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Investigation of flocculation dynamics under changing hydrodynamic forcing on an intertidal mudflat

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ABSTRACT

In situ floc size and turbulent shear stress were measured together with suspended sediment concentration to investigate the floc properties under changing hydrodynamic forcing over the intertidal mudflat. A tripod system was established in the field for a period of approximately one month, including ~6 days of stormy conditions in the middle of the investigation period. Mean floc size exhibited strong temporal variations within a tidal cycle, and inverse relationship was found between mean floc size and shear stress. Suspended sediment concentration (SSC) can modulate the flocculation dynamics when shear stress decreases down to enhancing flocculation. Asymmetrical behaviors of floc sizes between flood and ebb phases were identified, with overall larger floc sizes in flood than in ebb tide under the same shear stresses. Floc structure showed different properties under calm and stormy conditions, and the variable fractal dimension and variable primary particle size were more convincing in simulating the variation of floc effective density with mean floc size during the storm period, which was inferred to be related to the resuspension of bed sediment as well as organic matter. A total of 110 mm bed erosion was measured during the storm, and erosion events occurred only around low water, due to the high current-wave combined bed shear stress and off-shore current. After the storm, ~40% of the erosion recovered within one week, and the fast settling of large flocs around high water plays significant role in the deposition process, leading to ~60% of the recovery.

1. Introduction

Intertidal mudflats provide a transition zone and protective barrier between land and estuary, and they have valuable functions in terms of ecosystem development (Dyer, 1998). The overall development of a mudflat depends on the relative balance between hydrodynamics (erosion) and sediment supply (sedimentation). On a short time-scale (i.e. the tidal cycle and spring-neap cycle), hydrodynamics dominated by tidal currents and waves determine the variations of suspended sediment flux and bed level. Sedimentation usually happens during relatively calm conditions due to settling and tidal asymmetry when the sediment supply is large (Christie and Dyer, 1998; Andersen and Pejrup, 2001; Deloffre et al., 2006). Episodic energetic events like storms are important for tidal flat development and can cause significant erosion within just a few tidal cycles (Christie et al., 1999; Andersen and Pejrup, 2001). On a seasonal time-scale, the importance of biological characteristics in modifying the initial erosion of the surface layer on a mudflat has also been found (e.g. Andersen, 2001; Uncles et al., 2003).

The transport of cohesive sediment is more complicated than non-cohesive sediment in particular due to flocculation, which is the result of simultaneously aggregation and floc break up processes (Winterwerp and Van Kesteren, 2004). Flocculation has been widely observed in varying fresh (e.g. river, lake), brackish (e.g. estuary, river deltas), and marine (e.g. open sea) waters (Droppo and Ongley, 1994; Fennessy et al., 1994; Manning and Dyer, 2007; Guo and He, 2011; Fettweis et al., 2014). Controls on flocculation processes are numerous and complex, including a number of physical and biochemical factors such as: the turbulent intensity, suspended sediment concentration (SSC), differential settling of particles, composition of primary particles, salinity, and content of organic matter and polymers, etc. (see e.g. Milligan and Hill, 1998; Manning and Dyer, 1999; Fugate and Friedrichs, 2003; Mietta et al., 2009; Verney et al., 2009; Sahin, 2014, among others).

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The conceptual diagram proposed by Dyer (1989) established that at low concentrations mean floc size first increases with shear stress at low values, followed by a decrease due to floc break up as shear stress increases, and at higher concentrations flocs are larger but more easily to be disrupted by shearing. This conceptual model was confirmed by a number of laboratory experiments and field measurements (e.g. Manning and Dyer, 1999; Kumar et al., 2010; Sahin, 2014). However, Winterwerp (1998) suggested that the long residence time of flocs required to achieve the equilibrium at low shear stress conditions (~ 2–$3\ s^{-1}$) could explain the increase of floc size with shear rate. In the flocculation experiments using kaolinite, Mietta et al. (2009) found that when the shear rate was $< 35\ s^{-1}$, flocs became smaller with shear rate decreased as deposition prevented flocs from reaching the equilibrium. Moreover, in the laboratory experiments of Milligan and Hill (1998) and field survey of Xia et al. (2004) in a microtidal estuary, they found the influence of SSC on flocculation is minor. The inconsistency in these studies may be caused by varying constitutions of flocs and environmental conditions, therefore further studies in different estuarine systems with varied hydrodynamic forcing are required to extend our knowledge of flocculation dynamics.

Investigations on mudflats have shown that sediment deposition is predominantly in the form of flocs and that the fraction of flocs decreases with the increase of bed elevation at tidal scale (e.g. Christiansen et al., 2000; Voulgaris and Meyers, 2004; Hill et al., 2013; Law et al., 2013). The settling velocity of aggregated flocs is likely orders of magnitude larger than the settling of the primary particles. Flocculation therefore leads to an increased settling flux of mud to the bed (Soulsby et al., 2013; Mehta et al., 2014) and is particularly important to the mudflat deposition (Kranck and Milligan, 1992; Manning and Dyer, 2007). Higher turbulence levels tend to resuspend sediment from the bed and disrupt flocs, while as the tidal currents approach high or low water slack, large SSC combined with low turbulent intensities encourage the aggregation of flocs and result in rapid settling (Christie et al., 1999; Milligan et al., 2007). As the effective density of a floc tends to decrease with size due to increasing water content (Fennessy et al., 1994), floc settling velocity is controlled by both floc size and structure. However, variations of floc size as well as structure over a mudflat are still partially known as both hydrodynamic forcing and SSC can be highly variable around the low water environment, especially under episodic events like storms.

