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Observation and modeling of the storm-induced fluid mud dynamics in a muddy-estuarine navigational channel

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ABSTRACT

Observations of storm-induced fluid mud dynamics have been conducted at the North Passage deepwater navigational channel (DNC) of the Yangtze Estuary in October to December 2010, during the occurrence of a cold-air front. The measurement data reveal that just after the critical wind wave event, a large amount of fine sediment was trapped in a state of fluid mud along the channel. The observed thickness of the fluid mud was up to about 1–5 m, which caused some significant economic and safety problems for shipping traffic in the Yangtze Delta area. The mechanisms and transport processes of the storm-induced fluid mud are analyzed and presented from the angles of both process-oriented and engineering-oriented methods. With the help of hydrodynamics and wave modeling, it could be inferred that the behavior of the storm-induced fluid mud event mainly depends on the overall hydrodynamic regimes and the exchanges of sediment, which is released by storm-wave agitation from adjacent tidal flats. These sediments are accumulated as fluid mud, and subsequently oscillate and persist at those locations with weaker longitudinal residuals in the river- and tide-dominated estuary. In addition, the downslope transport of fluid mud is also thought to have stimulated and worsened the fluid mud event observed in this study. Our modeling results and observations demonstrate that: (1) the transport of fluid mud is an advective phenomenon determining the central position of fluid mud layer along the channel, and it's also a tidal energy influenced phenomenon controlling the erosion and accumulation of fluid mud; and (2) both suspended particulate matter availability and local residual flow regime are of critical importance in determining the trapping probability of sediment and the occurrence of fluid mud.

1. Introduction

The occurrence of fluid mud is widely covered and commonly witnessed in many locations, such as estuaries (e.g. Mehta, 1989; Winterwerp, 1999), lakes (e.g. Li and Mehta, 2000; Bachmann et al., 2005), rivers (e.g. Wang, 2010), waterways (e.g. Li et al., 2004) and even open sea (e.g. Puig et al., 2004). Fluid mud exists in the water column (Fig. 1, Table 1) as a transitional stage (McAnally et al., 2007a), when the net rate of sediment falling from the upper suspension layer into the bottom layer exceeds the dewatering rate of the high-concentration sediment–water mixture, and the bonds of the interconnected matrix structure are not strong enough to form an erosion-resisting consolidated layer. The characteristics of fluid mud differ significantly from those of both suspensions above and the consolidated bed below. The temporal transition status varies quickly in response to sediment availability and intensity of currents (when fluid mud is 'left alone' it will consolidate).

Considering the condition of sediment availability or supply, it may relate to micro-scale sediment mixing, such as flocculation and hindered settling (Le Hir et al., 2000); it could form a stepped vertical profile of suspended sediment concentration (SSC) and trap sediment in the near-bed layer. At the same time, the sediment supply is also associated with macro-scale sediment movement and circulation (Shi, 2010), where transport of enough fine sediment mass from nearby shoals and beaches to the navigational channel favors the formation of a fluid mud layer. The current dynamics can also be divided into micro- and macro-scale processes, where the micro-scale processes include turbulence damping, drag reduction and some stratification effects of flow, while the macro-scale refers to the regime of currents, residual circulation, tidal asymmetry and so on.

Therefore, there are two types of viewpoint from which to study the dynamics of fluid mud. The first approach is process-oriented or micro-mechanism driven, which is conducted primarily by sedimentologists, geomorphologists and oceanographers; they focus on some responses and influences on sedimentary processes and vertical profiles of currents and SSC, such as flocculation, re-suspension, deposition, erosion, turbulence damping, drag reduction, density flow, and turbidity maximum. The second method can be called engineering-oriented or

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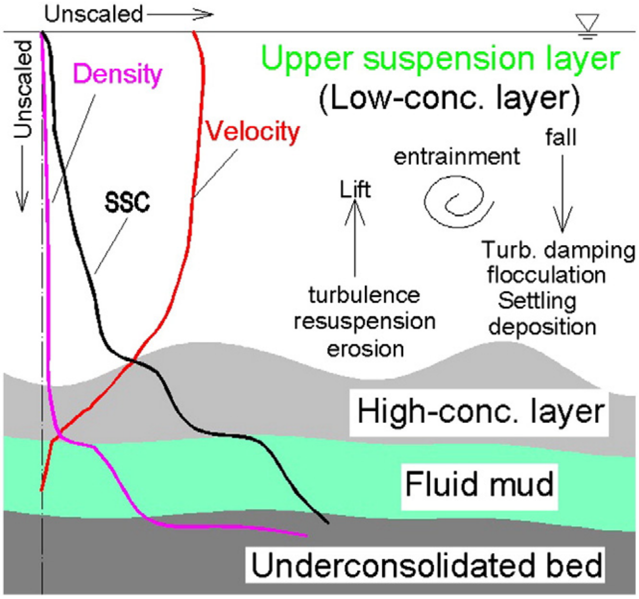

Fig. 1. Perspectives on the dynamics of the fluid mud in the water column (SSC is suspended sediment concentration).

macro-mechanism driven, which is the approach chosen mostly by hydraulic and coastal engineers, who are concerned with the horizontal and overall regime of currents and sediment; typically the keywords in this type of research are residual circulation, tidal asymmetry, sediment availability, flow regime and so on.

