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Intra-tidal sedimentary processes associated with combined wave–current action on an exposed, erosional mudflat, southeastern Yangtze River Delta, China

Qin Zhu [a,b], Shilun Yang [a,*], Yanxia Ma [c]

[a] State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China
[b] Department of Hydraulic Engineering, Faculty Civil Engineering and Geosciences, Delft University of Technology, 2600 GA Delft, The Netherlands
[c] Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA

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ABSTRACT

Numerous deltaic coasts in the world are eroding in response to a decline in sediment supply as a consequence of river damming. Near-bed sediment dynamics are key mechanisms of erosion and deposition. To understand the sediment dynamics of an exposed, erosional mudflat on the delta front of the Yangtze River, China, we measured wave parameters, near-bed current profiles (for 30 layers located up to 50 cm above the seabed), suspended sediment concentration (SSC) profiles (at 6, 15, 35, and 75 cm above the seabed), bed-level changes, and sediment properties, at a low flat site. We found that bed shear stresses induced by waves can be important to sediment dynamics on the mudflat, even in periods of offshore winds. SSC-measurements close to the seabed revealed the presence of a highly dynamic fluid mud layer. At the high tides, SSC at the near-bed 6-cm layer increased to >8 kg/m^3, as a result of sediment deposition from the overlying water column. During the ebb tides, however, an increase in hydrodynamic variations resulted in resuspension, and the near-bed SSC was reduced to <2 kg/m^3. The bed-level changes predicted on the basis of bed shear stresses due to combined wave–current action (τ_{cw}), critical bed shear stress for erosion (τ_{cr}), and SSC were in good agreement with the results measured using a Pulse-Coherent Acoustic Doppler Profiler (PCADP) and a triple-rod manual method. In contrast, the calculated bed-level changes on the basis of bed shear stresses induced by only currents or waves instead of τ_{cw} were far from the observed results. This study therefore highlights the importance of employing combined wave–current action and measurements close to the sediment surface in coastal sediment dynamics.

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1. Introduction

Sedimentary processes in coastal areas have implications for studies in geomorphology, engineering, ecology, and biogeochemistry (Hooke et al., 1996; Riggs et al., 1998; Schoellhamer et al., 2007; Montserrat et al., 2011). Coastlines are one of the most dynamic boundaries on the Earth, and include extensive reservoirs of unconsolidated sediments. Tidal flats are an important sedimentary coastal environment (Gao, 2009; Friedrichs, 2011), and tidal flat processes are closely connected to patterns of human activity in many regions of the world. Progradational tidal flats provide groundwork and space for the expansion of salt marshes, and reclamation of upper salt marshes is frequently undertaken to increase the amount of land available for human activities (Wang et al., 2012). For example, the land area of Chongming Island in the Yangtze Estuary (Fig. 1) has doubled since the 1950s on account of reclamation of salt marshes (Yang et al., 2005b). However, under the impact of river damming and sea level rise, many mudflats in delta fronts are changing from progradational to recessional (e.g., Chu et al., 2006; Blum and Roberts, 2009; Yang et al., 2011). Knowledge of sedimentary processes is fundamental to an understanding of the mechanisms of morphological evolution in these areas, and for predicting the future evolutional trends of mudflat development or decay.

In addition to their value as potential land areas, and more importantly in many cases, tidal flats provide ecological and environmental functions, such as in providing habitat and nursery grounds for various species of wildlife, and as natural sewage purification systems (Costanza et al., 1997; Goodwin et al., 2001; Barbier et al., 2008). Sedimentary processes (e.g., erosion, transport, deposition, and resuspension) are important factors influencing these ecological and environmental functions.