Given the many uncertainties as well as partially known aspects of floc dynamics on intertidal flats, a field campaign was set up. This paper is based on the results of in situ observations of floc properties and hydrodynamics on a mudflat covering continuous stormy and calm weather conditions. We aim to further explore the time-variant floc size and structure under different forcing conditions and how these contribute to the deposition of sediment on the mudflat.

2. Methodology

2.1. Site description

Fieldwork was conducted on the Kapellebank tidal flat, located in the lower part of the Westerschelde (Scheldt) Estuary in the Netherlands (Fig. 1a). The Scheldt estuary is a semidiurnal meso- to macro-tidal regime and extends 160 km in length. The mean tidal range at the estuary mouth fluctuates between 4.2 and 3.1 m during spring and neap tides, respectively. It increases up to about 6 m at a distance of 95 km landward, then gradually decreases to about 2.3 m. The mean SSC value in the lower Scheldt estuary (from the mouth to 58 km landward) is about $50\ mg\ l^{-1}$, and the main turbidity maximum zone (TMZ) locates at roughly 60 to 100 km from the mouth, mean SSC in the TMZ can reach $200\ mg\ l^{-1}$ (Chen et al., 2005a). The study site Kapellebank is a semi-enclosed flat at the channel outer-bend (Fig. 1b). It is about 35 km from the mouth, where the mean tidal range is ~ 4.5 m, and this area is classified as well-mixed. Bed sediment on the Kapellebank is predominantly mud with a median grain size $< 50\ \mu m$ (Kuijper et al., 2004). The geometry of the tidal flat has a triangular shape with a length and width of approximately 1.8 and 0.8 km, respectively. The highest elevation of this tidal flat is about 0.6 m above the Normal Amsterdam Peil (NAP, which is approximately mean sea level). Bed level decreases towards the channel with a mild bed slope of about 3‰ (Fig. 1c). The observation site has an elevation of about -1.8 m and is approximately at the interface between intertidal and subtidal flats.

2.2. Field measurements

Field observations were conducted in 2014, between April 28 and May 22. The time-series were interrupted twice, i.e., May 2–3 and May 13–15, when instrument batteries were exchanged. A storm occurred between the 6th and 12th of May with the maximum wind speed reached $18\ m\ s^{-1}$ at the meteorological station Vlissingen, which is on the west side of the Kapellebank (Fig. 1b). Instruments were mounted on a frame constructed with stainless steel pipes and hammered at least 1.5 m into the bed to reduce horizontal and vertical vibrations.

Near-bed 3D current velocities were measured with a 6-MHz downward-looking acoustic Doppler velocimeter (ADV, Nortek Vector) with the sampling volume ($2.65\ cm^3$) at 15 cm above the bed (cmab). ADV collected data at a sampling rate of 8 Hz continuously for 90 s, with a time interval between bursts of 10 min. Bed level variation was also measured by the ADV through recording the vertical distance between the acoustic transmitter and the bed surface with a resolution of 0.1 mm and an accuracy of $\pm$ 1 mm. Turbidity at 15 cmab was measured by an Optical Back-Scatter (OBS) 3+ sensor, which was logged by the ADV on one of its analogue channels. Wave climate at the study site was measured by a wave logger (OSSI-010-003C, Ocean Sensor Systems), which collected 4096 data points in 20 min bursts at a sampling rate of 10 Hz.

In situ floc size distributions were measured by a laser in situ scattering and transmissometry (LISST-100X, type C) instrument with the particle size spectra range between 2.5 and 500 μm. The instrument emits laser light through a sample volume of water, then it records the energy of scattered laser and inverts it into particle size distributions based on volume concentrations at 32 logarithmically spaced ring detectors, and each detector corresponds to one size range (Agrawal and Pottsmith, 2000). Laboratory and field evaluations by Gartner et al. (2001) demonstrated that the LISST is capable of determining particle size to within $\sim 10\%$ with increasing error as particle size increases. Numerous articles have confirmed that LISST worked reasonably well over a range of environmental conditions (e.g. Mikkelsen and Pejrup, 2001; Guo and He, 2011; Safak et al., 2013; Ramírez -Mendoza et al., 2016). The work of Chen et al. (2005b) on a mud tidal flat ~ 30 km downstream from our study site with a camera showed that the largest floc size was 290 ± 170 μm, indicating that the major portion of flocs in this area can be detected by the LISST-100C. The LISST was placed at 15 cmab with a sampling period of 3 min, and a 50% path reduction module was deployed to increase its sensitivity in turbid waters. For each sample period, 10 volume concentration distributions were collected over 30 s, and the averaged result was used to reduce short-time variations (Mikkelsen and Pejrup, 2001).

2.3. Data processing

2.3.1. Hydrodynamics

Commonly there are four methods to estimate shear stress: (1) Log Profile (LP) method, (2) Reynolds stress technique, (3) Turbulent Kinetic Energy (TKE) approach, and (4) energy dissipation measurement. The TKE approach was concluded as the most consistent one (Kim et al., 2000), and it best suited to this investigation with the presence of waves because the instantaneous velocity measurements from the ADV could provide both turbulent and wave characteristics