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A heuristic examination of cohesive sediment bed exchange in turbulent flows

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ABSTRACT

Prediction of the concentration of suspended cohesive sediment in the marine environment is constrained by difficulties in interpreting experimental evidence on bed exchange, i.e. erosion and deposition of particles, which remains sparse in mechanistic details. In this paper, conditions under which bed exchange in turbulent flows collectively determines the concentration of suspended matter have been examined in the heuristic sense based on selective experimental data. It is argued that interpretation of such data can be significantly facilitated when multi-class representation of particle size, collisional interaction between suspended particles and probabilistic representations of the bed shear stress along with variables describing particle behavior (critical shear stress for deposition, bed floc shear strength) are taken into account. Aggregation—floc growth and breakup kinetics—brings about shifts in the suspended particle size distribution; bed exchange is accordingly modulated and this in turn determines concentration dynamics. Probabilistic representation of the governing variables broadens the suspended sediment size spectrum by increasing the possibilities of inter-particle interactions relative to the mean-value representation. Simple models of bed exchange, which essentially rely on single-size assumption and mean-value representation of variables, overlook the mechanistic basis underpinning particle dynamics.

1. Introduction

Erosion of cohesive sediment in turbulent boundary layer flows is often modeled using expressions for the sediment flux driven by the bed shear stress as a mean-value variable, and disregarding ubiquitous heterogeneity in particle size. To obviate this hurdle, present-day numerical modeling approaches using multi-phase equations for flow and sediment transport internalize the bed-water boundary and thereby attempt to bypass the use of expressions for sediment fluxes at the bed (e.g. Hsu et al. 2007). However, in numerous instances of engineering and ecohydrological interest such a “continuous-phase” modeling protocol is tedious, and explains the continued popularity of models based on the mean-value approach (Wolanski 2007).

Unfortunately, the simple approach raises questions regarding the validity of assumptions that are invoked when deposition is modeled in combination with erosion. In this paper we evaluate some of these constraining assumptions of the simple mean-valued approach. We will attempt to elaborate on the underpinning limitations based on a heuristic interpretation of previous experimental data on cohesive sediment bed exchange, i.e. erosion and deposition. The significance of coupling multi-class representation of sediment size and probabilistic variables governing bed exchange is examined using the numerical laboratory approach (e.g. Tolhurst et al. 2009), which incorporates the effects of aggregation, i.e. the kinetics of floc growth and breakup, on eroding and depositing sediment. An analytical strength of numerical experiments is that they permit the determination of net bed exchange from gross erosion and deposition fluxes, which are typically not measured separately in laboratory experiments.

2. Physical basis

Cohesive sediment characteristically conforms to a different transport regime than cohesionless particles. In the probabilistic development of Einstein (1950) for the transport of sand, the condition of equality between eroding and depositing particle number fluxes is postulated. In order to interpret this development in terms of the transport of flocculated cohesive sediment, Partheniades (1965) considered all flocs to be effectively identical with a uniform shear strength τ_s (equivalent to the critical shear stress for erosion τ_{cr} of cohesionless sediment) resisting erosion. As a consequence, for treatment of flocs of different sizes the Partheniades model must be applied repeatedly to each size as in the development of Einstein for sand, and the total erosion flux calculated as the sum of contributions from all size classes. This essentially means that aggregation involving interactions between suspended particles of different sizes is ignored. Therefore, that approach cannot account for experimentally observed shifts in the size distribution of suspended flocs arising mainly from aggregation due to turbulent shear, and to a lesser extent due to differential settling and Brownian motion (Winterwerp and van Kesteren 2004). Another ramification of the single-size assumption is

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that even though the bed shear stress τ_b represented by its probability density function (pdf) is time-dependent, at any instant only erosion can occur if τ_b is greater than τ_s and only deposition when τ_b is lower than τ_s. Observe that a change in the floc size distribution of suspended sediment can occur through exchange of flocs with the bed deposit. However, to reproduce the loss of the finest flocs in a flow condition that excludes deposition of those flocs requires the inclusion of aggregation processes in the analysis.

For tidal flows the pictorial depiction in Fig. 1a of the exclusive erosion or deposition paradigm requires a sub-division of the flood and the ebb phases of the tidal cycle into sub-periods. Starting from slack water the first sub-period, in which only deposition (flux δ) can occur, corresponds to the duration when the bed shear stress τ_b is less than the critical shear stress for deposition τ_d, i.e. the stress below which all initially suspended (single-size) sediment deposits and above which remains in suspension indefinitely (Krone 1962). In the second sub-period τ_b is between τ_d and the bed floc shear strength τ_s, which must be exceeded by τ_b for erosion to occur. In this sub-period there is neither erosion (flux ε) nor deposition. In the third sub-period, when τ_b is greater than τ_s, there can be erosion but no deposition. The reverse sequence follows as the bed shear stress begins to decrease past its peak value at the strength of flow.

