

Modeling Dune dynamics in situations with bimodal sediment distributions.

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Abstract

Despite the significant progress that has been made in modeling dune dynamics in the marine environment in situations with abundance of movable sand, little progress has taken place in the understanding of dune dynamics in areas of mixed sediment including sand and gravel mixtures. In large parts of the North Sea, sand is transported as migrating dunes over a bed consisting of gravel. This paper presents some initial results from a multi-grain model using a Cellular Automaton type model based on the work of Bishop et al. (2008). The sediment is represented as unit slabs and the movement of these slabs within the model is based on a stochastic set of rules based on the flow and the gradient of the bed sediment. Transport takes place over a given distance that is also dependent on the local bed gradients. As part of this movement the model checks to see if the sediment bed slope exceeds a critical value, and if this value is exceeded avalanching occurs.

1. INTRODUCTION

Cellular automata (CA) have been shown to be capable of capturing the complex patterns of sand wave, ripple and dune formation, which have proven particularly difficult for conventional process-based modeling techniques to reproduce (Nield and Baas, 2008, Bishop et al., 2002, Wilson, 1972, Hammond, 1979).

The original CA models are deceptively simple and were intended to provide an understanding of the fundamental rule system which underlies the patterns and features we observe in nature (Bishop et al., 2002). In order to apply these models for prediction to the real world we need to add complexity and flexibility without losing the essential simplicity that is their major strength. Therefore, the base CA model was adapted to incorporate the ability to represent variable flow fields using process-based hydrodynamic models (in this instance the TELEMAC system), multiple grain sizes, and simplified ecological rule systems. A series of simplified tests were undertaken to demonstrate the model's ability to reproduce a range of complex bedform patterns that are

observed in nature (other than simple dunes and dune fields).

2. CELLULAR AUTOMATA (CA)

CA models are a class of individual based modeling where each particle in the model is restricted to a spatial grid (Fonstad, 2006). The spatial restriction helps reduce computational overhead in calculating millions of iterative steps of movement and these models can, therefore, be used to show how small scale processes can impact large scale patterns. Nevertheless, coding for speed is important, and the size and complexity of these models can be limited by computing power. Any instruction (rule) that is replicated may impact the overall performance severely and so there is always a trade-off between computational efficiency and rule complexity. For instance, the model developed during this project uses a 3-dimensional domain with over 40 million explicit cells, which each need to be classified and tracked through the model runs.

The large scale patterns that develop in the model are called emergent behavior of the model.

Emergent behavior is often difficult to predict from analysis of the simple cellular rules that drive the model. In a ‘strict’ cellular automaton a cell’s state is only determined by its four or eight nearest neighbors (Von Neumann and Moore neighbors, respectively). In the present case, the state of a cell can be determined by cells far distant across the grid, and multiple slabs can be ‘stacked’ on a single grid position (cell), in an attempt to parameterize the model such that the emergent behavior matches some of the patterns observed in reality.

CA models allow interactions to be defined between cells that are deterministic, probabilistic or rule based (Fonstad, 2006). In comparison to mathematical deterministic models, they are more flexible and often more simple to initialize, understand and operate. CAs have been used to model biological colonization and succession on Aeolian sand dunes (Feagin et al., 2005; Baas and Nield, 2010) and other physical sedimentary dynamics, such as river braiding (Murray and Paola, 1994).

Models specifically aimed at representing complex ephemeral bedforms such as sand dunes are often complicated and reasonably limited to highly theoretical cases (Duran et al., 2010), which is not to say they are inaccurate. On the other hand, theoretical CA models ‘look right’ and that in itself is an important fact mitigating for their benefit in capturing the essential dynamics (Wolfram, 2002). However, we must exercise extreme caution in suggesting that they are exact representations of reality and in using them for prediction when we have not tested their results rigorously against reality. There is much left to do and the best predictions are always likely to be made by using a combination of all model types (Paola et al., 2006).

3. MODEL DESCRIPTION

The model adopted to describe the underlying sediment processes is the simple one-dimensional model described by Bishop et al. (2002), hereafter called the ‘basic model’. This model was then incrementally enhanced to reflect some of the aspects of the real system we wish to model. An outline of the model is given below.

