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OBSERVATIONS AND PREDICTIONS OF BEDFORMS IN TIDAL INLETS AND RIVER MOUTHS

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LONG-TERM GOALS

The long-term goals of the study are to model and measure bedforms in tidal inlets and river mouths. This one-year study was intended to prepare for a longer-term study, the goals of which are: 1) using an existing self-organization model to predict multiple scales of bedform formation, growth and migration in combined steady, tidal and wave-driven flows, 2) making measurements of multiple scales of bedforms within these combined flow environments, 3) comparing model predictions with measurements (from both the literature and from a tidal inlet/river mouth experiment), 4) testing the hypothesis that subaqueous bedforms will grow indefinitely for a given set of conditions and that different scales of bedforms will occur simultaneously because of this continuous growth, and 5) incorporating this bedform model into community modeling systems to improve modeling of sediment transport and morphology change in river mouths and tidal inlets.

OBJECTIVES

The specific objectives of this one-year study are to

- develop and adapt the present model for flows in river mouths and tidal inlets (expand the model to 2-D flows, improve flow drivers, and begin to examine multiple bedform scales).
- begin working with Jim Syvitski and the CSDMS so that the present model can be incorporated into that community modeling environment.
- participate in the ONR program review in the early summer of 2010.

APPROACH

Bedforms in sandy environments are ubiquitous, occurring in rivers, river mouths, estuaries, tidal inlets and on open-coast beaches. Bedforms act as roughness elements, altering the flow and creating feedback between the bed and the flow. In doing so, they are intimately tied to erosion, transport and deposition of sediments (eg Parsons et al. 2005, Ernstsen et al. 2005). It has been suggested that bedforms in rivers and tidal inlets are dynamically similar to Aeolian dunes and bedforms on the continental shelf and in the surf zone (Best 2005, Frank and Kocurek 1996, Nemeth et al. 2007, Gallagher 2003). Because of this similarity, Gallagher (accepted 2010) developed a model for bedforms in the nearshore, based on the principles of work by Werner (1995), who hypothesized that Aeolian dunes were self-organized features and as such could be modeled with a relatively simple model.

It has been suggested that self-organization is responsible for the formation of many different types of morphological patterns, including river meanders (Stolum 1996), sorted-patterned ground (Kessler & Werner 2003), beach cusps (Coco et al. 2000), wind ripples (Nishimori & Ouchi 1993) and Aeolian dunes (Werner 1995). In each of these pattern-forming systems, complexity arises from nonlinear interactions between the system and the environment, from dissipative processes such as friction, turbulence and sediment transport, and from being open (both material and energy are exchanged across system boundaries) and therefore never in equilibrium (Werner 1999).

Werner (1995) used a 'hierarchical' approach (Ahl & Allen 1996) to modeling self-organized systems, wherein processes at different temporal and spatial scales are distinct from each other and can be separated. With this approach, grain-scale sediment transport is parameterized with simple rules to drive bedform-scale dynamics. Gallagher (accepted 2010) developed a hierarchical model to predict nearshore, combined flow megaripples. The model consists of a matrix of sediment slabs that represent a spatial domain or a region of a bed across which sediment is moving. The sand slabs are picked up and moved according to a transport model (either simple rules similar to Werner (1995) or a physics-based formulation, e.g. Bailard 1981, Ribberink 1998). Sediment transport is driven by the free stream velocity, *u*, which is modeled with a sinusoidal velocity, a measured velocity signal from the natural surf zone and with a Rayleigh distributed wave velocity signal (a new edition). At each time step, the flow is the same at all locations in the domain except for an imposed random spatial fluctuation representing local turbulence. However, once bedforms are created, the flow around the bedforms is altered via feedback: flow is reduced in the lee of a bedform to simulate a velocity shadow zone (Fig 1a) and flow is accelerated over the crest of a large bedform (Fig 1b). In addition, the slope of the bed is not allowed to exceed 17°. Feedback is required for bedform growth and development (Gallagher accepted 2010).