Physical evidence supporting the sequence of processes in Fig. 1a has not been found in the marine environment. Sanford and Halka (1993) used a numerical modeling approach based on single size to explain the transport of tidally suspended fine sediment in the Chesapeake Bay. They showed that in order to reproduce the measured concentration time-series in the bay it was essential to permit continuous deposition (Fig. 1b); when the exclusive paradigm was used predictions were unsatisfactory. An important feature of this finding is that when the flow velocity is sufficiently high, there can be a sub-period when erosion and deposition occur simultaneously. An equally important inference, further elaborated upon by van Prooijen and Winterwerp (2010), is that in order to implement the single-size model in conjunction with continuous deposition, in addition to the bed shear stress the floc shear strength must be treated as a probabilistic variable. This is so because an overlap in the tails of the pdfs of these two variables is essential for simultaneous erosion and deposition to occur at the bed surface. By including the shear strength as a spatially distributed variable, the instantaneous bed shear stress will always be less than the shear strength somewhere, and make deposition possible. In addition, variability of the floc shear strength for a given size class is influenced by the inherent non-uniformity in the size of the primary particles from which the flocs are formed. This also affects the variability in the floc density and fall velocity for flocs within that size class. As we will see an extension of the Sanford and Halka model to account for multiple size classes and incorporating the probabilistic approach has important consequences with regard to the prediction of time-varying suspended sediment concentration.

3. Experimental data

The experiments selected to explore the exclusive and continuous-deposition paradigms include tests previously carried out in a counter-rotating annular flume (CRAF). This apparatus consisted of a 0.2 m wide and 0.45 m deep annular channel with a mean diameter of 1.5 m. Water in the channel was driven by shear generated from a rotating upper lid, with the ability to rotate the channel in the opposite direction from the ring to minimize radial secondary currents.

In a series of deposition-dominated tests, a kaolinite clay flocculated with small quantities of salt in 0.31 m deep water was used (Mehta 1973). In each test run the sediment was initially suspended at a concentration of 1 kg m^{-3} and then permitted to

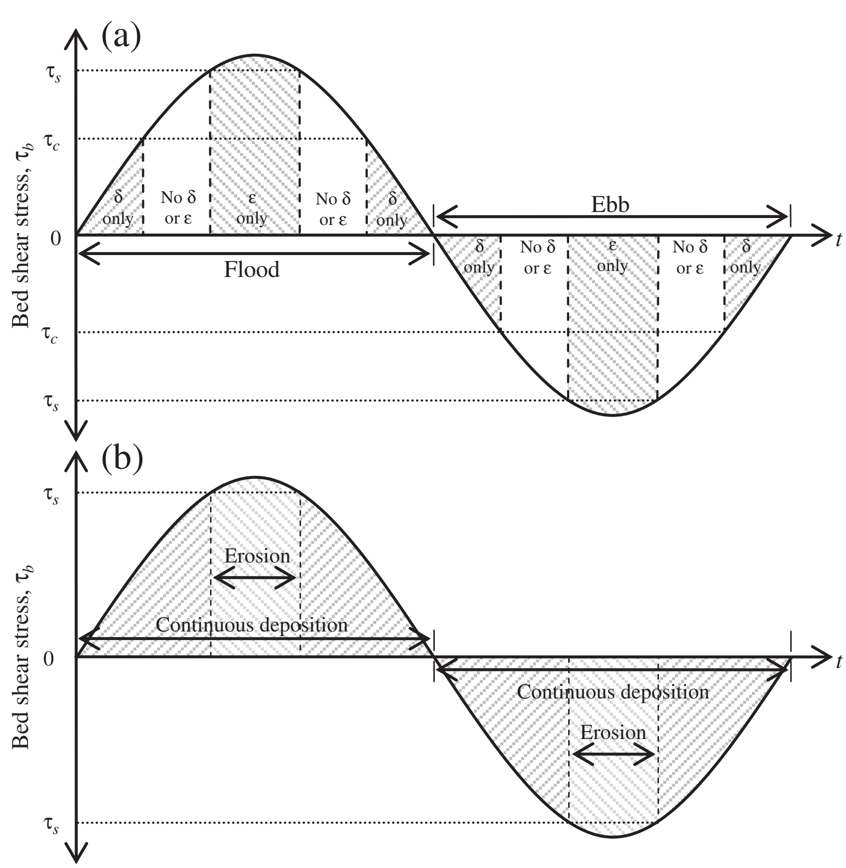

Fig. 1. Sub-periods of deposition flux (δ), erosion flux (ε) and no bed exchange during a tidal cycle: (a) Exclusive paradigm; (b) continuous-deposition paradigm.