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Time-dependent behavior of a placed bed of cohesive sediment subjected to erosion and deposition cycles

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Abstract This study aims to explore the behavior of a cohesive sediment bed that undergoes cycles of erosion and deposition under diluted conditions. A bed of bentonite (montmorillonite) sediment was placed in two annular flumes and subjected to daily erosion tests for a period of 80 days, mimicking intermittent moderate-energy disturbances like tidal currents and wind waves. After each erosion test, the suspended sediment was allowed to settle back in the flumes. The amount of suspended sediment measured at the top of the water column at the end of each erosion test decreased in the first 5 days, concurrently with an increase in the bulk-settling velocity near the bed. This pattern is explained by turbulence-induced flocculation of clay particles and consequent formation of a surface floc layer. After about 20 days, the amount of suspended sediment measured at the top of the water column at the end of each erosion test increased and the settling velocity decreased, whereas the suspended sediment concentration measured near the bed remained nearly constant. We explain such trend by the cumulative release of slow-settling particles from the bed. This experiment suggests that the superficial layer of a placed bed that is periodically eroded and redeposited experiences competing processes: the sediment that is resuspended at every cycle becomes less erodible, but prolonged exposure to shear stress increases the pool of eroded sediment over time. The total amount of resuspended sediment seems to become constant after several tens of cycle, suggesting that the release of particles from the bed by cumulative erosion is balanced by the binding of such particles to the bed.

Keywords Mud · Cycles · Erodibility · Flocculation · Long-term

1 Introduction

Muddy environments characterize a large fraction of the world coastline, particularly in tropical areas where the input of fine sediment from rivers is very large (Healy et al. 2002). The cohesive sediment characterizing these systems is constantly reworked by waves and currents, giving rise to an ever-changing landscape (Friedrichs 2011). A full understanding of the mechanisms responsible for the erosion of cohesive sediment in muddy coastal environments is important for the preservation of these delicate environments in the face of natural and anthropogenic change.

Because of the intermittency of hydrodynamic forcings, such as currents and waves, sediment in natural environments is subjected to cycles of erosion and deposition. Different from sand, the behavior of cohesive sediment strongly depends on their geologic history (Einsele et al. 1974), i.e., the time series of physical conditions they were subjected to. For example, sediment consolidates when left undisturbed in the bed (Hawley 1981) and flocculates when suspended under intermediate levels of turbulence and sediment concentration (Winterwerp 1998). Cycles of erosion and deposition can lead to the formation of a surface floc layer or surficial fine-grained lamina (Droppo and Stone 1994). Such layer, up to 8-mm thick, represents a transient sediment storage reservoir that is frequently reworked. The shear stress at which the sediment

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was deposited, one of the major parameters characterizing the depositional history, has a strong influence on the stability of the surface floc layer; beds formed by flocs deposited under shear are more resistant than beds deposited under quiescent conditions (Lau and Droppo 2000; Droppo et al. 2001).

Despite the evidence that beds of cohesive sediment are strongly influenced by cycles of erosion and deposition, most flume experiments investigate the characteristics of sedimentary beds, either created from a slurry (placed bed) or deposited under still water from a high concentrated suspension (deposited bed), subjected to a single erosion event (e.g., Parchure and Mehta 1985). The purpose of this study is to examine, in a laboratory-controlled experiment, the effects of repeated erosion and deposition events on the same sedimentary bed over a period of 80 days. Our experiment has some similarities with those of Winterwerp et al. (1993), in which a sedimentary bed was subjected to several "tidal" cycles of erosion and deposition. While in Winterwerp et al. (1993), the suspended sediment concentration reached values up to 10 g/l, and fluid mud formed during the slack water phase; the sediment concentration in our experiment never exceeded 1 g/l, and no fluid mud was observed. Our experiment hence reproduce diluted conditions, commonly found in sheltered coastal areas far from large riverine inputs, such as back-barrier mudflats (Mariotti and Fagherazzi 2012a) and estuaries (Fugate and Friedrichs 2003).