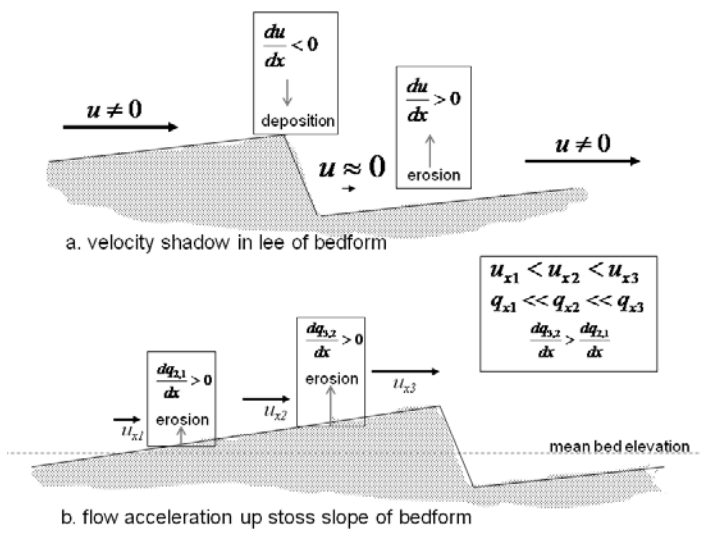

Figure 1. Illustration of feedback mechanisms employed by the model. a) There is a velocity shadow in the lee of the bedform owing to flow separation such that the velocity becomes very small when there is a steep downstream-facing slope. The figure illustrates that u is large both upstream and downstream of the slope, but near the slope the velocity is approximately zero. The resulting gradient in transport will cause erosion and deposition. b) As a bedform becomes larger, it will constrict the flow above it, causing the flow to accelerate as it flows up the stoss slope of the bedform. The figure illustrates that, as the flow accelerates, there is a gradient in sediment transport, q.

The long-term plan for this research is to work with the self-organization model, developed for nearshore bedforms. This model will be adapted for predicting bedforms in the combined flows of tidal inlets and river mouths. In these environments, oscillatory flows with wave frequencies are superimposed on the quasi-steady flows associated with tides (oscillatory but with a much longer period than the surf waves) as well as steady flows (possibly with seasonal variations) exiting river mouths. These complex, but naturally realistic, flows will be used to predict the growth and migration of dunes and the evolution of multiple scales of bedforms. In addition to combined flows and multiple scales, variations owing to spatially varying grain size will also be examined. This model lends itself to tackling these dynamically complex issues, because relatively simple changes can be implemented to test the importance of factors such as lateral flows, feedback changes, grain size and subtle 3-D morphology changes. Model results will be compared with data from the literature and with data collected as part of the River Mouths and Tidal Inlets DRI experiments in collaboration with Tom Lippmann (UNH) and Steve Elgar (WHOI).

In addition, the model will be submitted to the Community Surface Dynamics Modeling System. CSDMS is a community of experts promoting modeling of earth surface processes. They develop, support, and disseminate integrated software modules that predict the movement of fluids and the flux of sediments and solutes in landscapes and sedimentary basins (for more information see their website at http://csdms.colorado.edu/wiki/Introduction). Here, the bedform model can be used and improved by others and integrated into larger-scale morphodynamic models with the intention of improving predictions of various surface processes.

WORK COMPLETED

Significant progress has been made in adapting the bedform model for river mouths and inlets. The flow model, which drives sediment transport and bedform dynamics, has been extended from 1-D to 2D. Preliminary results suggest that this advance has improved model predictions significantly. Other improvements to the model flow field that have also improved predictions are the addition of a Rayleigh distributed wave field and the addition of flow-dependent turbulence. Other improvements that are being implemented included multiple scales of turbulence and nested domains for examination of multiple scales.

The model will soon be submitted to the CSDMS system. The CSDMS annual meeting is being help Oct 14-17, 2010 and I will be attending this meeting, participating in workshops and presenting results from this nearshore bedform modeling effort. I intend to come away from this meeting with the ability to submit the model to the CSDMS library with the necessary documentation and support materials.

Finally, I participated in the ONR program review that took place in Chicago in June, 2010. I presented work from a previously funded ONR project on sediment grain size measurements on beaches. That work indicated that indeed grain size varies significantly in space across a rip channel/shoal system and in time from one storm to the next as the rip channeled morphology changed. This work has led to funding from NSF to proceed with morpho-dynamic modeling that incorporates spatial grain-size variations. The objective of the new NSF study is to determine the importance of including grain-size information in predictions of beach morphodynamics.

RESULTS

The results of this preliminary model show a striking resemblance to observed megaripples (Hay and Wilson 1994, Gallagher et al. 2003, Clarke and Werner 2004). For example, the predicted bedforms have wavelengths of 2-5 m and amplitudes of a few tens of centimeters and they are generally short-crested with a crescentic shape if there is a steady flow (Figs 2a, b and d) and irregular and oval-shaped if the flow is purely oscillatory (Fig 2c): in plan-view modeled features look similar to observed megaripples.

