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Experiment inspired numerical modeling of sediment concentration over sand–silt mixtures

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ABSTRACT

A series of flume experiments has been conducted to investigate sediment transport of sand–silt mixtures in both wave-only and wave-with-current conditions. Two types of sediments collected from a typical silty tidal flat were used: a silt-sized mixture with median grain size of 46 μm, and a very fine sand-sized mixture with median grain size of 88 μm. A high concentration layer (HCL) was observed near the bottom together with ripples under wave-only conditions. Sediment concentrations inside the HCL are quasi-stationary with the bulk Richardson number approaching a constant value. The thickness of the HCL can be scaled with approximately two times the damped wave boundary layer thickness. For the concentration profiles, we find that the vertical profile of the silt concentration appears different from the profile of the sand concentration, since the silt concentration decreases logarithmically within HCL, while homogeneously distributes outside the HCL. Finally, the reference concentration formulation of van Rijn (2007b) was recalibrated for the silt classes and applied in a multi-fraction model to predict the vertical concentration profile for silt and sand classes. The results show a promising agreement with the measurements, for both wave-only and wave-with-current conditions.

1. Introduction

Deposits on tidal flats are generally a mixture of clay, silt and sand. As the bed composition affects the bed forms, sediment transport, morphological changes etc., it is necessary to understand the dynamic behavior of such mixtures in tidal flats. Historically, many studies have been conducted to describe the processes of sediment transport for pure non-cohesive sediments (e.g., Nielsen, 1992; Soulsby, 1997; van Rijn, 1993), and cohesive sediments (see Winterwerp and van Kesteren, 2004 for an overview). However, these existing theories are difficult to apply to describe the behavior of the mixed sediment in the tidal flat area directly. Several experiments have demonstrated that the critical bed shear stress can increase dramatically with the increase of the clay component in the mixture (Jacobs et al., 2011 and Mitchener and Torfs, 1996). In addition to the clay content, van Ledden et al. (2004) and Bartzke et al. (2013) have suggested that the network structure (i.e., packing density) also plays a role on erosion behavior of mixed sediment. Therefore, in order to simultaneously predict the non-cohesive and the cohesive sediments transport in the mixture, the interaction between sand and mud should be considered. Several sediment transport models (Sanford, 2008; van Ledden et al., 2006 and Waeles et al., 2008) were developed to compute the sediment concentration using different sediment fractions. These modeling strategies usually separate the mixture into non-cohesive and cohesive fractions (e.g., sand fraction and mud fraction), and subsequently resolve the sediment transport equations separately. The influence of the cohesive mud fraction is taken into account by the critical mud content, which determines a sediment bed to be cohesive or non-cohesive. Recently, Le Hir et al. (2011) proposed a more complicated modeling frame including consolidation processes due to mud contents.

The above mentioned approaches usually treat the mud content, which mainly consists of the silt and clay fractions, as cohesive. However, the cohesive characteristic of the mud is determined by the content of the clay and the very fine silt (of which the grain size is less than 8 μm) (van Rijn, 2006). The critical clay content is found from 5 to 10%, controlling the cohesion of the mixtures (van Ledden et al., 2004). Thus, these approaches are more applicable for clay-dominated (or cohesive) mud, and therefore it is not yet evident whether the same approach can be applied to silt-dominated mud (Mehta and Lee,

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1994). Although van Ledden et al. (2004) argued that silt-dominated mud is rarely found in natural systems, yet such mixtures are found to be abundant in the tidal flats of China (Wang et al., 2002). For example, along the central Jiangsu coast (eastern China), a large area of silt dominated tidal flats exists sheltered behind the radial sand ridge field (Shi et al., 2012; Wang and Ke, 1997 and Zhang, 2012). The development of the silt-dominated tidal flats along the Jiangsu coast is attributed to the abundant sediment supply from two silt-enriched rivers: the Yangtze River which discharges in the south of this region, and the (Old-) Yellow river, which discharged into the north of this region in the period from 1128 to 1855 (Gao, 2009; for locations of the two rivers, see Section 2).

The mineral compositions of silt consist mainly of quartz and feldspar, which are basically non-cohesive (Lambe and Whitman, 1979). However, the erosion tests suggest that the silt-enriched mixtures exhibit cohesive-like behavior (Roberts et al., 1998), but flocculation has not been observed based on the settling experiments on silt (Slaa et al., 2013, 2015). Thus, the silt (grain size larger than 8 μm and less than 64 μm) may hold the dual-features of both non-cohesive and cohesive sediments. We refer to these features of silt as pseudo-cohesive to differentiate from the non-cohesive and cohesive materials in this study.