Although numerous studies have been conducted on sedimentary processes and their associated hydrodynamics in intertidal zones, most of them have focused on either: (1) intra-tidal and neap–spring variations in current velocity and SSC (e.g., Pejrup, 1988; Collins et al., 1998; Le Hir et al., 2000; Andersen and Pejrup, 2001; Quaresma et al., 2007), or (2) bed-level changes based on surveys undertaken after ebb and when the tidal flat is exposed to air (e.g., Kirby et al., 1992; de Brouwer et al., 2000; Andersen and Pejrup, 2001; Yang et al., 2003;

* Corresponding author.
E-mail address: slyang@sklec.ecnu.edu.cn (S. Yang).

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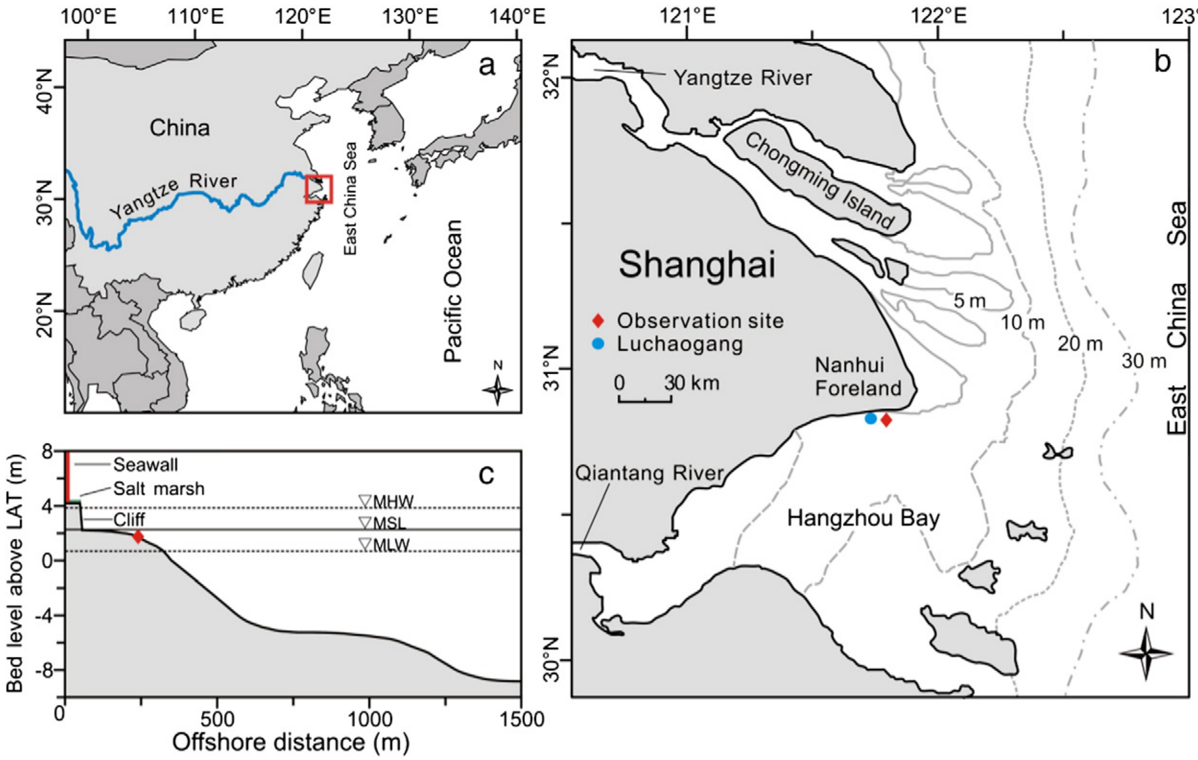

Fig. 1. Sketch maps of the study area. (a) Map of the Yangtze River and East China Sea. (b) Map of the Yangtze River Delta (location is shown by the red square in (a)) showing the study area and observation site (red diamond). (c) Cross-shore bathymetric profile on which the observation site stands. The elevation datum is based on the lowest astronomic tide (LAT).

