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Sediment transport and fluid mud layer formation in the macro-tidal Chikugo river estuary during a fortnightly tidal cycle

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ABSTRACT

The erosion and deposition dynamics of fine sediment in a highly turbid estuarine channel were successfully surveyed during the period from August 29 to September 12, 2009 using an echo sounder in combination with a high-resolution acoustic Doppler current profiler. Field measurements were conducted focusing on the tide driven dynamics of suspended sediment concentration (SSC), and fluid mud at the upstream of the macrotidal Chikugo river estuary during semidiurnal and fortnightly tidal cycles. Morphological evolution was observed especially during the spring tide over a period of two weeks. The elevation of the channel bed was stable during neap tide, but it underwent fluctuations when the spring tide occurred owing to the increase in the velocity and shear stress. Two days of time lag were observed between the maximum SSC and peak tidal flow, which resulted in the asymmetry between neap-to-spring and spring-to-neap transitions. During the spring tide, a hysteresis loop was observed between shear stress and SSC, and its direction was different during flood and ebb tides. Although both fine sediments and flocs were dominant during flood tides, only fine sediments were noticed during ebb tides. Hence, the net elevation change in the bed was positive, and sedimentation took place during the semilunar tidal cycle. Finally, a bed of consolidated mud was deposited on the initial bed, and the height of the channel bed increased by 0.9 m during the two-week period. The observed hysteretic effect between shear stress and SSC during the spring tides, and the asymmetrical neap-spring-neap tidal cycle influenced the near-bed sediment dynamics of the channel, and led to the formation of a fluid mud layer at the bottom of the river.

1. Introduction

Accumulation of cohesive sediments is a common feature encountered in river mouth estuaries. This process has a significant influence on the physical, chemical, and biological characteristics of an estuary. The suspended sediment is deposited in the vicinity of ports, harbors, and navigation channels, thereby reducing the navigation depth and flood-carrying capacity (Wolanski et al., 1992; Petersen et al., 2002; Franz et al., 2014). To prevent flooding of cities and to preserve the integrity of the navigation channel, estuarine channels were dredged and widened. The organic-rich cohesive sediments absorb all types of nutrients or minerals from water, either organic or inorganic, and circulate them in the aquatic environment (Hakanson, 1984; Liang et al., 2013). Therefore, it is important to understand the morphological changes for solving managerial problems, such as dredging, river channel maintenance, and its impact on the estuarine ecosystem.

A specific region, known as the estuarine turbidity maximum (ETM) zone, is formed owing to the accumulation of these sediments, especially at the interface between freshwater and saltwater (Uncles, 2002; Mitchell et al., 2016). The location and magnitude of the ETM depend on the spring-neap transitions and the suspended sediment concentration (SSC) from the river and the tidal flat (Dyer, 1986; Azhikodan et al., 2014). ETM zone is characterized by the presence of fluid mud layers (Mikhailova and Isupova, 2006; Becker et al., 2013).

Fluid mud is composed of concentrated cohesive sediments (a few grams to several hundreds of grams per liter) in a weakly consolidated state located close to the bed in the middle of the estuary (Mcanally et al., 2007). Formation and entrainment of fluid mud layer has occurred in many estuaries (Sottolichio et al., 2011; Becker et al., 2013). Fluid mud transport processes can be

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described as continuous cycle of erosion, resuspension, transport, settling, consolidation, deposition, erosion, and so on, in highly turbid estuaries (Eisma et al., 1980; Grabemann et al., 1997; Wan et al., 2014).

Previous studies on erosion properties discussed two features. The first is the critical erosion threshold. Houwing (1999) determined the erodibility of cohesive sediment beds on intertidal mudflats using an in-situ erosion flume. Biological components have been shown to influence sediment erodibility. Extracellular polymeric substances (EPS) secreted from microphytobenthos and phytoplankton form a protective film on the surficial sediment, bind particles, and stabilize sediments (Taylor and Paterson, 1998; Uncles et al., 2003; Le Hir et al., 2007). The second is the large-scale scour that causes river bed degradation. The timing and magnitude of tidal bank erosion events can be monitored using a novel system called a photoelectronic erosion pin (PEEP) system with two thermistors (Lawler, 2005). Yokoyama et al. (2009) reported that bed scours in an estuarine channel reached 0.7 m during a storm using vertically connected thermometers, and he discussed the relationship between the erosion rate and the shear stress at the bottom of the channel.

In contrast to the number of studies on erosion properties, few field investigations have been conducted on sedimentation properties. Deloffre et al. (2007) and Marion et al. (2009) used an ultrasonic altimeter to measure the elevation change and sedimentation rate on intertidal mudflats and salt marshes. These studies underline the complex responses of intertidal mudflats to hydrodynamics (tidal currents and waves) and sediment supply conditions, ranging from semidiurnal to annual scales. Tolhurst et al. (2009) explained the importance of field studies in understanding the erosion process of cohesive sediments since they are complex in nature.