Here, we will describe and interpret the results from two identical laboratory experiments, highlighting the presence of competing processes that determine the resuspension of a cohesive sediment bed subjected to multiple erosions. The same experiment was replicated to identify possible biological contamination (Linten et al. 2002) and errors associated with the erosion procedure, both of which might have occurred during the 80 days long experiment.

2 Methods

2.1 Experiment set up

Two annular flumes were constructed partly based on the design of the previous flume studies (Fig. 1) (Amos et al. 1992; Thompson et al. 2003). The flumes, already used in previous experiments (Valentine et al. 2014), have an external diameter of 53 cm and an internal diameter of 23 cm. Bentonite sediment (montmorillonite, median diameter ~5 μm) was used to examine the physical processes controlling the resuspension of cohesive sediment. Salt water was made with diatom-filtered tap water and table salt (3 % in weight). The salt water was mixed with the bentonite to create a mixture with 75 % water content in weight, thoroughly blended with an electric mixer for about 1 h. An even layer of the mixture (~4 cm) was placed at the bottom of each flume and then gently covered with the salt water, creating a 16-cm deep water column. This procedure resulted in a placed rather than settled bed (sensu Amos et al. 1992). Hence, the bed is expected to be weakly stratified and to be characterized by a time-limited (type 2) erosion behavior (Mehta and Partheniades 1982).

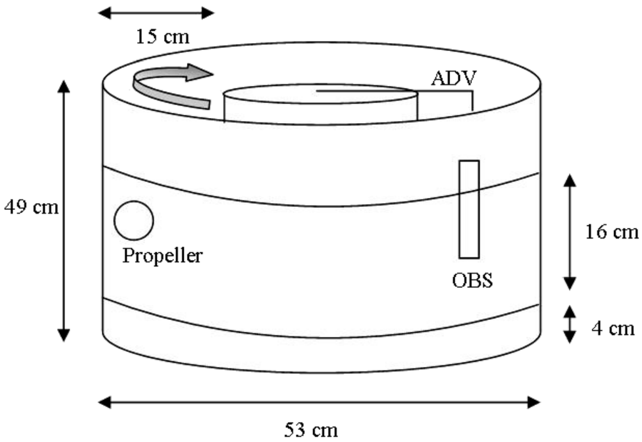


Fig. 1 Schematic of the annular flume apparatus used for erosion experiments. The outer walls and the bottom of each flume were polyethylene and the inside walls were glass

Flow in the flume was created with a small controllable propeller (Koralia 2, Hydor, USA), placed 2 cm below the water surface. Erosion tests were repeated every day for 36 days. After this period, both flumes were not eroded for 22 consecutive days, and then erosion tests were repeated again daily for other 22 days. During each erosion test, the velocity in the flume was increased every 10 for 80 min until reaching a maximum value, starting at approximately 0.18 m/s and attaining 0.31 m/s at peak velocity. After each erosion test, the sediment was allowed to settle until the next erosion test. The experiment mimicked an environment in which sediment are eroded and deposited in the same area, i.e., an environment that is spatially uniform and isolated from external sediment sinks or sources.

A Nortek^R Acoustic Doppler Velocimeter (ADV) was positioned in the flume, on the opposite side of the propeller. The ADV measured the three-dimensional velocity at 32 Hz, sampling a volume 4 cm above the bed, centered in the flume cross section. Bed shear stresses were computed using the turbulent kinetic energy equation (Stapleton and Huntley 1995),

$$\tau = 0.19\rho\left\langle \left(v_x'\right)^2 + \left(v_y'\right)^2 + \left(v_z'\right)^2 \right\rangle \Big/ 2, \qquad (1)$$

where v'_x, v'_y, and v'_z are the fluctuating velocities in the three Cartesian directions and ρ is the water density equal to 1030 g/L. Measured shear stresses were approximately

0.13 Pa for the first erosion step and reached 0.4 Pa at the last erosion step. The drag coefficient C_D was computed by applying the quadratic stress law,

$$\tau = C_D \rho U^2, \tag{2}$$

where U is the total velocity magnitude and resulted in an average value of C_D=0.0038. By using the half depth as the length scale and the bed shear velocity as the velocity scale, the turbulent diffusivity ranges from 9 to 16 cm^2/s.

