The intertidal erosion rate of cohesive sediment: a case study from Long Island Sound

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Abstract

Over the past decades, many attempts have been made to generate useful bottom erosion models for the study of cohesive sediment movement. This study addresses some of the key questions involved in determining the functional relationship between erosion rate and bottom shear stress. Current, wave, and turbidity data were collected from a bottom mounted instrument array in a moderately energetic estuarine environment. The bottom shear stress was calculated from a wave–current interaction model. The erosion rate was derived from the observed sediment concentration using a vertical mixing model. Examination of the relationship between erosion rate and bottom stress showed that the erosion rate varied at intertidal frequency. When averaged over the tidal fluctuation, the erosion rate remained approximately constant at low stress, but increased sharply when the shear stress rose above a critical value. This suggests two-stage erosion. The bed has a layered structure, in which a thin layer of loose, high water content material overlies a more consolidated bed. The top layer of high water content material (fluff) was easily disturbed and re-suspended by tidal currents, but the consolidated bottom layer was eroded only under conditions of high shear stress.

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1. Introduction

Understanding the movement of cohesive sediment is important for the development and maintenance of harbours and navigation channels in estuaries. Cohesive sediments can also serve as a source or sink for pollutants introduced into the water column, and their movement is important for the fate of pollutants. Obviously, there is a need for better understanding of the behaviour and rate of erosion of the cohesive sediment. In the past decades, many laboratory flume studies of cohesive sediment transport under controlled conditions have been conducted. These experiments have tested the erodibility of the sediment bed as a function of sediment size fraction, mineral composition, water content, organic fraction, and degree of bioturbation. They have resulted in many models of the empirical relation between erosion rate and shear stress (Bedford, Wai, & Libicki, 1992; Mehta & Parchure, 2000).

Erosion conditions in the field are much more complex than in flume experiments, as environmental conditions, such as surface waves, unsteady or mean currents, and saline and thermal conditions may change the sediment properties (Burt, 1986). As a result, laboratory results may not be directly applicable to the real world. On the other hand, there have been very few attempts to determine the relationship between erosion rate and bottom shear stress from field observations. Lavelle, Mofjeld, and Baker (1984) were among the pioneers of field studies on the subject. They estimated in situ erosion rates from current and turbidity measurements at 5 m above the bottom of 202 m water depth in the Puget Sound in Washington State (USA). They suggested that the erosion rate (\(\varepsilon\)) could be related to bottom stress (\(\tau\)) by a power law, \(\varepsilon = x\tau^\beta\). The coefficients \(x\) and \(\beta\) were empirically determined by assuming a constant settling velocity; for example, \(x = 1.7 \times 10^{-6}\) g cm\(^{-2}\) s\(^{-1}\) and \(\beta = 4.0\) for a settling velocity of 0.1 cm s\(^{-1}\) and eddy diffusivity of 78 cm\(^2\) s\(^{-1}\).
In Lavelle et al. (1984), the field study was conducted in a deep basin. Their results may not be valid in shallow estuaries where the waves and currents are much more energetic (Butman, 1987; Shi, Hamilton, & Wolanski, 2000). Recently, Tolhurst et al. (2000) used four in situ devices to determine the shear stress and the erosion of sediment in the Humber Estuary (UK). They were interested in developing a standard analytical procedure for comparison of different stability measurements. However, their results showed that because of the effects of device size and spatial heterogeneity, the erosion rates varied by orders of magnitude between different devices and deployments. Houwing (1999) measured the bed shear strength on a tidal mudflat using an in situ erosion flume. He also could not determine a clear relationship between critical erosion threshold and sediment properties.

This study is based on a set of field data covering a wide range of conditions, including tidal currents and wave influence. The relationship between erosion rate and shear stress is examined for both the instantaneous and tidally averaged conditions. The approach is similar to that of Lavelle et al. (1984).

### 1.1. The instantaneous erosion rate

Data used in this study were collected in centre of Long Island Sound (Fig. 1) in late 1983, using a bottom mounted instrument array of current, wave, and turbidity sensors (Wang, Bohlen, & O’Donnell, 2000). Using the wave and current data, the bottom shear stress was calculated according to Grant and Madsen’s (1986) model. The resulting bottom shear stress indicated semidiurnal tidal fluctuations with peak amplitudes of about 3 dyne cm$^{-2}$ (Fig. 2). The largest shear stresses, however, were wave-induced, with peak values of over 15 dyne cm$^{-2}$. The erosion rate was derived from the time variation of sediment concentration using a vertical mixing model (Chen, Horrigan, & Wang, 1988; Mellor & Yamada, 1982). A similar approach using a three-dimensional model was reported by Brun-Cottan, Guillou, and Li (2000). In the (one-dimensional) vertical mixing model, the effect of horizontal advection is assumed to be small. This is justified using two lines of evidence. First, the near-surface sediment distribution is rather uniform over the tidal excursion distance (Fig. 1). Second, the fluctuations in suspended sediment concentration are similar between the flood and the ebb (Fig. 2). Both suggest that the tidal horizontal advection is small.

To formulate a relationship between erosion rate and shear stress, erosion rate is plotted against bottom shear stress (Fig. 3). The negative values, which represent deposition dominant, are not included. The erosion rate can be expressed as a two-term power-law function with shear stress: $e = a_1 \tau_1^{b_1} + a_2 (\tau - \tau_c)\beta_2$. For a given critical shear stress ($\tau_c$), the coefficients ($a$ and $\beta$) can be derived using regression procedures. For example, for $\tau_c = 5$ dyne cm$^{-2}$, $a_1 = 0.8 \pm 0.09 \times 10^{-6}$ g cm$^{-2}$ s$^{-1}$, $\beta_1 = 0.07 \pm 0.03$, $a_2 = 0.21 \pm 0.07 \times 10^{-6}$ g cm$^{-2}$ s$^{-1}$, and $\beta_2 = 0.78 \pm 0.11$. All values are mean ± 1 standard deviation.