There are only few studies that dealt with the near-bed fluid mud dynamics in estuarine channels especially using the high-resolution devices (<0.1 m). Shi (2010) measured the near-bed SSC and sediment transport processes based on acoustic observations (vertical resolution of 0.1 m) in the turbid Changjiang river estuary. Schrottke et al. (2006) and Becker et al. (2013) surveyed the fluid mud in the Weser estuary turbidity zone using high-resolution side-scan sonar, and a parametric sub-bottom profiler. This was one of the most accurate among the cited studies with a vertical resolution of 0.06 m. However, the discussion on the process of channel bed formation was inadequate due to the lack of continuous data over a two-week period. The continuous data acquisition for such a long duration is difficult owing to the prevalence of the strong tidal currents.

Detailed and continuous field surveys using high spatio-temporal resolution instruments over two-week periods are needed for the better understanding of the fluid mud dynamics near the river bed. In this study, we used an echo sounder in combination with a high-resolution acoustic doppler current profiler (ADCP) to analyze the erosion and deposition dynamic processes. We have attempted to describe natural shoaling owing to the deposition of suspended sediments and the evolution of a fluid mud layer during a fortnightly tidal cycle.

2. Methods

2.1. Study area

The Chikugo river is located on the South Western island of Japan (Fig. 1) and drains a watershed of 2860 km^2 to the Ariake Sea. Freshwater flows into the Ariake Sea through the estuary. The mean freshwater inflow into the estuary is 54 m^3 s^{-1} during the dry season, and it exceeds 2800 m^3 s^{-1} during the rainy season (Azhikodan et al., 2014; Azhikodan and Yokoyama, 2014). The annual precipitation in the watershed is 2100 mm, reaching a maximum of 3000 mm from the mountainous areas. The Chikugo river estuary is one of the most productive aquatic systems in Japan supporting a large number of semi-endemic species (Suzuki et al., 2009).

The estuarine channel extends 23 km upstream from the river mouth. In the lower 8 km, the river bed sediments consist of sand. In contrast, the channel is floored by silt, and clay in its upper reaches, where the mud fraction can reach 98% of the total sediment (Azhikodan and Yokoyama, 2016). The bottom mud of the estuarine channel is flushed away to a depth of 1–2 m, and a layer of sand appears during storm runoffs every July (Yokoyama et al., 2009). The estuarine channel at 14 km landward from the river mouth is approximately 250 m wide, and has maximum and minimum depths of 8 and 2.5 m at high and low tides, respectively (Fig. 2b). The measurement cross-section is located in a curved channel with a radius of curvature of approximately 1.5 km.

Previous studies showed that the estuary experiences semidiurnal tidal amplitudes of 1.5 m at neap tide and 5 m at spring tide. The large tidal range causes strong currents at a speed of 1.2 m s^{-1} at the water surface and the SSC exceeds 3000 mg L^{-1}. The tidal discharge in the Chikugo river estuary reached 2000 m^3 s^{-1} during spring tide and 500 m^3 s^{-1} during neap tide, which are by far larger than the mean freshwater discharge (Azhikodan and Yokoyama, 2015). Therefore, the estuary is dominated by tidal conditions during most of the year. Even though the ETM in the Chikugo river estuary generally oscillated between the river mouth (0 km) and upstream (16 km) during a semidiurnal tidal cycle (Azhikodan et al., 2014), there was a well-developed ETM at a location of approximately 14–15 km upstream (Azhikodan and Yokoyama, 2015).

Additionally, few studies have been undertaken to assess the ETM and the ecosystems of the Chikugo river estuary and Ariake Sea (Islam et al., 2006; Islam and Tanaka, 2007; Suzuki et al., 2008, 2009, 2012). Because these studies have largely been focused on fish or zooplankton, both SSC and salinity distributions were measured during high-water at spring tide. According to them, a high concentration of particulate organic matter (POM) was found at the ETM zone that resulted an abundance in biomass of copepods in the ETM. Therefore, the ETM supports fish communities in this area. The main source of POM was the accumulation of detrital phytoplankton in the ETM zone (Azhikodan and Yokoyama, 2016).

2.2. Field measurements

Field measurements were carried out at a location in the upper region of the Chikugo river estuary, 14 km landward from the river mouth. Surveys were conducted over 14 days during the period from August 29 to September 12, 2009. The field measurement methodology comprised a transverse survey of 14 km cross-section, monitoring of the changes in the bed elevation at a fixed station, and physical condition measurements of the water and sediment.

A digital sonar system equipped with a differential global positioning system (D-GPS) (Eagle, Fishstrike-2000C) was mounted onto the side of a fishing boat, and a transect cruise was conducted at a speed of approximately 6 km h^{-1}. The acoustic images below the water surface and the horizontal positions were recorded onto a secure digital (SD) card. The frequency of the acoustic transducer was 200 kHz, and the vertical beam spread was 9°. Further, the elevation of the water surface was monitored at 10 min intervals, and the water surface oriented along the vertical axis was converted into the elevation.

Vertical profiles of salinity and turbidity were measured using another fishing boat at the cross-section of stations A, B, C, D, and E, from the left bank to right bank. A total of five measurement