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Quasi-hydrodynamic lubrication effect of clay particles on sand grain erosion

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Abstract

Minor changes in the mass physical properties of submerged sand beds can have significant consequences relative to bed stability against erosion. To examine the effect of small amounts of clay-sized particles in bed pore water on the critical shear stress τ_c for the erosion of sand grains, flume experiments were carried out on the erosion of quartz sand beds impregnated with clay particles. Starting with no clay, as the clay mass fraction ψ was increased, τ_c was found to decrease below the value for pure sand τ_{co} at $\psi = \psi_m$, then reverted to τ_{co} at $\psi = \psi_r$ and continued to increase above τ_{co} as ψ was increased further. Post-experimental analysis suggests that ψ_r is the pore space-filling fine sediment fraction above which sand erosion is significantly influenced by clay. In the range of $\psi \geq \psi_m$, slider-bearing type lubrication due to the viscosity of the clay-laden interstitial fluid appears to govern the dependence of τ_c on ψ, mimicking Petroff's law of thick-film lubrication. When $\psi < \psi_m$, as ψ decreases lubrication is increasingly curtailed by grain asperities, and τ_c reverts ultimately to τ_{co} at $\psi = 0$. An equation relating τ_c to ψ is proposed in analogy with the quasi-hydrodynamic Stribeck function for lubrication. The observed effect of clay particles appears to be significant enough to require its consideration in coastal and estuarine sediment transport modeling. It may also be a factor in the estimation of bed stability when biological activity in the benthic boundary layer introduces fine particles in clean sand beds.

Keywords: bed stability; erosion control; coastal waters; estuaries; sediment mixtures; clay particles; benthic boundary layer

1. Introduction

Coastal and estuarine beds are usually composed of heterogeneous particles often consisting of sand- and clay-sized material. Yet, because knowledge of the transport behavior of such mixtures is poor, it has gained a new research impetus in recent years. Among the reasons for this is the recognition that minor changes in the physical properties and stability of bed sediments can play a crucial role in the benthic ecological processes (e.g., Flemming and Delafontaine, 2000). In that regard, a subject of interest is the behavior of the critical shear stress of sand grains, τ_c, in the presence of clayey particles in the pore water. Past experiments on current-induced erosion of quartz sand beds containing small fractions of clay-sized particles have suggested that τ_c varies in a distinctly non-linear way with increasing clay (dry) weight fraction ψ (e.g., Nalluri and Alvarez, 1992; Huygens and Verhofen, 1996; Panagiotopoulos et al., 1997). Some data have even suggested a reduction in τ_c below its value (τ_{co}) for pure sand, e.g., those of Torfs (1995) on the erosion of mixtures of 0.23 mm (d_{50}, the median diameter) sand with a kaolinite and a montmorillonite. As indicated in Table 1 based on that work, with the addition of kaolinite, τ_c decreased from $\tau_{co} = 0.35$ Pa to a minimum value $\tau_{cm} = 0.31$ Pa (an 11% drop) at a clay fraction $\psi_m = 0.02$. The stress τ_c then increased, surpassed τ_{co} at a clay fraction $\psi_r = 0.04$, and continued to increase beyond. The values using montmorillonite were $\tau_{cm} = 0.33$ Pa (6% drop), $\psi_m = 0.04$ and $\psi_r = 0.07$.

Torfs et al. (2001) surmised that the observed reduction in the critical shear stress for sand erosion may be attributable to

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Table 1
Critical stress parameters from Torfs (1995)

Sand, d_{50} (mm)	τ_{co} (Pa)	Fine sediment	ψ_m	τ_{cm} (Pa)	$1-(\tau_{cm}/\tau_{co})$ (%)	ψ_r
0.23	0.35	Kaolinite	0.02	0.31	11	0.04
0.23	0.35	Montmorillonite	0.03	0.33	6	0.07

the effect of clay particles acting collectively as a lubricating agent. Unfortunately, the data of Torfs (1995) were too sparse in the low range of ψ ($<\sim 0.15$) to draw a definitive conclusion to that end. Other investigations cited above showed similar lacunae in data because, like the study of Torfs, they were mainly concerned with examining the variation of τ_c in a general way over a wider range of ψ.

As mentioned, a change in the critical shear stress of sandy beds with the addition of even small clay fractions may be of consequence relative to benthic processes. Accordingly, the aim of the present study was to conduct laboratory experiments to examine the effect of clay particles on τ_c in an unambiguous way, and subsequently provide a mechanistic explanation for the observations. This development is described in the sequel.