The dynamics of the silt-dominated sediment have not yet been well understood. A few studies suggested that the sediment transport processes of the silt-dominated mixtures are different from both sand and cohesive mud (Cao et al., 2003, 2005 and Slaa et al., 2013). The sediment in the silt-enriched area is very sensitive to the hydrodynamic conditions. For example, during stormy weather, sediment concentrations near the bottom increase dramatically, forming a High silt-enriched Concentration Layer (HCL), which has been reproduced by several flume experiments (Lamb and Parsons, 2005 and Zhao, 2003). When the weather becomes more moderate, the high density suspensions deposit rapidly, leading to massive sedimentation in tidal flats or tidal creeks. A typical example is the severe siltation happened in the Huanghua Harbor, China, after a gale (with a maximum wind speed of 31.9 m/s) on October 10–12, 2003 (Kuang et al., 2015; Yang and Hou, 2004). Van Maren (2007), Van Maren et al. (2009) and Slaa et al. (2013) identified that the sedimentation processes play a role in the morphodynamics of the Yellow River because of high silt contents. When the high density suspension deposits, the pore pressure dissipates faster for a silty bed than that for a clayey bed causing the bed in a rapid packing or in a consolidation-like behavior. Li and Cao (2009) compared the deposits of two tidal flats, and found that the wet bulk density of the deposit of a silty tidal flat (Rudong in the Jiangsu coast) is around 1.8 g/l after 24 h, while the wet bulk density of the deposit of a muddy tidal flat (near Tianjin) is only around 1.6 g/l even after a half year. Therefore, sediment of the silt-dominated mixtures yields different transport mechanisms compared with sand and cohesive mud. It is uncertain whether the previous formulations and modeling frameworks, which are mainly for sand and cohesive mud, are suitable for the silt-dominated mixtures.

In order to extend the knowledge of sediment transport in the silt range, a series of flume experiments was carried out. Two types of sediments, with different sand–silt–clay ratios, were collected from the silty tidal flats of the Jiangsu Coast, China. The present experimental study focuses mainly on the suspended sediment transport under various hydrodynamic (i.e., wave and current) conditions. Through the experimental study, we attempt to gain deeper insights into the sediment transport processes (i.e., dynamics of the bed forms; properties of the high concentration layer; the vertical distribution of the suspended sediment concentration) of the silt–sand mixtures on tidal flats. Next, we aim to improve the existing sediment modeling approach for sand–silt mixtures and to validate the improved approach with experimental data. This study is meant to provide the basis for a systematic investigation of the morphological changes of the silty tidal flats, such as the Jiangsu tidal flats.

2. Flume experiment

The experiment was conducted in the wind–wave–current flume in Hohai University, Nanjing, China. The flume has a total length of 80 m, a width of 1 m and a depth of 1.5 m (Fig. 1). The wave generator is located at one end of the flume. Three wave height probes are installed on the wave paddle for the detection of the secondary reflected wave, which can automatically be absorbed by adjusting the placement of the paddle. A gravel beach slope is positioned at the other end of the flume to minimize the reflection of the wave. These functionalities can guarantee the long time wave generation to be stationary during the experiments. In the case of regular wave conditions, preliminary tests showed that the shape of the wave had the same form as the Stokes second-order waves. A glass separator is installed along the central axis of the flume and a set of pumps is positioned at the end of the separator (see plan view in Fig. 1). By means of the pumps and the separator, the bidirectional, adjustable and stable current can be generated and cycled around the separator inside the flume. The reason for adding the separator is to restrict the sediments cycling inside the flume. The sediment consumption is then reduced as the sediments can be easily collected at the end of the experiment.

The in-situ sediment samples were collected from the silty tidal flats near Jianggang, located in the center of the Jiangsu coast (Fig. 2a). The distribution and characteristics of the silt tidal flats/silt-enriched systems will not be introduced in this study, as they are reported in several previous studies (more details in Liu et al., 2011; Slaa et al., 2013; Wang and Ke, 1997; Wang et al., 2002; Wang et al., 2012, etc.). Fieldwork for sediment sampling was carried out in the period of September and November, 2013. The sediment samples were collected from the upper zone (referred to as sediment S1) and the middle zone (referred to as sediment S2) of the tidal flat, respectively. The sediments deposited at the surface layer of the tidal flats with a thickness of approximate 10 cm were sampled. These sediment samples were processed and used as the bed materials for the experiment. A flat sediment bed, with a length of 15 m and a thickness of 0.15 m, was placed at one side of the glass separator. Before each group of experiments, the sediment bed was re-prepared to make sure that the bed composition was the same. The grain size distributions of the two bed samples (i.e., sediments S1 and S2) were measured by a Malvern Mastersize 3000 laser particle size analyzer at the beginning and at the end of the experiments. Fig. 2b shows the averaged sediment composition at the beginning of the experiments. The sediment S1 is a silt-enriched mixture with a median grain size of 46 μm, while the sediment S2 is a very fine sand-enriched mixture with a median size of 88 μm. At the front and at the end of the sediment bed, two concrete ramps were placed to support the sediment bed. Each ramp consisted of a 50 cm long horizontal section with the same elevation as the sediment bed, and a 1:40 side slope as the transition from the flume bottom to the horizontal section and the sediment bed. Next, the flume was slowly filled with water until the desired water depth was reached.

The water surface elevation was measured by three Wave Height Meters (WHMs) at 3 locations along the sediment bed. The current velocity was measured by an Acoustic Doppler Velocimeter (ADV), which was fixed on a mobile beam of a measuring frame (Fig. 1). During the steady state, the instantaneous current velocity was recorded at 7 elevations. Another beam of the measuring frame was attached with three Optical Backscatter Sensors (OBS 3+) to vertically monitor the suspended sediment concentration (SSC) with an interval of 3.5 cm. The lowest vertical position of OBS was set at approximately 1 cm above the flat bed. Preliminary tests have shown that OBS sensors have no disturbing effect on the local bed forms. The (quasi-) steady state (when the sediment concentration is basically unchanged) is assumed to be present when the OBS-signals show a (quasi-) steady behavior. Fig. 3 shows an example of the OBS outputs in a preliminary test of sediment S1 at three different elevations under wave-only conditions. Time-series OBS outputs suggest that the sensors at lower