Ocean Engineering 130 (2017) 523–530

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Erodibility of fluidized cohesive sediments in unidirectional open flows

Minxi Zhang[a], Guoliang Yu[a,*], Andrea La Rovere[b], Roberto Ranzi[b]

[a] SKLOE, CISSE, School of Naval Architecture, Ocean & Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[b] Department of Civil, Environmental, Architectural Engineering and Mathematics, University of Brescia, Brescia, Italy

ARTICLE INFO

Keywords:
Erodibility
Cohesive sediment
Sediment fluidization
Scour rate
Critical condition
Threshold motion

ABSTRACT

In this study, the erodibility of fluidized cohesive sediments from the seabed of Hangzhou Bay, China, was experimentally investigated in unidirectional open flows. The results indicated that the yield stress is a major factor influencing the erodibility of cohesive sediments. As the yield stress increases, the critical Shields parameter, critical velocity, and critical shear stress increase, but the scour rate decreases. However, a lower yield stress of sediment indicates higher potential of being eroded. Furthermore, the equation for the critical condition of sediment motion, as well as the equation for the scour rate, without considering the degree of fluidization of sediments, may have limited application ranges. Hence, the bed shear stress, critical shear stress, and yield stress should be considered to predict the scour rate. Finally, a modified empirical equation based on the Partheniades (1962) equation is proposed by introducing the yield stress, which is a rheological parameter, in order to calculate the scour rate of cohesive sediments.

1. Introduction

Sediment deposition causes a loss of approximately 1% in the storage volume of worldwide reservoirs every year (Novak et al., 2007), giving rise to a number of serious problems. Sediment deposition not only threatens reservoir safety, but also enhances clog risk in channels, basins, and estuaries and the possibility of re-suspension of solids and associated pollutants. In addition, reservoir sedimentation affects downstream sediment concentration, with implications on the equilibrium of river systems (Walling, 2011; Ranzi et al., 2012). Problems become more critical if sediments are cohesive because such sediments contribute to creating resistant deposits, which are more difficult to remove than granular deposits. According to Mitchener and Torfs (1996), resistance to erosion is greatly increased if deposits contain a high percentage of fine particles.

Researchers and engineers are investigating ways to reduce sediment deposition in reservoirs and other water bodies. One of the most effective techniques for deposition reduction is hydraulic flushing, in which deposited sediments are hydraulically removed via a high flow rate. Under appropriate conditions, hydraulic flushing can remove cohesive as well as coarse sediments (Fan, 1985; Wu, 1990). Hydraulic flushing has been studied and applied extensively, as observed in the literature (White and Bettess, 1984; Shen et al., 1993; Fang and Cao, 1996; Scheuerlein et al., 2004; Emamgholizadeh et al., 2005). On the other hand, Breusers et al. (1982) stated that hydraulic flushing methods are not very effective for cohesive sediments, because only a limited amount of sediments close to the outlet can be scoured away, even when considerable water discharge is used. The erodibility of cohesive sediments, however, is a key factor influencing the efficiency of hydraulic flushing.

A series of studies have been carried out to investigate the erodibility of cohesive sediments (Raudkivi, 1976; Lavelle and Mofjeld, 1987; Shaikh et al., 1988; Mulder and Udink, 1990; Slagle, 2006; Crowley et al., 2012). Several researchers express erodibility using a simple linear relationship, i.e., $E=M(\tau_b-\tau_c)$ (Partheniades, 1962; Mclean, 1985; Odd, 1988; Hawley and Lesht, 1992; Sanford and Halka, 1993; Mei et al., 1997; Hanson and Simon, 2001; Sanford and Maa, 2001). Here, E is the erosion rate (kg $m^{-2}s^{-1}$), $\tau_b$is the bed shear stress (Pa), $\tau_c$is the critical shear stress (Pa), M is a dimensionalized (s m^{-1}) material constant whose units depend on the units used for erosion rate. Erodibility can be calculated by determining the bed shear stress, critical shear stress, and erosion parameter. The erosion parameter is found to be dependent on specific sediment properties at a given excess shear stress (Mehta et al., 1989; Ziegler and Nisbet, 1995; Sanford, 2008; Grabowski al., 2011). The scour rate model is acceptable for granular sediments; however, the mechanisms governing erosion resistance are still unclear for cohesive sediments, as interparticle attractions between cohesive sediments are strongly influenced by a large number of sediment properties in complex ways (Black et al., 2002; Winterwerp and Kesteren, 2004).

The properties of sediments are more complex at sea coasts and lake shores than in reservoirs. At sea coasts and lake shores, wave

---

* Corresponding author.
E-mail address: yugl@sjtu.edu.cn (G. Yu).

http://dx.doi.org/10.1016/j.oceaneng.2016.12.021
Received 14 June 2016; Received in revised form 28 November 2016; Accepted 18 December 2016

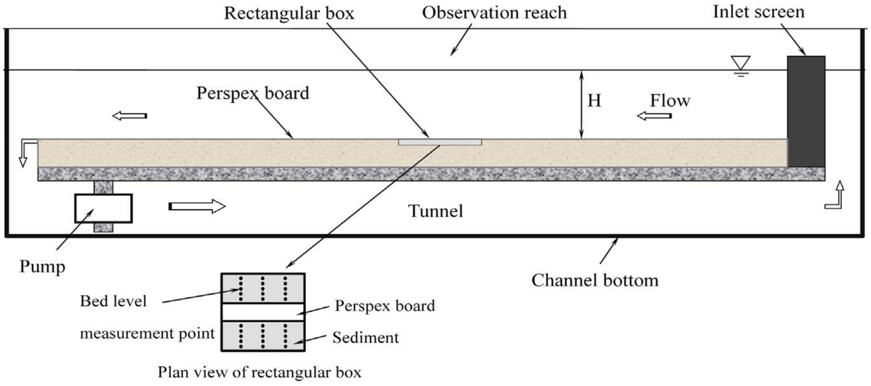

Fig. 1. Sketch of test flume.

