Bedform migration in an intertidal environment influenced by cohesion

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ABSTRACT: The migration rate of small-scale bedforms is important in determining bed material transport for the management of coastal morphology. Although many coastal and estuarine environments are dominated by mixtures of non-cohesive sand and cohesive, biologically active mud, there is a lack of field data on the effects of cohesion in mixed sediment. To address this gap in knowledge, measurements were taken of migrating bedforms in sand-mud mixtures on intertidal flats. When clay and EPS contents were below 2% and 0.04% respectively, the derived field bedform migration rates were found to not be significantly different from laboratory results for non-cohesive sand bedforms. Above these limits, cohesive forces hindered bedform migration. These results are important for sand-only bedform migration transport formulae in mixed sand-mud environments, as they can only be applied below these low limits of clay and EPS content when the sediment can be considered free of physical and biological cohesion.

1. INTRODUCTION

Sediment transport models are essential for managing coastal and estuarine morphological change. Many of these environments are dominated by mixtures of sand and mud. While reasonably accurate sediment transport predictors are available for pure sands, a knowledge gap exists for the behavior of mixed sediments composed of cohesive mud and non-cohesive sand. In addition to the physical cohesion caused by clay minerals in the mud, mixed sediments are also affected by biological cohesion, resulting from extracellular polymeric substances (EPS) produced by benthic organisms.

Knowing the rate of migration of sedimentary bedforms, such as ripples and dunes, is important in determining the bed material transport rate in sediment transport models (e.g., van Rijn, 2006; van den Berg, 1987). Such models may be inaccurate, if the bedform migration rates in sand-mud mixtures and non-cohesive mud-free sands are different.

Recent laboratory experiments using mixed cohesive and non-cohesive sediments have shown that bedforms dimensions and development rate are reduced by physical and biological cohesion (Baas *et al*., 2013; Malarkey *et al*., 2015). This implies that cohesive forces within the bed may control the bed material transport rate, as a few percent of clay and more than 0.063% of EPS can be sufficient to significantly slow bedform growth (Baas *et al*., 2013; Malarkey *et al*., 2015). However, Baas *et al*. (2013) and Malarkey *et al*. (2015) also showed that the clay and EPS were selectively taken into suspension while bedforms formed and migrated on the bed, causing them to migrate as if they were composed of clean sand.

Here experimental laboratory data of bedform migration for pure-sand in unidirectional current (Baas *et al*., 2000) are compared with similar bedforms in sand-mud mixtures on intertidal flats in the Dee Estuary, United Kingdom.

2. FIELDWORK

Fieldwork was carried out on intertidal flats in the Dee estuary, United Kingdom, near West Kirby. The Dee is tidally dominated, with a 7-8 m mean spring tidal range at the mouth. The intertidal flats studied are at the mouth of the Dee, separated from the main estuary by an Island. Waves affecting the intertidal flats are mainly generated locally within Liverpool Bay.

Three sites were selected over a spring-neap cycle in May and June 2013, in order to cover different mixtures of substrate sand and mud. Instrumentation was deployed at each site consecutively to measure the currents, waves, and bedform morphology, when the tidal flats were inundated. The bed sediment was sampled when the flats were exposed during low tide. This study presents the hydrodynamic data, collected using an Acoustic Doppler Velocimeter, and the seabed topography data, provided by a 3D Acoustic Ripple Profiler.

3. DATA ANALYSIS

The bedform migration rate was calculated from the spatial difference between successive half-hourly 0.5 by 0.5 m bed scans, determined by 2D cross-correlation (van den Berg, 1987). The minimum ripple migration rate detectable was 2.8×10^{-6} m s^{-1}, and values at and below this limit were excluded from the regression analysis.

The wave-related, current-related, and combined maximum bed shear stress were calculated from the wave and current parameters (Malarkey and Davies, 2012) and used to calculate the Shields mobility parameter. Using the combined maximum bed shear stress accounted for the influence of waves, allowing comparison with the current-only laboratory data.

Baas *et al*. (2000) proposed a simple power law relationship between experimental data of the bedform migration rate, u_b, for current ripples and Shields parameter, θ' (Figure 1):

$$u_b = \alpha\theta'^{\beta} \qquad (1)$$

where α and β are coefficients that vary with the bed sediment size. The bed material transport rate per unit width, Q_b, can then be calculated from the migration rate and the size of the bedforms (van den Berg, 1987):

$$Q_b = \rho_s(1-p)fu_b\eta \qquad (2)$$

where η is the bedform height, f is the bedform shape factor and p is the porosity of the bed (van Rijn, 2006; van den Berg, 1987). Equation (2) was used to calculate bed material transport rate by mass at each site, with the heights of the bedforms computed using the zero-crossing method. The zero-crossing method detects where the bed profile crosses the mean level, between these points lie the crests and troughs, and the difference between successive crest and trough gives the bedform height. The shape factor, *f*, the porosity, *p*, and the sediment density, ρ_s, were kept constant at 0.6, 0.4, and 2650 kg m-3, respectively (van den Berg, 1987; van Rijn, 2006).

