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An experimental study on the effects of physical, mechanical, and electrochemical properties of natural cohesive soils on critical shear stress and erosion rate

Navid Kimiaghalam [a,*], Shawn P. Clark [a], Habib Ahmari [b]

[a] *Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba, Canada R3T 2N2*
[b] *Water Resources Department, Manitoba Hydro, 360 Portage Avenue (15th Floor), Winnipeg, Manitoba, Canada R3C 0G8*

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ABSTRACT

The field of cohesive sediment erosion is still not fully understood, in large part due to the many soil parameters that affect cohesive sediment erodibility. In this study several undisturbed natural soil samples were taken from different river banks in Manitoba, Canada. The samples mainly contained clay and silt with 24–94% clay content, thus the study covered a wide range of cohesive soil. For each sample 13 different physical, mechanical, and electrochemical properties were measured. Critical shear stress of erosion and erosion rate were quantified using an Erosion Measurement Device (EMD). Stepwise regression was used to find the variables most significantly correlated to critical shear stress and erosion rate, which led to the development of a new empirical equation to estimate the critical shear stress of cohesive soils. It was found that the critical shear stress is highly correlated with cohesion, while both cohesion and sodium adsorption ratio (SAR) had significant influence on the erosion rate.

1. Introduction

Due to the complex behavior of cohesive soil, the process of cohesive soil erosion is not currently fully understood. Cohesive soil behavior is influenced by the inter-particle bonds that are highly dependent on the interaction of physical, electrochemical, mechanical, and biological factors. Delft Hydraulics used 28 different soil and pore-water properties to characterized cohesive sediments (Huang et al., 2006). This list did not include biological factors; which some researchers such as Paterson (1997) have shown may be important. Table 1 shows a list of many factors that may influence the behavior of cohesive soil and sediment. Many researchers have tried to find a relationship between different physical, mechanical, and electrochemical properties of cohesive sediments and critical shear stress; however, there are only a few studies that have considered the interaction of these variables (Knapen et al., 2007; Zhu et al., 2008; Debnath & Chaudhuri, 2010). Dunn (1959) found a relationship between critical shear stress and sediment shear strength (τ_s) and plasticity index (PI)

$$\tau_c = 0.01(\tau_s + 180)\tan(30 + 1.73\ \mathrm{PI}) \tag{1}$$

Smerdon and Beasley (1961) obtained relationships between critical shear stress and plasticity index (PI) and also clay percentage (C_p)

$$\tau_c = 0.163PI^{0.84} \qquad \tau_c = 0.493*10^{0.0182\ C_P} \tag{2}$$

Carlson and Enger (1962) reported several correlations between different physical and mechanical soil properties and critical shear stress. They used linear correlations to find a relationship for estimating cohesive soil critical shear stress. Eq. (3) shows one of their relationships for estimating critical shear stress. However, many measurements are required to estimate critical shear stress based on their results and also, electrochemical soil properties are not considered

$$\tau_c = -0.03414 + 0.00001PI + 0.00031D + 0.00029k'_{\varnothing}\sigma_{\varnothing}M_{\varnothing} + 0.00325VS + 0.00004\,D\% + 0.00102\ \mathrm{LL} \tag{3}$$

where D [lb/ft^3] is the density of natural soil, $k'_{\varnothing}\sigma_{\varnothing}M_{\varnothing}$ is determined based on the grain size distribution, VS [lb/ft^2] is the vane shear value, $D\%$ is the percent of maximum proctor density, and LL is the liquid limit.

Owen (1975) found a relation between dry density (ρ_{dry}) and critical shear stress:

$$\tau_c = 6.85*10^{-6}{\rho_{dry}}^{2.44} \tag{4}$$

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[*] Corresponding author. Tel.: +1 2045588511.
E-mail addresses: kimiaghn@myumanitoba.ca (N. Kimiaghalam), shawn.clark@umanitoba.ca (S.P. Clark), hahmari@hydro.mb.ca (H. Ahmari).

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Table 1
Potential factors that may influence cohesive soil behavior (Winterwerp et al., 1990; Berkhovskikh et al., 1991; Huang et al., 2006; Meng et al., 2012; and Kimiaghalam et al., 2013).

