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Experimental studies on initiation of current-induced movement of mud

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ABSTRACT

The initiation movement of mud exposed to currents was investigated experimentally. The initial movement of mud with different sedimentary densities was determined by measuring the flow velocity and grey level of water's image synchronously. A new method to determine the initiation movement of mud is provided (i.e., the method of relative grey value of water's image in the flume). The experimental results show that the initiation movement of mud can be classified as slight erosion and chunk erosion. The sediment concentration on a muddy bed is low for the slight erosion, and the variation in water's relative grey level is of the order of ~10. The sediment concentration for the chunk erosion corresponding to a jump in the curve of relative grey value clearly increases, and the variation in relative grey value at that instant is larger than 20. The critical flow velocity, critical friction velocity, and critical shear stress of initiation of movement of mud increase with the increase in deposit density.

1. Introduction

Muddy coasts widely exist in the world, andthe sediment at the muddy coasts is mainly composed of mud. The initial movement of mud in the tidal current significantly affects the maintenance of muddy coasts. The initiation of movement of noncohesive particles has been widely studied, and this process is relatively well understood [1–5,7]. For cohesionless sediments, the main resistance to erosion is provided by the submerged weight of sediment. However, in cohesive beds, the net attractive interparticle surface forces, frictional interlocking of grain aggregates, and electrochemical forces control the resistance to erosion and detachment. These forces vary with the type of clay, prior moisture conditions, type of shear application, and drainage conditions [6,8]. According to a study [9], the cohesion of soils significantly affects the deformation. Recently, Perret et al. [10] conducted experiments on the initiation condition of gravel–silt sediment mixtures; the effects of fine sediments were evaluated by testing beds with sand, artificial fine sand, or cohesive silt infiltrated in the gravel matrix.

The main mechanisms that cause the movement of sediment in flowing water are the velocity of flow, shear and normal stress resulting from flow turbulence (e.g., [11]). When the hydrodynamic force in a turbulent flow exceeds the resisting force of a cohesive sediment bed, the sediment is detached from the bed, and the flowing water becomes turbid. This stage is characterized by the initiation of erosion [12].

In the early 1930s, Shields [1] conducted a pioneering study on the threshold of particle movement and investigated the bed-load movement using similarity principles. Later, many researchers carried out experiments with sediments of different sizes and mineralogies and deduced the threshold velocity formula of mud by considering the cohesive forces between particles [13–22]. Smerdon and Beasley [17] conducted experiments in a flume and investigated the relationships between the shear stress of critical erosion, plasticity index, and dispersity. Partheniades [18] presented two modes of cohesive sediment erosion, i.e., surface erosion and mass erosion. In recent years, biological effect on the stabilization of sediment of mud has been studied by some researchers [23–27]. In these studies, a phenomenon known as "biostabilization" occurs, defined as "a decrease in sediment erodibility caused by biological actions" [28].

During the 1980s, Cao and Du [29] used muddy clay with different porosities to study the relationships between scour rate and shear stress on the bed. The results reported by Xu [30] show that consolidation compacting degree is the main factor influencing the critical erosion of cohesive soil. Kamphuis [31] conducted a series of studies on the erosion of cohesive soil and found that the critical shear stress of erosion is related to the plasticity index of sediment and the vane shear strength of sediment. Biological activity also affects the erosion behavior [32,33], and the erosion resistance increases with organic content [34]. Huang et al. [35] provided a model for the initiation of movement of

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cohesive soil by correlating critical shear stress and shear strength. Roberts et al. [36] evaluated the effects of particle size and bulk density on the erosion of quartz particles. They found that cohesive effects become significant as the particle size decreases. The critical shear stress depends on the bulk density and particle size.

Jin et al. [37] evaluated the effects of bentonite on the erosion rates of quartz particles. Lick et al. [38] developed a theoretical description of initiation of movement of sediments consisting of uniform-size, quartz particles. Xiao et al. [39] conducted laboratory experiments on the critical erosion of cohesive clay in a flume and discussed the effect of wet unit weight of soil on critical erosion. The results reported by Xiao et al. [39] show that the critical erosion pattern of cohesive clay is mainly suspension load. Recently, some experimental studies were conducted to determine the relationship between critical shear stress, erosion rate, and deposition rate with different mechanical, physical, electrochemical, and biological soil properties [40,41].

The mode of erosion of cohesive sediment was studied in the past. For coarse sand-clayey mud mixtures, Muray [42] found that sand moves as bed load, whereas the fines move as suspension. The visual observation of erosion processes reported by Kamphuis and Hall [31] reveals that the size of particles eroding from the bed decreases with the increase in sand content. At low shear stresses, the finer fraction is washed out, and at higher shear stresses, the larger grain size material is eroded. Amos et al. [43] reported two modes of erosion for cohesive beds: "Type 1″ erosion with a peak in the erosion rate that rapidly decreases with time, also known as "benign" erosion; "Type 2″ erosion where a high erosion rate is sustained, also known as "chronic" erosion of material from the bed.