4. RESULTS

4.1. Flow forcing and bedforms

During the study period the tide changed from neaps to springs and back to neaps (Figure 1a,b). North-westerly winds dominated at Site 1, from moderate breezes up to gale force (5.8 - 17.6 m s-1), generating wind-driven flows that increased the bed shear stress of the flood tide, compared to the fair-weather conditions at the other sites (Figure 1b). The combined maximum bed shear stress shows that bed stress is dominated by the currents, except for part of Site 1 that was influenced by waves (Figure 1b,c,d).

The time-series of mean bedform height is compared with the predicted equilibrium heights for current ripples, calculated from the grain size using empirically derived formulae (Baas, 1999; Soulsby *et al*., 2012) (Figure 1e). During periods of strong forcing the bedforms became larger than expected for current ripples, transitioning towards dunes, scaling with the water depth and the bed shear stress. The time-series of maximum bedform migration rate for each tidal cycle is shown in Figure 1f. The migration rates at Site 1 appear to have been enhanced by wind-driven flow and waves. The bedforms at Site 2, which was dominated by relatively fast-flowing tidal currents, had higher migration rates than the bedforms at Site 3, where bed shear stresses were only able to move the bedforms for the first four tidal cycles.

4.2. Bed composition

The bed samples collected during the exposure period at low tide were analyzed for mud content. X-ray diffraction data, based on samples taken during the fieldwork, show that the mud fraction at the field sites contained on average 36% cohesive clay minerals and this fraction was used to calculate the clay content of the mud.

Separate bed samples were collected and analyzed for carbohydrate content (EPS) and clay fraction. From these samples it was found that low EPS fractions less than 0.04% corresponded to clay fractions below 2% at Sites 1 and 2, and high EPS and clay fractions were found at Site 3.

4.3. Flow and migration comparison

Figure 2 shows the relationship between bedform migration rate and skin friction Shields parameter for the field data, and the data of Baas *et al*. (2000) for comparison. The field data reveal a strong positive relationship between u_b and θ'_{max} for cohesive clay fractions below 2%. These low bed mud and clay fractions coincided with low EPS values of below 0.04%.

The migration rate of the bedforms in the field, for D_{50} = 227 μm, appear lower than the migration rate of the bedforms in the laboratory obtained with similar pure sand, D_{50} = 238 μm (Figure 2). When the bed material transport rate is calculated, using Equation 2, the inclusion of bedform height corrects for the difference in bedform dimensions between the laboratory and field data. This results in the bed material transport rates of mixed mud-sand from the field being not significantly different from non-cohesive sand in the laboratory at 95% confidence, for bed clay fractions below 2% and EPS fractions below 0.04%.

The clay content of the bed remained below 2% until 31 May. When the cohesive clay fraction increased above 2% (blue line, Figure 1f), the migration rate reduces below the limit of detection. This occurs despite the bed shear stress being above the threshold of motion (Figure 1d). These cohesive clay fractions above 2% cluster along the line of 'no migration' in Figure 2 (purple line).

5. CONCLUSIONS

The field bed material transport rates for sand-mud mixtures were not significantly different from laboratory results of sand-only bedforms, after the effect of waves is accounted for, when the clay content was below 2% and the EPS below 0.04%. Above these limits, which correspond approximately to where clay and EPS begin to significantly affect the migration rate and bedform dimensions in the mixed clay-sand laboratory experiments of Baas *et al*. (2013) and the mixed sand-EPS laboratory experiments of Malarkey *et al*. (2015), the cohesive forces hindered bedform migration for the presented field data.

These results are important for the application of sand-only bedform migration transport formulae in natural mixed sand-mud environments; particularly as 2% clay is within the common definition of 'clean sand' (Shepard, 1954). Existing formulae for the transport rate associated with bedform migration can only be applied below these low limits of clay and EPS content, when the sand can be considered free of physical and biological cohesion. Further research is needed to establish whether these threshold values are universal or unique to the sediment type on the tidal flats off West Kirby in the Dee Estuary.

6. ACKNOWLEDGMENTS

This work was supported by the UK Natural Environment Research Council (NERC) under grant NE/I027223/1 (COHBED). We are grateful to the NOCL Ocean Technology and Engineering group, for instrument set up and deployment, and to the Liverpool Bay Coastal Observatory for weather data.