Using the model to examine megaripple formation processes, it is found that bedforms will never form from a flat bed without a perturbation. The turbulent component (*va*) provides spatial variability in the flow and in resulting sediment transport across the domain. These variations lead to an initial perturbation on the bed surface upon which a feedback mechanism can work. Random perturbations of the bed surface (with *va*=0) have the same effect.

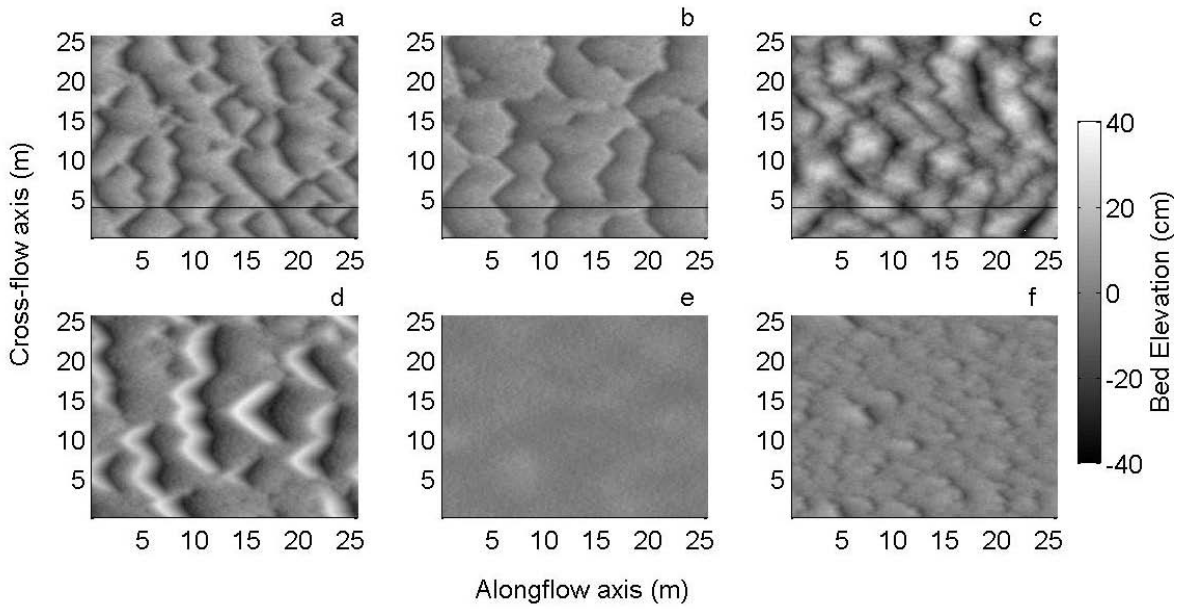

Figure 2. Plan view of simulated bedforms starting from a flat bed (onshore is to the right). In all cases (except d) the simulation was run for 13 min (~800s). In panel a) typical surf zone conditions were used with a sinusoidal flow amplitude of A=75cm/s, a period of T=10s and a co- directional steady flow with a magnitude of S=20cm/s (to the right). In b) a steady flow only (A=0cm/s, S=50cm/sec) was used to generate bedforms. In c) the steady flow was removed: A=95cm/s, T=10s, S=0cm/s. In d) the cross-shore component of measured velocities from the natural surf zone were used and the simulation was run for 4.2 hrs. In e) the model was run for an additional 13 min, starting from the bed in a), but the feedback mechanisms were both removed and the bedforms were destroyed. In panel f) a number of new flow conditions were tested simultaneously to illustrate the models capability to predict a more realistic growth rate (A(x-direction)=75cm/s, T=10s S(ydirection)=20cm/s). Lines in panels a), b) and c) are the locations of the profiles shown in Fig 3.

As has been observed in many morphodynamic systems, the growth of bedforms is owing to feedback between initially small perturbations on the bed and the flow. Once feedback is established, orderly bedforms emerge and grow, and the feedback is reinforced. This concept is tested and verified by removing the feedback mechanisms. When the velocity shadow feedback mechanism (Fig 1a) is disabled, irregularities form on the bed owing to random variations in the transport, but no bedforms

grow from those perturbations (not shown). If the acceleration-with-elevation feedback mechanism (Fig 1b) is disabled, bedforms will grow quickly and become excessively tall and steep (not shown). As depicted in Fig 1, the first mechanism acts to build bedforms and the second mechanism acts to control amplitude growth.