1.1. Basic Model

The model consists of a three-dimensional lattice, which can be considered as a grid of stacked slabs. The model is initialized with a stack of slabs on each cell of the grid. The model operates by picking a cell at random and moving the top slab, the moved slab is shifted forward in the direction of the current (the strength of the current determines a jump length in an integer number of cell widths). The current is parallel to one of the axes of the base grid (a ‘one-dimensional’ current) and the moved slab is deposited on top of the stack of slabs at the destination cell. A slab reaching a destination cell may ‘stick’ and remain there or ‘bounce’ and move again - this process of sticking or bouncing is designed to represent the process of saltation in the real situation where particles sometimes bounce along the ground or surface of the bed (bedload). When a cell is stuck a process of local avalanching is initiated. Avalanching involves a move to a neighboring cell if the slope of the stack of slabs in that direction is higher than the angle of repose (an initialization parameter), and the local avalanching process continues until no more slabs move. (There is a mirror image process at the site which the moving slab left, in which the angle of repose is again maintained by a process we call ‘fillback’). Once a slab has moved, and initiated an avalanche and fillback (if either or both are required) then a new cell is randomly selected and moved. A single model step is deemed to have passed once the number of random selections of cells is equal to the total number of cells in the grid - i.e. on average each cell has been selected once.

A key aspect of the basic model is shadowing, without which interesting patterns do not form (Nield and Baas, 2008). Shadows are cast by stacks of slabs downwind of the current direction at the shadow angle (which is an initialization parameter). If a slab is in shadow it does not move if its cell is selected (the selection attempt is still counted against the number for a model step). If a cell moves into a position which is in shadow it always sticks and does not bounce.

Modifications were made to the basic model to improve the application of the model to real world situations.

1.2. Variable direction currents

To vary the flow field during the simulation, a method was developed to advect each slab independently based on a current field that is overlain on the grid. In this case the current grid need not be the same as the cellular grid as long as the current can be interpolated at a center point of each grid cell. The slab is then pushed forward by the current (or in some relationship to the current resolved in 'cell widths') and lands on the cell with the center point closest to the destination. The key difficulty in this scheme is not pushing the cell forward but calculating the shadow, which will be different for each cell relative to its velocity. A critical factor here is speed of processing as any scheme selected for calculation of shadow must be comparable to the basic case where the program merely has to look along the row or column upwind of a cell. A simple straight line calculation was used to look upwind of a cell to determine if it was in shadow and allowed a restriction on the maximum distance that the shadow influence was calculated. This method is restricted to cases of smoothly varying current directions, if the current changes direction significantly within the length of the shadow a method which follows the current (in reverse) to determine shadows would be superior.

1.3. Conical avalanches on a square grid.

The basic model uses an avalanche system that is determined by the 8 nearest neighbors of a cell (Moore neighborhood - In cellular automata, the Moore neighborhood comprises the eight cells surrounding a central cell on a two-dimensional square lattice), therefore, it was assumed that the pyramidal shapes appeared due to the avalanching system not accounting for increased distance of diagonal neighbor cells compared to adjacent neighbor cells (Von Neumann neighbors). This effect was imperceptible for angles of repose relating to lower heights between neighbors as a single slab height was greater than the variation between a direct neighbor and a diagonal neighbor. As such, the random nature of the avalanching system caused approximately conical shapes. An alternative was to move to a system of Von Neumann neighbors for avalanches, however, this produced a square based pyramidal shape at 45° to the one caused by the Moore neighborhood approach.

In an attempt to create a more realistic pyramidal base the height of the diagonal neighbors were divided by the square root of 2 to account for increased distance from the center of the starting cell. This also produced a square pyramidal shape rotated at 45°. However, by taking an equal random choice of the root 2 corners and the normal system (with a similar adjustment to the angle of repose) it produced an almost conical avalanche.