2.2 Suspended sediment concentration

Suspended sediment concentration (SSC) in the water column was measured with a Campbell Scientific^{R} Optical Backscatter Sensor (OBS 3+), positioned 5 cm below the water surface. The sensor measured at 1 Hz, and the signal was processed using a filter with a moving window of 10 s. The OBS signal was linearly calibrated using samples from the water column collected at the OBS height. The acoustic backscatter (ABS) strength, filtered with a moving window of 10 s, was also used as a proxy for suspended sediment concentration near the bed (Fugate and Friedrichs 2002). The ABS strength was not converted to SSC because no sediment concentration samples were collected at the ADV depth.

The sediment dynamics through time was explored by focusing on the sediment concentration at two specific instants of a given erosion test (Widdows et al. 2000). These values are related to the erodibility of the bed, but are also influenced by the shear stress history of the erosion test and by the redistribution of sediment in the water column. The suspended sediment concentrations after 10 min of exposure to the lowest velocity, W_1 for the water column and B_1 for the near bed, are a proxy for the response to low disturbances (~0.1 Pa). The suspended sediment concentrations at the final stage in the erosion test, W_{max} for the water column and B_{max} for the near bed, are a proxy for the response to moderate disturbances (~0.4 Pa).

2.3 Settling velocity

Settling velocity, w_s, was computed using the water-clearing method (Krone 1962; Amos and Mosher 1985). For both the ADV and OBS sensors, we used the decrease in suspended sediment concentration after the propeller was turned off (after 80 min, see Fig. 2) to calculate settling velocity with the following equation,

$$-\frac{dC}{dt} = \frac{w_s}{d} C, \tag{3}$$

where C is the turbulence-averaged suspended sediment concentration and d is the depth of the sensor with respect to the water surface. Equation 3 is similar to the equation of Krone (1962) with shear stress set equal to zero.