Thus, the model predicts that bedforms begin as random irregularities on the bed and, via feedback between the flow and the bedform, evolve into short-crested bedforms and then into longer-crested, longer wavelength bedforms. Because bedforms with lower amplitudes propagate more rapidly, small lumps catch and merge with larger lumps contributing to the growth of bedforms with time. Similarly, the flanks of irregular bumps move forward faster than the larger crests, resulting in lunate or crescentic features, if there is a net transport in one direction. A net transport in one direction also results in features that have an asymmetric profile, with a steep lee (or downstream) slope and a shallowly-sloped upstream face. Using steady flow only (Fig 2b), the present model predicts highly asymmetric (Fig 3b), three-dimensional (lunate, barchan or barchanoid ridge) features that migrate downstream and are similar to those observed and predicted in aeolian flows (Bagnold 1941, Werner 1995) and in rivers (Jerolmack and Mohrig 2005). In the nearshore, there are often combined flows (waves plus steady flows), resulting in net transport in one direction with a superimposed oscillatory flow. These nearshore flows generate bedforms that are lunate (Figs 2a and d; Ngusaru and Hay 2004) and asymmetric (Fig 3a), but whose asymmetry is reduced by the oscillatory wave motions (compare Figs 3a and b). In dominantly oscillatory flows in nature, where net flows are very small, the bedforms lose their lunate shape and their directionality, and they become oval-shaped features that are symmetric in profile (Gallagher 2003). These oscillatory flow-dominated features are well-predicted by the model (Fig 2c, Fig 3).

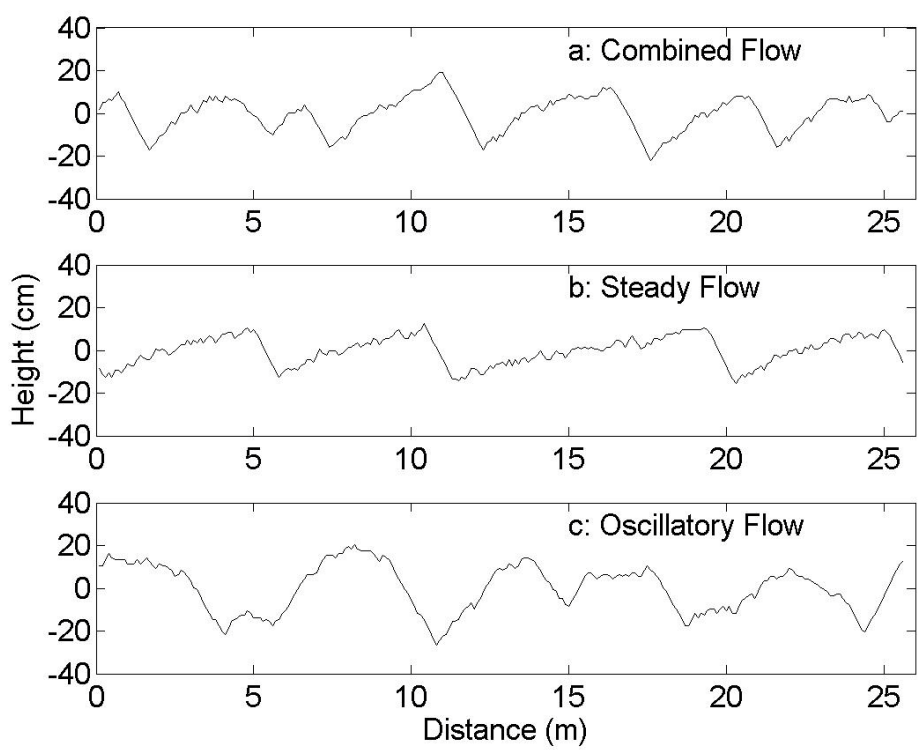

Figure 3. Profiles across simulated bedforms along lines marked in Figs 2a, b and c. In b) steady flow profiles are highly asymmetric, while in a) that asymmetry is reduced by a superimposed oscillatory current. In c), with no steady flow at all, bedforms are symmetric in profile.