Currently, some disagreements exist about the criterion of initiation of movement of mud. Many factors affect this problem: e.g., bulk density, particle size, size distribution, mineralogy, organic content, and size of gas bubbles) [36]. Most researchers obtained the friction velocity on the surface of mud only by measuring the mean flow velocity. In fact, for the same value of mean flow velocity, a different velocity profile corresponds to a different friction velocity. Moreover, the criterion of evaluating the initiation of movement of mud is not quantitative, and most of the existing studies determined the critical flow velocity of initiation of movement mainly by observation, leading to great subjectiveness about the results.

In this paper, a PIV velocimeter was used to measure the velocity profile to determine the friction velocity more precisely. To quantitatively determine the initiation of movement of mud, a new method is provided to determine the initiation of movement of mud by measuring the grey value of water's image. In this study, the initiation of movement of mud with different deposition densities in unidirectional currents was investigated experimentally in a flume. A continuous current dynamo was used to drive the water pump that changes the flow in the flume.

2. Experimental details

2.1. Experimental apparatus and method

The experiment was conducted in a flume with a length of 25 m, width of 0.5 m, and height of 0.6 m. An electromagnetic flowmeter was used to measure the water flux in the flume; the mean flow velocity was obtained from the water flux. The water level was obtained from the ruler installed on the side wall of glass. A propeller-type flow meter installed at the upstream of incoming flow was also used to measure the flow velocity with an accuracy of 0.1 cm/s. A DC motor was used to drive the water pump that changes the flow flux of water in the flume, and the flow velocity is changed correspondingly.

To precisely measure the velocity profile near the bed without disturbing the flow and erosion of soil, a PIV velocimeter, a noncontact measurement method, was used. The PIV is composed of a continuous laser, Photron Fastcam SA-1.1 high-speed camera with a resolution of 1024 × 1024, and data-processing software. The frame frequency of the camera was 1000 frames per second. Therefore, the accuracy of PIV can be up to 0.001 m/s, and the space resolution is 1 mm. In the PIV measurement, the density of tracer particle with a diameter of 15 μm is 1.05 g/cm^3; the particle was used before the occurrence of erosion. When the erosion of mud occurs, another tracer particle, i.e., pollen with a diameter of 50 μm, was used to eliminate the disturbance of mud particles in the water for the measurement of flow velocity with PIV.

With the increase in flow velocity, the water gradually becomes turbid. When the erosion of mud occurs, the water becomes clearly turbid. According to the principle of image processing, an image with different turbidity has a different grey value. The grey value for pure white image is 0, and that for pure black image is 255. Therefore, water at a different flow velocity has the corresponding grey value. The sediment concentration in water is small at the initial time, and the grey value of water's image is also small (e.g., the grey value of clear water is almost 0). When much mud is present in the water, then the sediment concentration in the water is larger, and it also has a higher grey level. During the test, the image of water at different times was recorded using a SONY camera, and the grey value of water's image at any time can be obtained. The grey value of water's image at the work section in the flume was regarded as the reference for each group test when the flow velocity is zero. The relative grey value of water's image, i.e., the difference between the grey value at any time and the reference, can be also acquired. This helps to estimate the initiation of mud's movement.

The test section was located at the middle of the flume. The cameras for PIV and grey value measurement of water's image were placed at the side of the flume. The laser device was placed over the flume. During the initial movement of sediment, the SONY camera recorded the variation of sediment concentration in the water, providing the grey value of water's image by image processing. The schematic of the setup is shown in Fig. 1.

The flow velocity and grey value of water's image were measured simultaneously, and the measuring area obtained by PIV for velocity is 10 cm × 10 cm. For each velocity, the acquisition time was 5 s to 10 s, and more than 1000 frames of velocity field data were obtained using a high-speed camera during this time. Then, the time-averaged velocity was computed from those frames of velocity field data. The velocity at the position 1–2 mm distance from the surface of mud can be measured using the PIV method.

2.2. Test samples and testing procedure

The mud used in the experiments was sampled from a natural harbor (i.e., located at the Lianyungang waterway in Jiangsu Province, China), and the deposit density of in-place mud is 1.400 g/cm^3. The grain density is 2.706 g/cm^3, and the mean size of the mud (d_{50}) is 5.12 μm. This indicates that it belongs to cohesive soil. The grain size distribution curve is shown in Fig. 2.

Before each test, the mud was mixed well and evenly placed along the bottom of the flume according to the designed density of mud. The

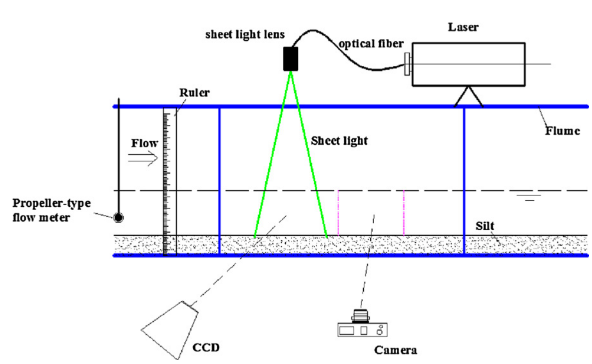

Fig. 1. Schematic of experimental setup.