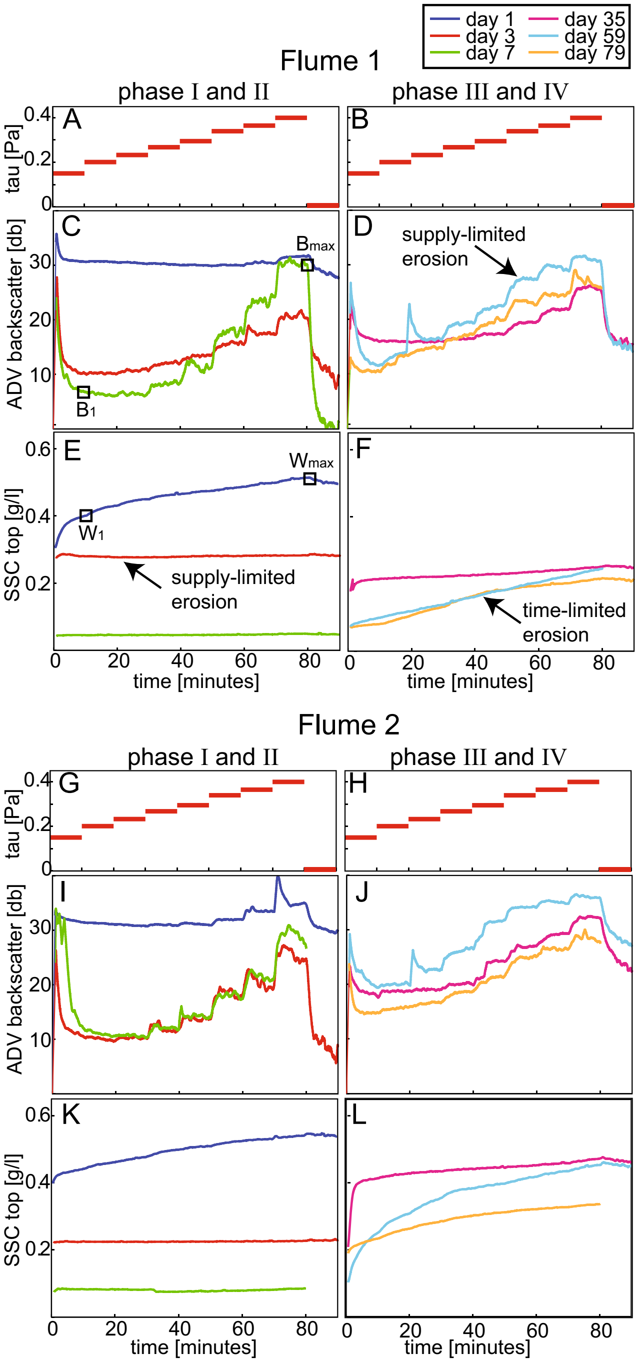


Fig. 2 Example of individual erosion tests. **a**, **b**, **g**, **h** In all tests, the shear stress is increased stepwise from ~0.13 to ~0.4 Pa. **c**, **d**, **i**, **j** ADV backscatter used as a proxy for the near bed sediment concentration. **e**, **f**, **k**, **l** Sediment concentration measured at the top of the water column

Settling velocity was also calculated with the eddy correlation method (Fugate and Friedrichs 2002). From the ADV data, we estimated the settling velocity assuming a steady state balance between upward turbulent sediment flux and gravitational settling (Fugate and Friedrichs 2002),

$$\left\langle v_z{}' C' \right\rangle = w_s C, \tag{4}$$

where C' is the fluctuating suspended sediment concentration. The ABS was used as a proxy for C and C'. This equation is strictly valid if the flow and suspended sediment concentration are stationary, horizontal gradients are absent, and settling velocity is constant in time. To closely meet these requirements, we restricted the application of this equation to the last 5 min of the last shear stress step.

3 Results

The temporal pattern of sediment resuspension during the course of the experiment follows a similar trend in both flumes, indicating reproducibility of the experiment (Fig. 3). Four phases in the experiment are identified and described using the measurements near the bed and in the water column.

3.1 Near bed

The near bed ASB at low disturbances, $B_{1,}$ decreases during the first 5 days (phase I), remains low until day 17 (phase II), steadily increases until day 30 (phase III), and then remains nearly constant until the end of the experiment (phase IV) (Fig. 3a, d). On the other hand, the maximum near bed ABS, $B_{\max,}$ only decreases by about 20 % during phase I, and then it remains approximately constant over the successive erosion tests, even though some fluctuations were present. The 22-day period without erosion does not create any evident change in either B_1 or $B_{\max}$ (Fig. 3a, d).

At the beginning of each erosion test, when the applied shear stress is about 0.1 Pa, the near bed sediment concentration increases in few seconds and then decreases after few minutes (e.g., Fig. 2c, i). During the successive erosion steps, erosion is supply-limited (Amos et al. 1997), as indicated by the stepwise increase in concentration after each increase in shear stress (Fig. 2c, i).

Both the water-clearing and eddy correlation methods give similar values for the settling velocity near the bed (Fig. 3c, f). Despite some large fluctuations, a trend over the timescale of the whole experiment is clearly detected: near bed settling velocity increases from about 0.1 mm/s to about 0.7 mm/s during phase I, remains approximately constant during phase II when B_1 is the lowest, and then it decreases to about 0.3 mm/s concomitantly with the increase in B_1. During phase I, the Rouse number, defined at the settling velocity divided by the shear velocity multiplied by the von Karman constant, ranged from 0.1 to 0.16, indicating a mild vertical stratification.

