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Modelling and analysis on high sediment concentration layer of fine sediments under wave-dominated conditions

Liqin Zuo[a,b,d], Dano Roelvink[b,c,d,*], Yongjun Lu[a,**], Hao Wang[b]

[a] State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Nanjing Hydraulic Research Institute, 34 Hujuguan Road, Nanjing, 210024, China
[b] IHE Delft Institute for Water Education, PO Box 3015, 2601, DA, Delft, the Netherlands
[c] Deltares, PO Box 177, 2600, MH, Delft, the Netherlands
[d] Civil Engineering and Geosciences Faculty, Delft University of Technology, PO Box 5048, 2600, GA, Delft, the Netherlands

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ABSTRACT

Experiments and field observations have revealed that when silt and very fine sand are subject to oscillatory wave motion, a high shear flow layer and a high concentration layer (HCL) exist near the bottom. The behavior of the HCL is still under researched. Firstly, an intra-wave process based 1DV model was established for fine sediment transport under the combined action of waves and currents. Some key processes that were included in the model are represented through approaches for different bed forms (rippled bed and 'flat bed'), hindered settling, stratification, reference concentration and critical shear stress. A number of experimental datasets were collected to verify the model, which shows that the model is able to properly simulate the flow and sediment dynamics. Secondly, sensitivity analyses were carried out on some factors which would impact the suspended sediment concentration (SSC) profile of the HCL by the 1DV model, such as bed forms, flow dynamics, stratification effects, mobile bed effects and hindered settling. Results show that bed forms play a significant role in the HCL and determination of the shape of the concentration profile. When a current is imposed, the SSC profiles become smoother; however, sediment concentration in the lower HCL is still dominated by the wave motions. For finer sediment, the stratification effects and the mobile bed effects strongly impact the HCL. In conclusion, this paper provides a tool for the study of the HCL and an evaluation of several impact factors on the HCL.

1. Introduction

On the basis of grain size, sediments can be simply classified as gravel ($d > 2$ mm), sand ($d = 63$ μm–2 mm), silt ($d = 4$–63 μm), and clay ($d < 4$ μm). Non-cohesive sand, cohesive mud sediments and even sand-mud mixtures have been studied extensively (e.g., van Rijn, 1993; Ribberink and Al-Salem, 1995; Winterwerp, 2002; Sanford, 2008; Kranenburg et al., 2013; Groenenboom, 2015). However, the behavior of silt-dominated sediments is relatively poorly understood (van Maren et al., 2009). Silt-dominated coastal areas are widely found in the east Bohai Bay and the Jiangsu coast in China. Recent field observations and flume experiments have shown that silt-dominated sediment has special characteristics, neither typical for non-cohesive sand nor for cohesive mud. Silty sediment is easily re-suspended and forms high concentrations near the bottom. Under strong wave conditions it can be stirred up in large volumes, moved by currents and deposited near infrastructure like harbors, waterways, and intakes. Due to its special behavior, this kind of sediment has drawn much attention from researchers in recent years, such as studies on the hindered settling (Te Slaa et al., 2015), sediment movement (Cao et al., 2009) and reference concentration (Yao et al., 2015).

Silt and very fine sand can be referred to as pseudo-cohesive or semi-cohesive sediment in order to be differentiated from non-cohesive and cohesive materials (Yao et al., 2015). Silt may hold features of both non-cohesive and cohesive sediments, i.e., it is a transitional material from non-cohesive to cohesive sediment. It is natural that there is no clear separation of cohesive and non-cohesive sediments and it is reasonable to have a transition zone between them from a sense of continuity. Silt-enriched mixtures show cohesive-like behavior during erosion tests (Roberts et al., 1998). However, flocculation and consolidation have not been observed in settling experiments (Te Slaa et al., 2013, 2015; Yao et al., 2015). According to laboratory experiments in combination with field work in silt-rich environments (Te Slaa et al., 2013), the transitional behavior in silt-rich sediment occurs at a

* Corresponding author. IHE Delft Institute for Water Education, PO Box 3015, 2601, DA, Delft, the Netherlands.
** Corresponding author.
E-mail addresses: lqzuo@nhri.cn (L. Zuo), d.roelvink@un-ihe.org (D. Roelvink), yjlu@nhri.cn (Y. Lu), l.zuo@un-ihe.org (H. Wang).

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threshold when the clay content is about 10%. Mehta and Lee (1994) suggested that the 10–20 μm size may be considered practically to be the dividing size that differentiates cohesive and cohesionless sediment behavior. Tevens (1991) proposed 16 μm to be the division between sediments that flocculate significantly. Some experiments (e.g., Zhou and Ju, 2007; Li, 2014; Yao et al., 2015) showed that the grain size of 45 μm–110 μm shared similar suspension behavior under wave-current conditions. Thus, this study focuses on coarse silt and very fine sand, which is considered to be the transition zone of non-cohesive and cohesive sediments.

One of the most important characteristics of silt and fine sand is a high sediment concentration layer (HCL) that exists near the bed bottom under wave-dominated conditions. The HCL is neither like the fluid mud layer of clay with flocculation and consolidation process nor similar to the intensive bed load transport layer of coarse sand. Sediment suspension is limited by the high oscillatory motion, and the sediment concentration near the bottom is much higher than that in the upper part. The HCL has been found in laboratory experiments (Dohmen Janssen et al., 2001; Yao et al., 2015) and field observations (Te Slaa et al., 2013). Some literature (Trowbridge and Kineke, 1994; Kineke et al., 1996) defines high concentration at the elevation where the concentration $c = 10\,\mathrm{kg/m^3}$, or $c = 21\,\mathrm{kg/m^3}$ by Winterwerp (1999). Lamb and Parsons (2005) defined the thickness of the high concentrated mud layer as the elevation where the concentration $c = 0.1\, c_{bed}$ (where c_{bed} is arbitrarily set at 1400 g/L). Experiments have shown (Zhou and Ju, 2007; Li, 2014; Yao et al., 2015) that there is a distinct interface between the HCL near the bottom and the clear water in the upper part under wave conditions, as shown in Fig. 1. In this study we define the HCL as the higher concentration layer below where the gradient of sediment concentration changes abruptly in the upper part.