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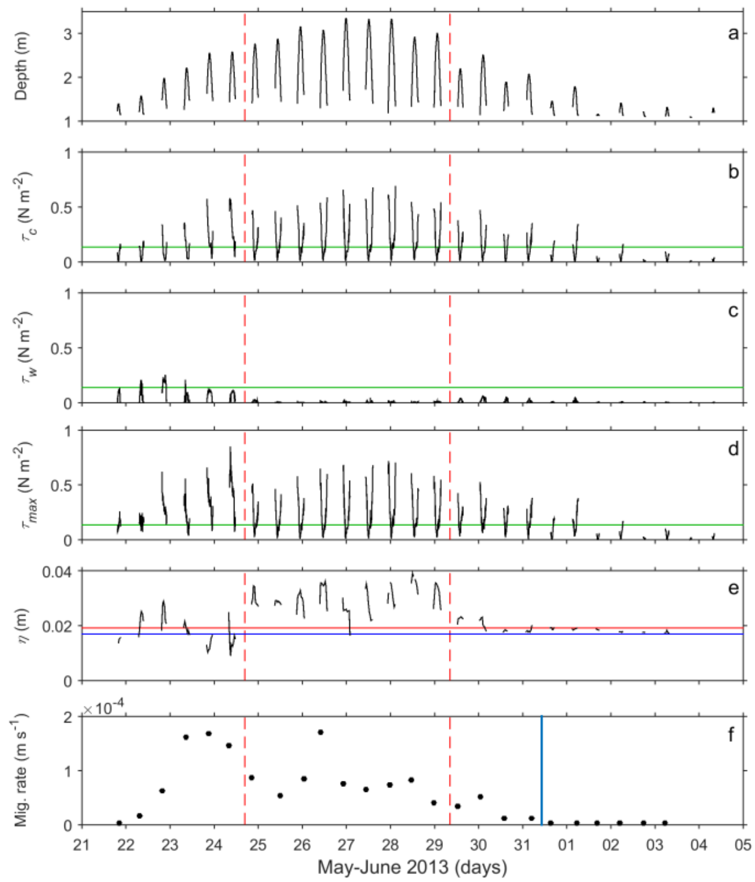

Figure 1: (a) water depth; (b,c,d) current, wave and combined maximum bed shear stress, τ_c, τ_w, τ_{max}; (e) bedform height, η, (the blue and red lines are the ripple equilibrium heights of Baas (1999), 0.017 m, and Soulsby *et al*. (2012), 0.020 m, respectively) and (f) maximum bedform migration rate for each tidal cycle (the vertical blue line marks the point where the bed clay content increases above 2%). The vertical red dashed lines separate the three sites. The horizontal green lines denote the critical stress limit of bedform migration, based on the best-fit equation for the migration data (Figure 2).

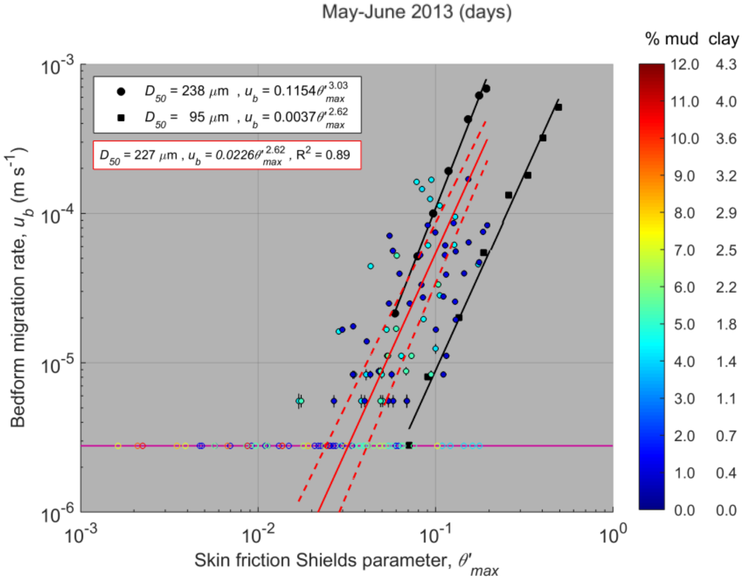

Figure 2: Bedform migration rate against Shields parameter for combined currents and waves. The color filled circles denote the field data; the black dots and squares denote the experimental data of Baas *et al*. (2000). Marker colors represent % bed mud and % bed clay fraction for the field data points. The colored open circles are bedform migration rates that were too low to be determined with sufficient confidence and lie on the purple line denoting the minimum migration rate measurable. The black lines denote the regression lines for the laboratory data of Baas *et al*. (2000). The red line is the regression line for the field data, with the red dashed lines denoting the 95% confidence limits of the regression line. The data points represented by the open circles were not included in the regression analysis. The error bars for u_b represent the 3D-ARP resolution.