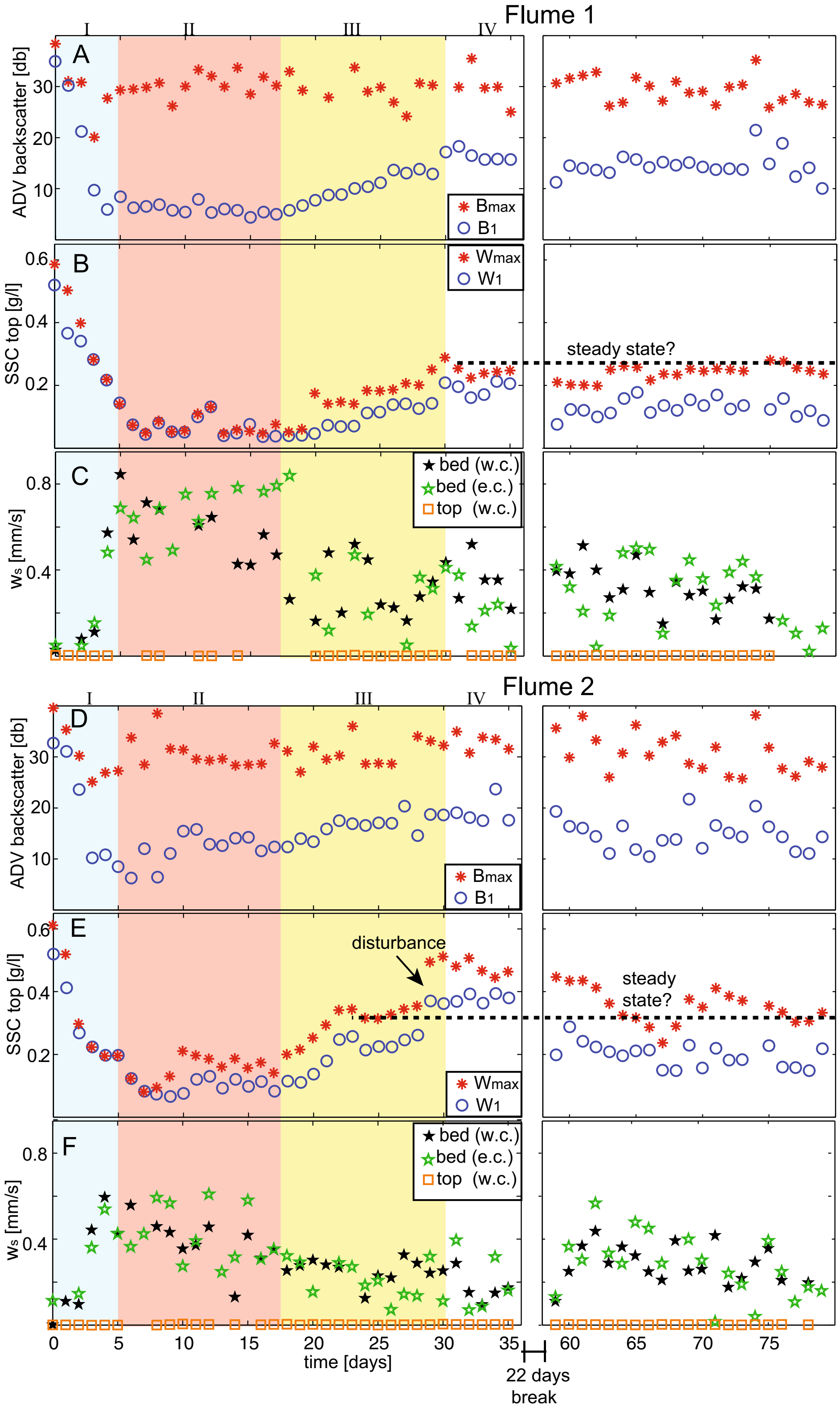
Fig. 3 Synoptic plots of the erosive experiments performed over a period ▶ of 80 days. Comparison between flume 1 (**a**, **b**, **c**) and flume 2 (**d**, **e**, **f**). The *light blue background* indicates phase I of the experiment, when sediment resuspension decreases with time; the *light pink background* indicates phase II, when sediment resuspension remains low; the *yellow background* indicates phase III, when sediment resuspension increases with time; and the *white background* indicates phase IV, when sediment resuspension approaches a steady state. **a**, **b**, **d**, **e** Suspended sediment concentration at the lowest and the highest shear stress, near the bed (using the ADV backscatter as a proxy) and at the top of the water column (*squares*). **c**, **f** Settling velocity near the bed and at the top of the water column (*squares*), computed with the water clearing (w.c.; *filled stars*) and with the eddy correlation (e.c.; *green stars*) methods