The presence of bed forms, i.e., rippled bed or 'flat bed' (sheet flow), has a large influence on sediment transport (Ribberink and Al Salem, 1994). The eddy viscosity and sediment transport mechanisms are different under different bed forms. For silt and very fine sand, since the bed forms transform easily, the effects of bed forms are more important. Some laboratory experiments have shown that, under gentle conditions, normally $h = 0.3$–0.5 m, $H = 0.1$–0.2 m, the bed forms of silt and very fine sand are rippled beds (Zhou and Ju, 2007; Li, 2014; Yao et al., 2015). Sheet flow is usually present under stronger dynamics. Normally, the criterion of bed forms can be represented by the Shields number or mobility number (Dingler and Inman, 1976; Nielsen, 1992),

$$\psi = \frac{u_{wc}^2}{(s-1)gd_{50}}$$

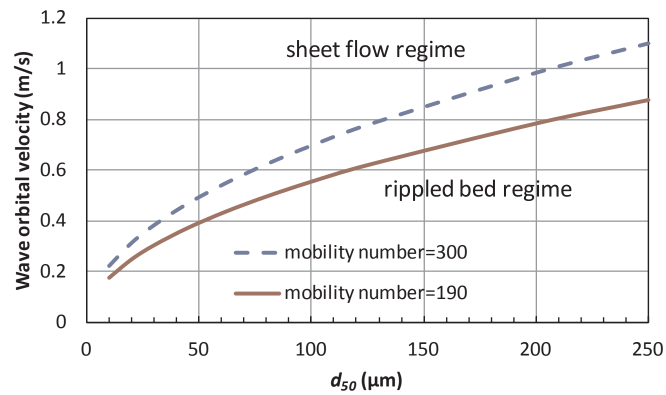

Fig. 2. The criterion conditions of bed forms according to O'Donoghue et al. (2006).

where u_{wc} = the velocity of combined wave-current, $s = 2.65$ = relative density, g = gravity acceleration, and d_{50} = median diameter of sediment grain size. According to O'Donoghue et al. (2006), flat bed (sheet-flow) regime prevails when $\psi > 300$, the ripple regime happens when $\psi < 190$ and a transition regime prevails when $190 < \psi < 300$. Fig. 2 shows the criterion conditions of bed forms according to sediment grain size and wave orbital velocity u_w. It can be seen that, sheet flow only exists in strong dynamics condition for sand (when $u_w > 1.0$ m/s for $d_{50} = 200\,\mu$m), but silt may experience both rippled bed and sheet flow under common conditions (bed type may change when $u_w = 0.30$–0.38 m/s for $d_{50} = 30\,\mu$m). Silt that with smaller grain size than sand is easier to transform from rippled bed to sheet flow. Therefore, the bed form regime is one of the important factors for silt transport. Although some scholars (e.g., Ribberink and Al Salem, 1994; Ribberink et al., 2007) have analyzed the bed forms' influence on sediment transport qualitatively, more studies are needed on the quantitative modeling of turbulence, flow dynamics and sediment dynamics.

In addition to experiments, bottom boundary layer models (normally 1DV) are powerful tools for studying sediment transport mechanisms. A number of numerical models for sediment transport have been developed over the years. Sediment transport modelling was started in the last century with the development of 1DV models (Smith and McLean, 1977; Grant and Madsen, 1979; Grant et al., 1984; Stive and De Vriend, 1994). Because of their simplicity and precision, these models are valuable for some special issues, such as the intra-wave vertical distribution of velocity, shear stress and concentration. Different models have been developed to predict sediment transport under waves or wave-current conditions. These models can be divided into

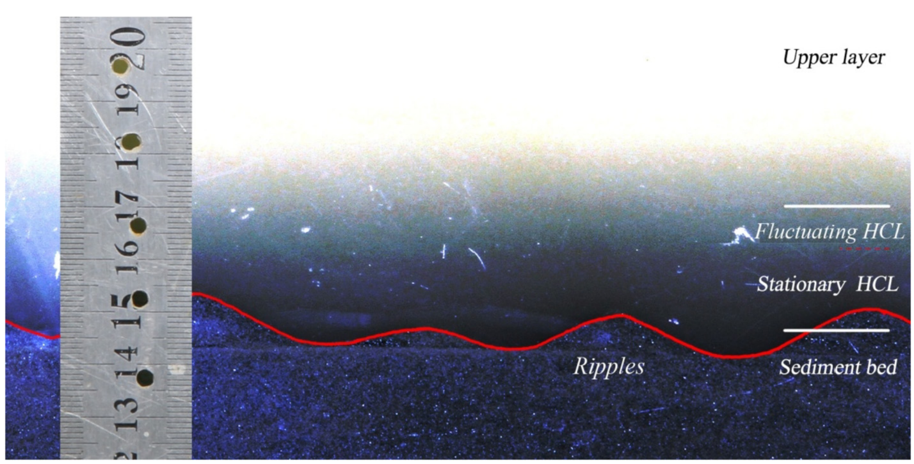

Fig. 1. High concentration layer (HCL) measured in flume experiment with median sediment grain size of 88 μm (Yao et al., 2015) (The darker color represents higher sediment concentration).

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