2. Experiments

2.1. Flume setup and shear stress measurement

Sand erosion experiments were carried out in a 4.3 m long, 15 cm wide, and 19 cm deep flow-recirculating flume with 3 cm thick Perspex walls and aluminum framing. The head bay of the flume received water from the tail bay via a 15-cm diameter return pipe through which flow was driven by a centrifugal pump. A return-flow bypass line and a sluice gate at the downstream end of the flume were used to adjust the water elevation and the current velocity. A 2.5-cm high Perspex false-bottom was placed along the length of the flume except over a distance of 60 cm. The resulting trench, which began 200 cm from the head of the flume, served as a container of test beds. The uniformity of the flow velocity field along this reach of the flume was documented by careful measurements of current vertical profiles using a miniature propeller current meter (Barry, 2003). The bed shear stress was calculated from measured discharge, water depth and surface slope, after accounting for the effect of sidewall friction. The applied shear stress range was 0.13–1.81 Pa, and the associated Reynolds number range was 3.0×10^4–1.1×10^5, which meant that the flow was turbulent.

The accuracy of the shear stress calculation was established by erosion tests on beds using three types of moist but dense montmorillonitic pottery clays from Bennett Pottery Supply of Orlando, Florida. The wet bulk densities of beds prepared from these clays ranged from 1435 to 1963 kg m^{-3}, and the corresponding dry density range was 698 to 1547 kg m^{-3}. One set of tests was conducted in a rotating cylinder apparatus (Jiang et al., 2004). In this device a cylinder-shaped (7.6 cm tall and 9.6 cm in diameter) soil sample could be molded within an aluminum mandrel consisting of two end discs of the same diameter as the soil sample and separated by a thin rod driven through the sample. The mandrel could be placed inside an acrylic outer cylinder of slightly larger diameter than the sample and containing water as the eroding fluid. The mandrel was submerged in this fluid and hung from a load cell and a torque cell. When the outer cylinder was rotated the resulting fluid stress (obtained from the measured torque) eroded the sample. From the loss of sample mass over a given duration measured by the load cell the rate of soil erosion could be calculated.

The second set of tests was carried out in the flume using the same three clays. The rate of erosion was obtained by measuring the increase in the suspended sediment concentration as bed erosion proceeded under a constant applied shear stress. For each clay from both apparatuses, the critical shear stress was determined by plotting the measured erosion rates against the corresponding shear stresses and extrapolating the best-fit line to intersect the shear stress axis. This point of intersection was taken as the critical stress. Acceptable agreement (within ±6%) was found to exist for the values obtained from the two apparatuses, which in turn indicated that the bed shear stresses measured in the flume were reasonably accurate, inasmuch as those from the rotating device were calculated directly from known applied torques.

2.2. Sand erosion tests

For the sand bed erosion tests carried out next, Table 2 summarizes the properties of sands used. These include the median diameter d_{50}, the sorting coefficient $s_o = \sqrt{d_{75}/d_{25}}$ and the clay added to sand. The quantities d_{25} and d_{75} are the 25th and the 75th percentile grain diameters, respectively, obtained from the cumulative distribution of diameter d by weight. The sand size ranged between 0.41 to 1.2 mm, and all the clays had a nominal (dispersed) diameter in the range of 1–2 μm. In five of the six sets of experiments, beds were prepared from different combinations of sand and clay in fresh pore water in which the clays flocculated, as no effort was made to leach out any salts present in them. In one set of tests using kaolinite the pore water was made saline at 3 ppt. This salinity is sufficient to alter the floc structure of kaolinite, but was low enough to minimize salt corrosion in the discharge pump. The eroding fluid was fresh water in every case and its mean temperature was 23 °C.

Table 2
Sand and clay properties in flume tests

Set no.	Sand, d_{50} (mm)	Sorting coeff., s_o	Sand bed density (kg m^{-3})	Fine sediment
1	1.20	1.15	1830	Kaolinite
2	0.83	1.17	1700	Kaolinite
3	0.83	1.17	1700	Kaolinite[a]
4	0.83	1.17	1700	Clay Mixture 1[b]
5	0.83	1.17	1700	Clay Mixture 2[c]
6	0.41	1.08	1680	Kaolinite

[a] In 3 ppt saline pore water.
[b] 50% Kaolinite, 45% attapulgite and 5% bentonite.
[c] 50% Kaolinite, 35% attapulgite and 15% bentonite.