3.2 Water column

The temporal patterns in the SSC measured in the water column differ from the patterns in ABS measured near the bed (Fig. 3b, e). The maximum SSC, $W_{\max}$, decreases from 0.6 g/l to 0.05–0.1 g/l during phase I, it remains low during phase II, increases during phase III, and then remains approximately equal to 0.2 g/l during phase IV.

During phase I, $W_{\max}$ is about 30 % greater than W_1; whereas during phase II, W_1 and $W_{\max}$ are almost identical, i.e., the amount of suspended sediment at the lowest and highest shear stresses is the same. SSC in the water column increases during phase III, during which $W_{\max}$ is about 30 % higher than W_1. After the 22-day period without erosion, W_1 decreases by about half, while $W_{\max}$ is not affected. At day 28, a region of ~1 cm^2 of the bed in flume 2 was involuntarily perturbed (Fig. 3e), causing an increase in $W_{\max}$ on the following erosion test, clearly detectable by comparison with flume 1 (Fig. 3b). After this event, $W_{\max}$ decreases steadily, reaching values close to those before the perturbation.

Except for the first day, sediment erosion during phase I and II is supply-limited, that is when all the erodible sediment is suspended at the lowest shear stress, and the amount of eroded sediment does not increase with time (Mehta and Partheniades 1982) (Fig. 2e). During phase III, the amount of resuspended sediment increases with time for a fixed shear stress, indicating that the time scale for sediment depletion is much longer than the time scale for shears stress change (10 min) (Sanford and Maa 2001) (Fig. 2f). Surprisingly, the erosion rate seems to be independent of the intensity of bed shear stress.



Settling velocity at the top of the water column, about 0.002 mm/s, is two orders of magnitude lower than the settling velocity measured near the bed (see example of water clearing in Fig. 2c).

4 Discussion and conclusions

4.1 Limitations of the experiment

Before discussing the results, it is opportune to mention some limitations of the experiment. First, because the experiment was started just 1 day after salt water was mixed with the bentonite, chemical modification of the clay structure could have occurred throughout the experiment. Even though such modifications are not able to explain all the observations, we cannot a priori exclude their effect. Second, the experiment was performed on a placed bed, whose vertical gradients do not generally represent natural conditions. However, because of the large sediment resuspension that occurred during the first erosion test, the majority of the sediment eroded throughout the successive days was settled from the water column. Hence, the experiment is akin a bed with a freshly deposited surface layer that overlies a well-consolidated layer. Both limitations should be used as guidance if this experiment were to be replicated.

4.2 A tale of two sediment populations?

The experiment produced some unexpected results, namely the temporal changes in ABS near the bed and SSC at the top of the water column. Here, we interpret these results by hypothesizing the presence of multiple sediment populations, even though direct measurements of particle size were not carried out.

The bed surface layer starts with slow-settling particles, as indicated by the low bulk-settling velocity (~0.002 mm/s). This population is likely composed by individual clay particles (~5 um) that have not aggregated yet. These particles are attached to the bed, and some finite time is needed to erode them. After 3 erosion tests, the majority of the easily detachable particles have been eroded and redeposited at least once. The number of individual clay particles decreases throughout phase I, likely because of turbulence-induced collision between particles, which favors the formation of larger flocs and repacking of the bed. Indeed, there is an inverse relationship between $W_{\max}$ and the near bed settling velocity during the experiment, which is an indirect proxy for floc size (Fig. 4). At the end of phase I, the water near the bed becomes populated by fast-settling sediment, as indicated by an order of magnitude increase in settling velocity. This class of sediment is also more resistant to erosion, as suggested by the large difference between ABS near the bed at high and low shear stress, $B_{\max}$ and B_1. This result is in accordance with the previous observations that beds formed by flocs deposited under shear are more resistant than beds deposited under quiescent conditions (Lau and Droppo 2000; Droppo et al. 2001). Also, photographs of the bed taken after the deposition period reveal the presence of mud bedforms (Fig. 5), similar to the mud ripples formed in flume experiments in which flocs deposition was triggered by a decrease in the fluid velocity (Schieber et al. 2007). We believe that these bedforms coincide with the superficial floc layer (Lau and Droppo 2000) that it is reworked at every erosion cycle.