Many complex physical processes are related to the formation of fluid mud, such as flocculation, settling and mixing, deposition, re-entrainment, gelling, consolidation, liquefaction and erosion (Winterwerp, 1999). In addition, McAnally et al. (2007b) showed that physics, such as rheology, as well as chemical oceanography and microbiology also play a large role in fluid mud behavior. Many efforts (Wolanski et al., 1988; Kineke et al., 1995; Ali et al., 1997; Shi, 1998; Le Hir and Cayocca, 2002; Vinzon and Mehta, 2003; Guan et al., 2005; Winterwerp, 2006; Hsu et al., 2007; McAnally et al., 2007a) have been dedicated to investigating the formation of fluid mud. Among those studies, the effect of wave and storm processes on fluid mud has attracted considerable attention in recent years. McAnally et al. (2007a) pointed out that fluidization of soft sediment beds by wave agitation is one of three principal mechanisms of the fluid mud formation. Li et al. (2004) suggested that the formation of fluid mud phenomena may fall into three categories: slack water, storm and salt wedge. Through measurement data from two moored tripods, Traykovski et al. (2000) showed that the fluid mud could be trapped within the wave bottom boundary layer. Based on tripod data, Puig et al. (2004) also provided a clear picture of the influence of surface–wave activity on the rapid generation of a sediment gravity flow (fluid mud) by development of excess pore water pressure during storms. Warner et al. (2008) utilized ROMS and SWAN models to reveal that bottom sediment resuspension is controlled predominantly by storm-induced surface waves and transported by the tidal- and wind-driven circulation. With the aid of some laboratory experiments van Kessel and Kranenburg (1998) showed that the wave-induced liquefaction (fluid mud) of subaqueous mud layers may be a mechanism of rapid sedimentation observed in navigational channels after storms. In summary, wave energy has the potential to resuspend, release and load sediments in a submarine layer, which facilitates the formation of fluid mud; in particular, if it can stir up large quantities of sediment over mudflats and in shallow areas under wind wave conditions. In short, storm generation is considered one of the most significant causes of fluid mud.

In this paper, firstly, a storm-induced fluid mud event in a muddy-estuarine navigational channel is studied. Secondly, wind wave propagation is modeled to examine the condition of sediment availability under a cold-air front, and three-dimensional (3D) hydrodynamics are simulated to achieve a better understanding of the major mechanism determining the dynamics of fluid mud. Finally, both process-oriented and engineering-oriented methods are employed to investigate the possible factors influencing the mechanisms and transport processes of this storm-induced fluid mud event.

2. The fluid mud event

Recently, a 90 km-long and 12.5 m-deep (all elevations, heights and water depths in this paper are referred to the Lowest Astronomical Tide) deepwater navigational channel (DNC) in the North Passage of Yangtze Estuary, China was completed. The engineering construction of the DNC was launched in 1998, the water depth of the navigational channel was developed in three steps from 8.5 m in 2002 (Phase I), 10 m in 2005 (Phase II), to 12.5 m in 2010 (Phase III) (see Fig. 2).

In recent years, according to some in situ measurement data, the backfilling and siltation along DNC is so severe that it requires many efforts to study the possible mechanisms behind the massive trapping of fine cohesive suspended sediments in the river- and tide-dominated estuary. One specific case, a fluid mud event, may illustrate the fine sediment dynamics and trapping processes clearer than regular conditions.

At the end October of 2010, an intensified cold-air front affected most areas of southeastern China. The observed thickness of the fluid mud resulting from this storm along the channel was about 1–5 m. The field investigation of this event was expected to evaluate and analyze the distribution, influence and dynamics of fluid mud. First of all the forcing conditions of the fluid mud event are introduced, and then the measurement data are investigated to show the dynamics of the fluid mud.

2.1. Forcing conditions

This cold-air front was reported to be recorded as the strongest cold front during the past 5 years in China; the temperature dropped 6–14 °C sharply along the track of this winter storm.[1] The coastlines of eastern and southern China suffered a long-lasting intensive wind-induced storm, the maximum wave height observed in the DNC (the location is shown in Fig. 2) was up to 4.35 m.

The observed time series of wind speed and frequency of wind directions during the storm are shown in Fig. 3. The data show that maritime wind in this area during the cold-air front were estimated to be in the range of 6 to 7 (according to the Beaufort Wind Force Scale), and the wind was long-lasting (almost 10 days); the dominant wind direction was from the north. The observed significant wave height in the DNC during this storm episode is presented in Fig. 4. The significant wave height during the storm is about 0.5–2.2 m, and its variation is related to local tidal elevation and wind condition.

2.2. Dynamics of fluid mud

From 18th Oct. to 28th Nov., 13 profiles of along-channel fluid mud field investigations were collected. The observed channel–longitudinal dynamics of fluid mud (from echosounder[2] data) along the DNC just after the storm is shown in Fig. 5, the time-series of the total volume of observed fluid mud in the channel is given in Fig. 6, typical along-channel and cross-channel density profiles of the fluid mud are also

[1] Source: ChinaNews, http://www.chinanews.com/gn/2010/10-25/2611092.shtml (in Chinese).

[2] The low frequency and high frequency of echosounder applied in this study were 33 K Hz, and 210 K Hz, respectively.