1.4. Multiple grain types

In the real world marine soils are often variable in their makeup and consist of different grain sizes with different characteristics. These different characteristics will affect sediment transport and, therefore, it is considered that by being able to better represent this variability is advantageous when it comes to modeling seabed morphology. One of the principal reasons for trying to use CA type models to simulate sediment transport may well be in trying to understand what may happen when a 'slab' of one soil type of material is overlain by another type. Previous studies have taken a similar approach to explain the patterns found in terrestrial sandstone (Anderson and Bunas, 1993), but there are few studies of fluvial or aquatic dune formation. Anderson and Bunas (1993) describe a typical observed pattern of an aeolian dune, having a thin veneer of coarse particles on the upwind (stoss) slope, a coarser ridge and a finer downwind slope. They attributed this to less saltation for the heavier particles combined with the release of fine particles after impact with a heavy particle (Anderson and Bunas, 1993).

Using sediment slabs representing multiple grain size fractions is straightforward. The pick-up and deposition probabilities are varied depending on the sizes being represented. The heaviest particles might only move through avalanching.

The critical difference between a model that has specific grain types and the basic model which operates with a single sediment type is that each slab in the model needs to be identified and tracked within the computer program. In the basic model a stack of slabs on a cell are all expected to be the same, therefore, the computer needs only to record the height, thus the memory requirement to define the model is restricted to an integer value for each grid cell. However, if there are different

sediment types represented in the model and they occur at different levels within each stack then the memory requirement becomes three dimensional, the model has a 'height' and the absence of a cell is recorded as well as the type when one is present. In the present study 8 bit integer values were chosen for each cell leading to a limit of 255 types including 'no cell' and 'immoveable bedrock' cells. This system was, therefore, logical and simple to use.

4. SCENARIO'S

The results of three scenarios are presented here.

- Mound of mixed sediment in a constant current
- Bimodal sediment bed in a unidirectional variable current
- Bimodal sediment bed in a bidirectional variable current

5. RESULTS

1.5. Scenario 1: Mound of mixed sediment in a constant current

Figure 1 shows how a mixed mound of sediment (10% heavier particles) can be affected by a current travelling in a single direction. The heavier particles are not advected by the current but avalanche as the finer material is moved away, this leads to an armored mound and fine material moving away from the horns of the dune. If there is sufficient fine material it will form a separate smaller Barchan dune moving away with the current.

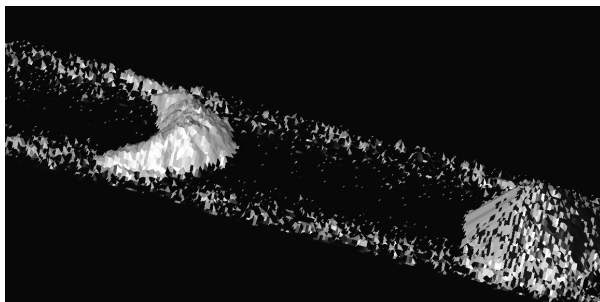


Figure 1. The sediment sorting of a mound of mixed sediments leads to a Barchan dune and ridges of fine material being formed.

1.6. Scenario 2: Bimodal sediment bed in a unidirectional variable current

Figure 2 shows the pattern emerging when the bed composition is bimodal and the forcing flow unidirectional but varying in speed. The first movement was from bottom right to top left aligned with the grid in which all the material moved in a similar way. The second subsequent phase of movement was in the same direction and the various grain sizes behaved differently. The light particles (black) moved whenever selected (and when not in shadow etc.) and the heavier particles (gray) only moved on 10% of occasions when they were picked. The pattern is slightly suppressed than with uniform condition with longer wedge shaped bedforms forming with less mobile particles on the upwind slopes and sorted faces on the downwind slopes. This is similar to the bedforms described in Boyd et al. (2006). Figure 3 shows the presence of coarse material veneers forming in the bed.

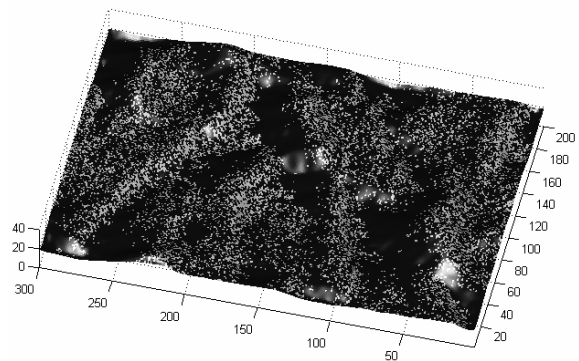


Figure 2. Bed pattern emerging from a bimodal bed under a unidirectional varying flow. Coarse material is gray, the fines are black.