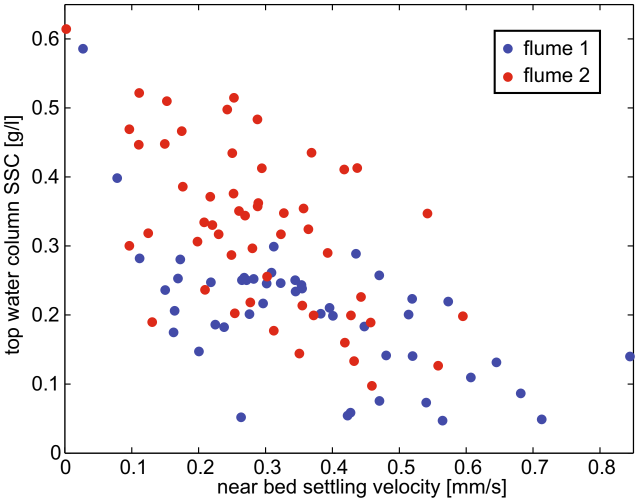


Fig. 4 Suspended sediment concentration at the top of the water column ($W_{\max}$) plotted against the near bed settling velocity, measured with the eddy covariance method

To summarize, the increase of bed resistance after cycles of erosion and deposition can be explained with existing theories, such as the surface fine-grained laminae recycling (Droppo et al. 2001). On the other hand, the increase in sediment concentration at the top of the water column during phase III does not have a straightforward explanation. Indeed, consideration about consolidation and flocculation suggested that sediment resuspension would decrease monotonically with time.

A possible explanation for the increase in $W_{\max}$ is the gradual breaking up of the large flocs that stay close to the bed. This possibility might be explained in term of a fatigue behavior of the flocs that are subjected to the cumulative shear of tens of erosion tests. However, we note that the increase in $W_{\max}$ is not associated with a decrease in $B_{\max}$. This suggests that the increase of eroded sediment reaching the top of the water column is not associated with depletion from the pool of

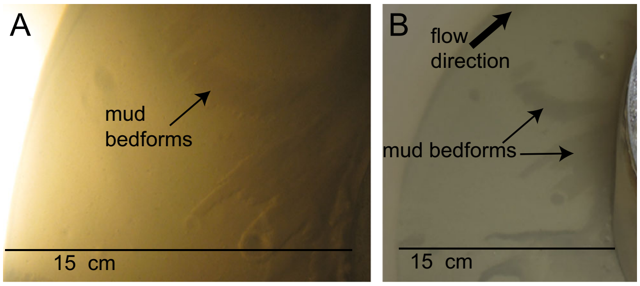


Fig. 5 Images of the bed before an erosion test showing the presence of mud bedforms (*thin arrows*). Flume 2 at day 75. **a** Top view as illuminated from the side. **b** Angled view

large flocs that populates the near bed region. If these particles do not originate from the previously eroded large flocs, where does this sediment population come from?