![Fig. 1. The study site (★) located at 20 m water depth in the Long Island Sound, USA, where the bottom sediment is composed mostly of silt and silty sand.](image-url)
1.2. The intertidal erosion rate

When the relationship over time between erosion rate and shear stress is plotted on a scatter plot, the results show large scatters (Fig. 3). This may be attributed to the elastic behaviour of the cohesive sediment and the complicated structure of the cohesive bed (Dyer, 1986; Parchure & Mehta, 1985). It is instructive to examine whether the scatters may be reduced through appropriate temporal averaging. To address this question, an auto-correlation test is applied to the shear stress time series. The result shows that the first secondary maximum of the auto-correlation function is 6 h (Fig. 4), which corresponds to the period of semidiurnal tide. (The shear stress has two maximums in one tidal cycle.) The second secondary maximum is about 12 h, corresponding to the side slope of the diurnal tidal period. The zero crossing of the auto-correlation function is at about 15 h, corresponding to the time scale of the storm events.

The auto-correlation test suggests that 6 h may be an appropriate time period to treat the data as independent samples. To obtain an ensemble average, in each half tidal cycle the four largest erosion rates and associated shear stresses are used to calculate the mean and standard deviation. This procedure reduces the scatters; however, the relationship between erosion rate and shear stress remains rather ambiguous. This suggests that the erosion rate could be different from one half tidal cycle to the other, caused by changes in sediment cohesiveness. To verify this argument, Fig. 5 shows four sets of erosion–stress relationship. In other words, although shear stress has a time scale of 6 h, change in the sediment bed has a longer time scale.

To eliminate the intertidal variation, the erosion rate and shear stress data are averaged over each half tidal cycle, and the resulting 6-h data are binned according to range of shear stress, with an increment of 1 dyne cm$^{-2}$. Within each bin, erosion rate mean and standard
deviation are computed. This process significantly reduces the large fluctuation in erosion rates (Fig. 6), and illuminates a definitive relationship between erosion rate and shear stress. The erosion rate is about constant, 0.48 ± 0.065 × 10^{-6} \text{g cm}^{-2} \text{s}^{-1}, for shear stress less than 4 \text{dyne cm}^{-2}, the upper limit of tidal induced shear stress. Above 4 \text{dyne cm}^{-2}, the erosion–stress relationship can be formulated from the regression analysis as 
\[ e = 0.576(\tau - \tau_c)^{0.19} \times 10^{-6} \text{ g cm}^{-2} \text{s}^{-1} \] and \( \tau_c = 4 \text{ dyne cm}^{-2} \), with \( \gamma^2 = 0.7 \).

1.3. The physical meaning

The erosion–stress formula suggests two different erosion processes with a transition at 4 \text{dyne cm}^{-2}, the upper limit of tidal shear stress. The low shear stress regime represents the ambient condition of surface sediment re-suspension by the tidal currents, while the high shear stress regime corresponds to the mass erosion (at much higher erosion rates) during high-energy episodic (wave) events. This hypothesis is supported by a REMOTS photograph taken at the study site (Wang et al., 2000), which indicates that the bed had a two-layer structure, with a thin layer of loosely consolidated material overlying a layer of more consolidated material. The top layer always remains in a high water content state (fluff) and can be easily disturbed and re-suspended into the water column. Indeed, the erosion rate tends to dip near the critical shear stress. This suggests that as the limited amount of fluff material is dispersed into the water...
column, there is less material available for erosion. The lower layer is eroded only when the shear stress becomes significantly higher than the background value and when the erosion rate increases rapidly with higher shear stress.

2. Discussion

In this study, the erosion rates of cohesive sediment are estimated from in situ measurements of suspended sediment concentration and bottom shear stress. The empirical relationship between instantaneous erosion rate and shear stress suggests that there is no threshold stress. Similar results, that there is no clear indication that a gradual change in shear stress leads to a sudden change in suspended sediment concentration, are reported in many previous investigations (Lavelle & Mofjeld, 1987). The power-law fit, however, has large scatters, indicating no definite relationship.

For intertidal variations, erosion rates can be grouped into storm and non-storm periods. Parameterization of the relationship between erosion rate ($e$) and shear stress ($\tau$) suggests that in $e = \alpha(\tau - \tau_c)^{\beta}$, coefficients $\alpha$ and $\beta$ each occupy one side of the curve and are separated by a breaking point at the critical shear stress $\tau_c = 4$ dyne cm$^{-2}$. In the low shear stress regime, $\beta = 0$, that is, the erosion rate is approximately constant. A constant erosion rate is balanced by a constant settling rate, since there is a large mean suspended sediment concentration of about 15 mg l$^{-1}$ (Fig. 2). In the vertical mixing model, the settling velocity is set to 0.3 mm s$^{-1}$, which gives zero net flux over the study period.

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In the high stress regime, a critical shear stress ($\tau_c$) is included. The need to include a critical shear stress in modelling storm-induced erosion is supported by several previous studies. For example, Lyne, Butman, and Grant (1990), in modelling variations in suspended sediment concentrations during storms, shows that the differences between predictions and observed data can only be resolved by establishing a limit on the depth of erodibility...
Further, Gross and Dade (1991) observe that peak sediment concentration occurs before peak velocity. The sudden burst of suspended sediment concentration is caused by the shear stress exceeding the critical value. The subsequent decrease in fine sediment concentration is due to the dilution throughout a thickening turbulent mixed layer during accelerating flow.

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