As bedforms continue to evolve, smaller, faster bedforms merge with larger, slower ones, causing crest- and wave-lengths to grow. Thus, younger bedforms tend to be short-crested, shorter in wavelength and irregular in shape, while more mature features are longer in both wavelength and crest length. This merging and lengthening is observed in nature (eg, CW04) and in other modeling studies (eg, Coco and Murray 2007, Werner and Kocurek 1999, Jerolmack and Mohrig 2005). Werner and Kocurek (1999) hypothesized that there would be a change in growth rate from early fast growth to later slower growth as bedform crests became longer (with fewer 'defects' or crest ends). CW04 observed this transition in growth rate for natural surf zone megaripples. With video from above, they observed a bed that had been flattened by shallow swash zone processes and became pocked with short-crested megaripples as the tide rose. These juvenile bedforms grew and transitioned at about 12 hrs to longer, slow-growing, more mature megaripples. The present model also predicts this transition in growth rate, suggesting that the model captures well the megaripple dynamics. However, at this time, the model predicted transition time is too short. Using this transition (from early fast to later slower growth) as a benchmark of bedform age, the modeled growth rate is compared with the field observations.

In Fig 2a, the bedforms were generated with a simple sinusoidal velocity amplitude A=75 cm/sec. For sinusoidal forcing, the transition time is ~25 minutes (compared with CW04's observation of 12 hrs). To simulate a more natural growth rate, cross-shore velocities from the natural surf-zone (the shore-perpendicular component only) measured with an electromagnetic current meter in about 2 m water depth (about 0.5 m above the seafloor) were used to drive the model instead of the sinusoidal flow. A data record was chosen from a period when megaripples were known to exist (Gallagher et al. 1998) to force the megaripple model and the predicted bed after 4.2 hr (~15,000 seconds) is shown in Fig 2d. When run with the real velocity record, the growth of the modeled bedforms is slower, with the transition at ~50 min. However, this is still much faster than the natural bedform growth with the transition at 12 hr.

The difference in growth rate of modeled megaripples driven with the sinusoidal versus the natural velocities may be explained by examining the velocity records. The largest amplitudes of the natural cross-shore velocity from the measured time series are over 100 cm/s and the root mean square (RMS) is 32 cm/s. The sinusoidal flows have amplitudes of 75 cm/s and a RMS of 65 cm/s. This difference is because the measured velocities are skewed (with the strongest flows having a short duration) and irregular, with the largest velocities (>75 cm/s) occurring infrequently. So, under natural flows, high transport rates are intermittent. In contrast, the sinusoidal flows reach their maximum velocity every cycle and drive high rates of sand transport consistently. Therefore, bedforms are built more quickly under the consistent sinusoidal flows and more slowly under the variable natural flows. Neither flow field reproduces the natural growth rate and transition time of 12 hrs observed by CW04. The long transition time observed in the natural surf zone likely results from the even higher variability of the total flow field, including more realistic turbulence, more realistic acceleration on the bedform crest (acting to reduce amplitude growth), variation in direction (here only 1-D, shore-perpendicular flows are considered), variation in tidal level, which CW04 state is the dominant controller of the magnitude of the depth-dependent, wave-driven flows in the surf zone (Raubenheimer 2002), and possibly the frequent interruption of the feedback mechanisms by turbulence from breaking waves. The effect of the last mechanism on existing bedforms is illustrated in Fig 2e. By removing the feedback completely

over a bed of existing bedforms (i.e., Fig 2a), the bedforms are destroyed. This might happen in the shallow swash or under breaking waves, perhaps as the tide level changes.

As part of the present, short-term study, adaptations have been made to the model to include more realistic flows. I have recently added 2-D flows and sediment transport, a Rayleigh distributed velocity, a more realistic variable turbulence and a routine for interrupting the feedback intermittently to simulate occasional surface wave breaking turbulence hitting the seafloor. The simulation in Fig 2f shows bedforms predicted with these new flow features. In this case, with conditions similar to those in Fig 2a ($A_{x\text{-direction}}$=75cm/s, T=10s, $S_{y\text{-direction}}$=20cm/s, and a simulation time of t=800s), the bedforms are growing much more slowly. Although the full simulation, to determine time to transition (as discussed above), has not been completed, the young age of the bedforms in Fig 2f is indicated by short wavelengths, short crest-lengths and irregular lumpiness.

IMPACT/APPLICATION

This model will be adapted and applied to many different environments. At this time the model is being compared to observations from high- and low-energy conditions outside the surf zone, inside the surf zone (including cases with strong and weak alongshore currents) and in rip channels. With continued funding, the model will be compared with observations from tidal inlets and rivers. This will be the first attempt at modeling tidal inlet and river mouth bedforms with the self organization model. It is expected that a simple model of this type could be expanded to model other environments. By beginning to work with CSDMS at this time, it is hoped that this model will be easily integrated into larger-scale flow and morphology models and will help improve the predictive capabilities of hydro- and morpho-dynamics in general.

RELATED PROJECTS

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