action can induce seabed liquefaction. Sedimentary beds are often fluidized by waves, resulting in the formation of high-concentration profiles that include mobile suspensions, fluid mud, a stationary bed, and a cohesive bed region (Ross and Mehta, 1989). Fluidization would enhance sediment transportation and produce highly moveable sediment sources. The degree of fluidization of cohesive sediments could vary depending on the composition of and the shear loads on the sediments. Sediments with a higher concentration of water have lower yield stresses, and the yield stress of a sample was proportional to its consolidation after structural destruction (Kessel and Blom, 1998). The elastic modulus and dynamic viscosity of sediments varied exponentially with volume concentration (Huang and Aode, 2009). An investigation on cohesive sediments in the Haihe estuary of China demonstrated that both the Bingham yield stress and viscosity increased exponentially with mud density (Bai et al., 2002). In addition to fluidization of sediments by waves and currents, mechanical vibrations were also effective in the fluidization of sediments (Yu et al., 2014). Cohesive sediments were fluidized by shear and mechanical vibration loads, and the high-frequency vibration loads significantly reduced the viscosity of the sediments (Yang et al., 2013). Furthermore, the rheological behaviors of dense cohesive sediments were non-Newtonian and time-dependent, and the rheological properties of cohesive sediments subject to shear loads were sensitive to both the shear rate and time (Yang et al., 2014).

Transport properties may be characterized by the rheological properties of bed sediments (Mehta, 1986) because the rheological properties determine both the resistance to flow and the response to external loads and structural changes (Berlamont et al., 1993). However, few studies have focused on the erodibility of fluidized sediments. Erosion of cohesive sediments depended on the internal structures associated with the mechanical behavior of the sample (e.g., strength and thixotropy) (Pouv et al., 2014). The rate of erosion was found to vary exponentially with $(\tau_b - \tau_s)^{0.5}$, where τ_s is bed shear strength (Parchure and Mehta, 1985). A rheological property was applied to the integrated parameter of interparticle cohesion, and a critical shear stress as a function of yield value for cohesive soft bottom sediments was proposed by Otsubo and Muraoka (1988), based on a series of experiments on the effects of rheological properties of cohesive materials on the critical shear stress. The application of vibration on sediments was able to enhance the erosion through artificially fluidizing the sediment, which was demonstrated by an experimental investigation on the effect of vibrator machine on desilting sediment in pressure flushing (Dodaran et al., 2014). In estuaries, the predicted erodibility of cohesive sediments was always lower than the measured erodibility. Wave loadings have a significant impact on the erodibility of silty sediments, which exhibit a linear increase with the increasing magnitude and cycle number of wave loadings in laboratory simulations (Zheng et al., 2013). Sediments in different states have different failure patterns under wave loadings, and the erodibility of the same sediment has different sensitivity to wave loadings over a range of magnitudes. Waves could enhance sediment re-suspension not only by excess shear stress, but also by liquefying the soil bed through excess pore-pressure accumulations (Jia et al., 2014). Furthermore, wave loading would fluidize seabed, and the wave action induce the inhomogeneity in the strength of seabed sediment that would affect the features of seabed erosion and mass-transportation activity (Liu et al., 2013).

As stated previously, it is necessary to understand the rheological properties of cohesive sediments to characterize the erodibility, which is affected by several factors such as water content, bulk density, sediment composition, and shear or mechanical vibration loads. Different degrees of fluidization of cohesive sediments would have different erodibility and sediment transport rates for the same hydraulic conditions. However, the relationship between the rheological properties and the erodibility is still unrevealed. The present study investigates the relationship between the yield stress and the erodibility of cohesive sediments in unidirectional free-surface flows. Accordingly, a series of laboratory experiments are conducted with cohesive sediments collected from Hangzhou Bay, China. From the obtained experimental results, a modified equation based on the Partheniades equation (1962) is proposed to calculate the scour rate.

2. Methods and material

The experiments were performed on the sediment samples by varying the yield stress to determine the relationship between the erodibility and the rheological properties of the sediments. For each test, the velocity profile of flow, water content, bulk density, the yield stress of the sediments, and the scour depth of the sediment bed were evaluated.

2.1. Methods

2.1.1. Test flume

The experiments were carried out in a circulating two-layer flume, which was 13 m long, 1 m wide, and 1 m high (Fig. 1). The floor dividing the lower and upper flows had a thickness of 0.05 m and formed a tunnel of length 11 m and a height of 0.3 m above the channel bed. The dividing floor was paved horizontally and contained sediments for a depth of 0.12 m. Both upstream and downstream ends of the tunnel were 1 m away from their corresponding inlet and outlet sections of the flume, respectively. At the downstream end, two pumps were installed with their outlets pointing into the tunnel. At the upstream end, some flow straighteners were installed to allow the flow to enter the test flume smoothly. A rectangular box was installed 5 m away from the inlet, in which the top rims were leveled to the bed (Fig. 2). The box, which is 1 m long, 1 m wide, and 0.05 m thick, was divided into three sections in order to contain different fluidized sediments. Smooth, flat perspex boards were also laid on top of the sediments, except on the box.