min</td>
<td>Mean</td>
<td>Std</td>
</tr>
<tr>
<td>Tide 1 (mudflat)</td>
<td>0.50</td>
<td>0.04</td>
<td>0.30</td>
<td>0.15</td>
</tr>
<tr>
<td>Tide 2 (mudflat)</td>
<td>0.48</td>
<td>0.05</td>
<td>0.23</td>
<td>0.1</td>
</tr>
<tr>
<td>Tide 3 (mudflat)</td>
<td>0.73</td>
<td>0.08</td>
<td>0.40</td>
<td>0.20</td>
</tr>
<tr>
<td>Tide 4 (mudflat)</td>
<td>0.30</td>
<td>0.03</td>
<td>0.14</td>
<td>0.07</td>
</tr>
<tr>
<td>Tide 5 (mudflat)</td>
<td>0.53</td>
<td>0.09</td>
<td>0.30</td>
<td>0.15</td>
</tr>
<tr>
<td>Tide 1 (marsh)</td>
<td>0.15</td>
<td>0.03</td>
<td>0.10</td>
<td>0.03</td>
</tr>
</tbody>
</table>

**Appendix Fig. 1.** Hourly wind speed and direction over the period of field measurement at the Sheshan gauging station.