A number of critical observations can be made to explain the origin of the particles reaching the top of the water column. First, we note that while the sediment concentration in the water column increases during phase III, the settling velocity remains very low. This suggests that the new particles populating the top of the water column have a slow-settling velocity. This observation also implies that the decrease in near bed settling velocity during phase III is due to an increase in the abundance of slow-settling particles over the whole water column rather than a decrease in the amount of fast settling particles. Second, we note that the sediment reaching the water column is released at a slower rate than the sediment remaining near the bed, as indicated by the individual erosion tests (Fig. 2). However, a fraction of the total sediment that reaches the water column is easily erodible, as indicated by the relative high SSC at the lowest shear stress (Fig. 2). Evidence of rapid resuspension can also be seen in the increase in near bed ABS after a few seconds of erosion at a low shear stress (Fig. 2d) followed by a decrease in ABS caused by dilution in the water column. Third, the total amount of sediment eroded at the end of each experiment gradually varies from day to day (except when the bed was involuntary disturbed, at day 28 in flume 2). The resuspension of this pool of sediment depends more on the cumulative shear stress overtime than on the instantaneous shear stress, suggesting a long-term memory in sediment erodibility. Fourth, this pool of sediment was the only one affected by the 22-day period without erosion. Indeed, after this quiescent period, this pool of sediment was not readily eroded by the smallest shear stress.

Given these observations, we suggest that the prolonged action of shear stress increases the pool of slow-settling sediment by gradually eroding it from the consolidated bed. The mechanism for release of new sediment might depend on turbulence bursts (Van Prooijen and Winterwerp 2010), by mechanical weakening of the bed, or by a decrease in charge capacity through time. Once it settles, some sediment binds to the bed, while other remains loose. The amount of sediment easily eroded during each erosion test depends on the amount of sediment eroded during the previous test and the amount of sediment bonded to the bed. Such binding is time dependent, as suggested by the large decrease in sediment resuspended at low shear stress after the 22 days without erosion (W_1).

Would the amount of eroded sediment increase indefinitely? Our experiment suggests that a dynamic balance might be reached, such that the production of the particles by cumulative erosion is balanced by the binding of such particles to the bed. This question is of great importance since the majority of natural environments, if subjected to regular or quasi-regular disturbances, would likely have the time to reach a dynamic equilibrium. Further investigation of a potential balance will need to focus on the details of sediment detachment from the bed (Sou and Calantoni, this issue), the stochastic nature of the disturbances (Van Prooijen and Winterwerp 2010), and the interactions between mud floc, bedforms, and the underlying bed of cohesive sediment (Schieber et al. 2007).

We have not specified the nature of the pool of slow-settling particles that dominate the last stage of the experiment. From our measurements, we are not able to discern whether this population is composed by individual clay particles, as those present at the beginning of the experiment, or by slow-settling flocs. The former scenario suggests the presence of a process that inhibits the flocculation of newly detached clay particles into large flocs, while the latter scenario suggests that flocculation occurs, but does not create the same flocs as those forming during phase I. Experiments in which the particle populations are monitored in detail, for example, using LISST and floc cameras (Fugate and Friedrichs 2003), are sought to solve this conundrum.

4.3 Implications for natural environments

Our experiment reveals that cohesive sediment, subjected to cycles of erosion and deposition under diluted conditions, undergoes changes in sediment resuspension on the scale of weeks to months. Two competing processes were identified. On one hand, resuspension allows sediment to experience turbulence and aggregate in larger flocs, rapidly decreasing the erodibility of the bed. On the other hand, prolonged exposure to shear stress increases the pool of eroded sediment overtime. Additionally, during the time spent in the bed, flocs can dewater and bind with other aggregates, decreasing their erodibility (Hawley 1981). Our results suggest that the concert of processes occurring in the water column and in the bed under simple and periodic disturbances leads to complex dynamics of cohesive sediment. Such dynamics will likely be complicated by the occurrence of biotic processes, such as time-dependent stabilization by biofilms (Valentine et al. 2014; Mariotti and Fagherazzi 2012b) and bioturbation by benthic fauna.

Previous observations showed that muddy environments subjected to periodic, moderate-energy erosion events, such as tidal currents or wind waves, are characterized by multiple sediment populations (Fugate and Friedrichs 2002). Our results suggest that these populations might form or be released overtime under similar cycles of erosion and deposition. We suggest the use of state-of-the-art laboratory settings to perform long-term erosion experiments, possibly matching field conditions, to untangle sedimentary processes occurring under periodic erosion events. Understanding the balance between the increase in erodibility by cyclic erosion and the consolidation processes occurring in the bed, and whether a steady state can be reached are of utmost relevance for the fate of coastal environments.

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