Fan et al., 2006). These between-tide surveys are useful for measuring the net bed-level changes associated with a succession of tidal cycles, but they are unable to record the details of erosion and deposition within tidal cycles. The magnitudes of erosion and deposition within a tidal cycle may be significantly greater than the net change between tidal cycles. Relatively little is known about sediment exchange processes between the water column and the seabed under combined wave–current action (Andersen et al., 2007; Shi et al., 2012). In particular, it is not clearly known whether fluid mud, or a thin near-bed layer of extremely high SSC (usually >10 kg/m^3) (Kineke et al., 1996; Ogston et al., 2000), can be formed on tidal flats under calm weathers. There is a great need to integrate high-resolution data on currents, waves, SSC, and bed-level changes during tidal inundation to more fully understand the sedimentary processes occurring on tidal flats.

In the present study, our goal was to investigate sedimentary processes on an erosional intertidal mudflat based on an integrated observation of currents, waves, SSC, sedimentary properties, and bed-level changes. Our specific objectives were to: (1) examine the importance of waves in sediment dynamics on the mudflat under moderate offshore winds; (2) document the formation and disappearing of near-bed fluid mud associated with combined wave–current action shear stress (τ_{cw}); (3) compare τ_{cw} values with critical shear stress values for erosion (τ_{cr}); and (4) relate the bed-level changes with τ_{cw}, τ_{cr}, SSC and sedimentary properties. This work is intended to deepen our understanding of the processes of sediment dynamics on tidal flats.

2. Study area

In situ observations were conducted on an exposed tidal flat on the Nanhui Foreland, located on the delta front of the Yangtze River Delta (Fig. 1). The Nanhui Foreland is located in a transition zone between Hangzhou Bay and the Yangtze Estuary (Fig. 1b). Because the sediment discharge into Hangzhou Bay from the Qiantang River is only 1% of that from the Yangtze River (Chen, 2004), the coastal evolution of the Nanhui Foreland is governed mainly by the Yangtze River. Over the past 2000 years, the Nanhui coast has prograded rapidly, at a rate >10 m/yr (Yang et al., 2001). However, in recent years, especially since the closure of the Three Gorges Dam (TGD) in 2003, sediment discharge from the Yangtze River has been drastically reduced, which has resulted in long-term erosion along the Nanhui coast (Yu and Lou, 2004; Yang et al., 2006).

The tides in the Yangtze Estuary and Hangzhou Bay are mixed semidiurnal, with the tidal range at Luchaogang, a gauging station close to our observation site (Fig. 1b), being 3.2 m on average and greater than 4.0 m during spring tides. The monsoon-driven winds are southeast in summer and northwest in winter. The multi-year averaged wind speed is 4 m/s on land areas of Nanhui (GSCI, 1988) and 7 m/s on the open sea (at the 5-m bathymetric contour off the Nanhui Foreland) (Zhu et al., 1988). The maximum wind speed recorded on the Yangtze delta is 43 m/s (Zhu et al., 1988). The Nanhui coast is wave exposed. The mean and maximum wave heights recorded at the 5-m bathymetric contour off the Nanhui Foreland are 1.0 m and 6.2 m, respectively (GSCI, 1988). Seasonal changes in bed level of the tidal flat at Luchaogang are up to 40 cm. The bed sediment of the tidal flat is generally silt (median grain size <63 μm), although very fine sand (63–125 μm) is occasionally found during seasons of strong erosion (Yang et al., 2008). The surface SSC at Luchaogang ranges from <0.1 kg/m^3 to >2 kg/m^3. The annual averaged surface SSC at Luchaogang has decreased by 25% since the closure of the TGD (Li et al., 2012).

The level of the presently studied mudflat (Fig. 1b) is below mean sea level (MSL). The presence of a 2-m-high cliff between the mudflat and an abandoned salt marsh (Fig. 1c) indicates that the upper part of the mudflat is eroding. The mudflat is now less than 300 m wide. The cross-shore profile of the mudflat is convex upward, with a mean gradient of ~7‰. The observation site is 200 m seaward from the armored cliff, and is 0.7 m below MSL and 0.9 m above mean

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