	Physical properties	Chemical properties	Mechanical and in-situ properties	Biological factors	Environmental factors
Soil	Grain size distribution Specific gravity Plasticity index Water content Sand, silt, clay content Porosity Atterberg limits Fissures and cracks	Mineralogy organic content Gas content Ions Cation exchange capacity Electrical conductivity pH Oxygen level Sodium adsorption ratio	Bulk density Shear strength Cohesion and friction angle Consolidation condition Upper and lower yield density Bingham viscosity Critical shear stress of erosion Critical shear stress of deposition Settling velocity Saturation condition	Different kinds of inhabitants in the soil structure or fluid such as effects of different plants, worms, crabs, and fish	Climate change, freeze and thaw, weathering
Eroding fluid and pore-water	Total suspended solids Viscosity Density Temperature	Ions Salinity pH Oxygen content Redox potential Chlorinity Mineralogy	River ice forces such as border ice Pore-water pressure		

Thorn and Parsons (1980) found another relation between critical shear stress and dry density

$$\tau_c = 5.42 * 10^{-6} {\rho_{dry}}^{2.28} \tag{5}$$

Otsubo and Muraoka (1988) presented a formulation for critical shear stress of surface erosion and mass erosion as a function of yield value (τ_{y1}). τ_{y1} was the intercept of shear stress axis after plotting measured shear stress versus shear rate curve that they were measured by a rotary viscometer. Michener and Torfs (1996) suggested a relation between sediment density and critical shear stress

$$\tau_c = 0.15(\rho_s - 1000)^{0.73} \tag{6}$$

Amos et al. (1997) found relationships for critical shear stress and erosion rate for fine-grained sediment from the Fraser River Delta

$$\tau_c = 7 * 10^{-4} \rho_b - 0.47 \tag{7}$$

$$E = 2.94 * 10^{-3} \varnothing^{-0.829} \tag{8}$$

where ρ_b is the bulk density, E is the erosion rate, and $\varnothing$ is the friction angle. Reddi and Bonala (1997) conducted an experimental study to find a relationship between cohesion and critical shear stress of sand-kaolinite mixtures. They found a linear correlation between cohesion and critical shear stress of samples with 30% kaolinite. Hanson and Simon (2001) found an experimental correlation Eq. (9) between erosion rate and critical shear stress for a cohesive bed with high erosion resistance in midwestern United States.

$$k_d = 0.2 {\tau_C}^{-0.5} \tag{9}$$

where k_d is a material dependent coefficient that can be found from erosion rate experiments using a jet device. Julian and Torres (2006) found a correlation between critical shear stress and clay–silt fraction (SC%)

$$\tau_c = 0.1 + 0.1779(\mathrm{SC\%}) + 0.0028(\mathrm{SC\%})^2 - 2.34 * 10^{-5}(\mathrm{SC\%})^3 \tag{10}$$

Leonard and Richard (2004) estimated critical shear stress from soil shear strength measured with a shear vane device. They found that there is a linear correlation between critical shear stress and shear strength. Mostafa et al. (2008) studied the effect of sediment specific gravity and liquid limit on the erodibilty of cohesive sediments. They found a good fitted Gamma distribution between non-dimensional Shields parameter and a function which included liquid limit and specific gravity of cohesive sediments. Meng et al. (2012) conducted an experimental study on erodibility of intertidal sediments in the Yellow River delta. They used an in-situ flume to estimate critical shear stress and also measured physical–mechanical properties such as grain size, bulk density, water content, plasticity index, and shear strength. Among these soil properties, they found a correlation between critical shear stress and shear strength.

Many researchers have investigated the effect of electrochemical parameters on the erodibility of cohesive soils. The chemistry of the fluid and the pore fluid between clay particles can play a significant role in the behavior of such soils (Mehta & McAnally, 2007). One of the important parameters is cation exchange capacity (CEC) which is a measure of the type and amount of clay and is defined as the number of milliequivalents of exchangeable cations per 100 g of dry soil. Ariathurai and Arulanandan (1978) showed that with increasing CEC the erosion rate decreases. Another important factor is the total content of dissolved salts in the pore fluid (Sherard et al., 1972). Sodium Adsorption Ratio (SAR) represents salinity in soil. Arulanandan (1975) showed that with decreasing SAR, erosion rate decreases. Alhammedi and Miller (2006) studied the effects of ionic strength and SAR on flocculation–dispersion behavior of eastern Arkansas soil. They found that SAR at low ionic strength has a significant effect on clay dispersibility. De Santis et al. (2010) studied effects of physical and electrochemical soil properties on clay–silt slopes of the Aliano area in Italy. They measured PH, SAR, total amount of dissolved salts (TDS), exchangeable sodium percentage (ESP), sodium percentage (PS), and CEC for their samples and found that the eroded slopes have higher PH, SAR, and PS than the non-eroded slopes. Also, they hypothesized that weathered eroded slopes can be stabilized by decreasing the SAR, PS, and ESP. Many other researchers have studied the effect of biological factors on the erodibilty of cohesive sediments (Alberts et al., 1995; Mamo & Bubenzer, 2001a, 2001b; Gyssels et al., 2006).

This study focused on the erosion of cohesive riverbanks in Manitoba, Canada where erosion has caused considerable damage