Figure 3. The sorting mechanism leads to veneers of coarse (black) material underneath the mobile fines (gray).

1.7. Scenario 3: Bimodal sediment bed in a bidirectional variable current

Figure 2 shows the pattern emerging when the bed composition is bimodal and the forcing flow unidirectional but varying in speed. The first phase of movement was from bottom right to top left and aligned with the grid in which all the material moved in a similar way. The second subsequent phase of movement was in the normal direction of the grid, bottom left to top right in which the different sizes of grains behaved differently. The light (black) particles moved whenever selected (assuming they were not in shadow etc.) and the heavy (gray) only moved on 10% of occasions when they were selected. The mobile sand sorted into waves of fine material and moving over a veneer of heavy particles.

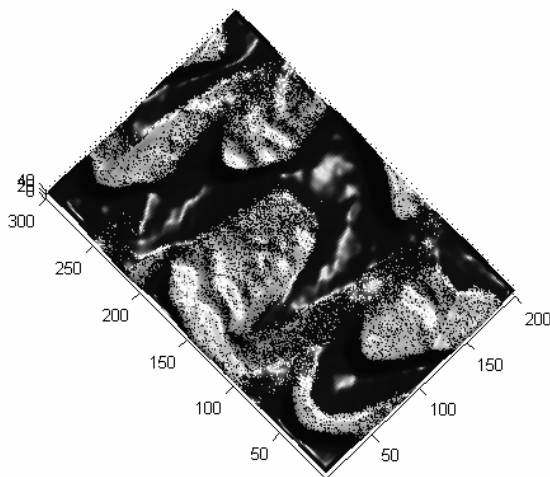


Figure 4. Bed pattern emerging from a bimodal bed under a bidirectional varying flow. Coarse material is green, the fines are blue.



Figure 5. The sorting mechanism leads to veneers of coarse (black) material mostly underneath the mobile fines (gray), but occasionally covering bedforms.

6. DISCUSSION

Two fundamental sediment patterns which occur in the North Sea are sediment sorting in bedforms and the existence of sediment veneers (HR Wallingford, 1995). Sediment sorting leads to progressively finer sediments in the direction of the current and sand wave type bedforms of well sorted finer sand. These patterns of sorting are common, and they have been used to infer the transport characteristics of the North Sea (HR Wallingford et al., 2002, Vanwesenbeeck and Lanckneus, 2000) and nearby UK coastal seas (Flemming and Stride, 1967). In this instance the veneers are defined as thin layers of heavier particles overlaying either fine or mixed sediments. In the southern North Sea the seabed sediments have been described as fine to medium grade sandy sediment overlying the underlying sediment (HR Wallingford et al., 2002). Buried veneers have also been described whereby finer material is drifting over a veneer (Flemming and Stride, 1967). A typical arrangement that is often described in the North Sea is one of sand waves covered with a veneer of heavier particles overlain by well sorted fine sand mega-ripples.

Apart from the armoring process, two processes operate that sort the sediment. First, in weakening flows the sediment to be deposited first consists of the largest grain sizes. Thus the troughs of bedforms are filled with relatively coarse sediment while the bedforms themselves consist of finer sediment. In weakening flows, such as occur over a tidal cycle, more and more sediment is deposited in the bedform troughs, leading to a fining upward sequence in the seabed below the active bedforms. This process is relatively well understood and is predictable using available bedload transport formulae for different size fractions.

The second process is due to the bedload sediment being sorted in the avalanche of grains along the lee side of the bedforms. This process is less well understood. The sediment that is transported over the length of the bedforms is deposited at the lee side of the bedforms. At the top or slightly downstream of the top the sediment avalanches from the dune. Every avalanche forms a new lamina in the set of layers called cross-bedding. During this avalanche the bedload sediment is sorted, with the coarse material being deposited preferentially deeper within the trough. The finer

material is deposited preferentially higher above the trough. The result is a fining-upward sequence in the bedforms.

7. CONCLUSIONS

Bedform formation and development in bimodal beds is simulated using a Cellular automaton. The results show patterns similar to those observed in nature. The model also captures the sorting mechanisms leading to veneers of large material in between and on top of layer of finer material.

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