Discrete Particle Model for Surf Zone Sediment Transport

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Introduction: Sediment transport in nearshore wave bottom boundary layers drives coastal geomorphologic change and can result in bathymetric changes of more than a meter in as little as a few hours, particularly in the region where waves are breaking. Predicting the evolution of surf zone bathymetry is of significant importance, with economic, legal, engineering, scientific, and military implications. Most formulae for predicting sediment transport in surf zone subsume the smallest scale physics of the phenomena by parameterizing interactions between grains. In contrast, computer simulations can be performed to directly model the collective and individual motions of sediment grains immersed in fluid. This type of simulation, known as a Discrete Particle Model (DPM),[1] is a cutting-edge research tool that is being used and further developed at NRL for studying nearshore sediment transport. In addition to sediment transport, such models, based on molecular dynamics, have a broad range of applications. For example, the DPM described here has been used to study objects impacting sediments and the formation of geologic faults. As well, similar models have been applied to traffic flow, schooling fish, crowd control, and other problems in which the particulate nature of the phenomena is of critical importance.

Discrete Particle Model: The DPM simulates the two-phase flow of fluid and sediment by coupling a one-dimensional (1D) eddy-viscosity fluid to 3D particles (Fig. 6). The DPM considers three types of interactions: grain-grain, grain-fluid, and fluid-fluid.[1] Grain-grain interactions occur between discrete elements representing sand grains. Sand grains may be represented with spheres or nonspherical elements composed of two overlapping spheres called composite particles. The particle interaction model is known as a "soft sphere" model, such that two particles may be in contact for many simulation time steps where collisions between grains are modeled with springs and friction.[2] Grain-fluid interactions include forces of buoyancy, drag, and added-mass. The model is fully coupled at every simulation time step so that the fluid exerts force on the sediment particles and the sediment particles exert equal and opposite force back on the fluid (Newton's Third Law).[3] Fluid-fluid interactions are accomplished by solving a 1D eddy viscosity model in which fluid turbulence is implicitly included through a mixing length determined by the vertical distance of the fluid from the mobile sediment layer. The effects of fluid turbulence on sediment transport rates are not well understood. Work is currently underway on the next generation of the DPM to couple a fully turbulent, 3D, direct numerical simulation of the fluid to the particles.

Research Applications: As part of an advanced research initiative, the effects of heterogeneous sediment characteristics such as size, density, and shape on bulk sediment transport rates are being explored using the DPM. These characteristics can be uniquely specified for every grain represented in a simulation, up to the present limit of 10^5 particles. Recently, the DPM was used at NRL to study the effect of particle shape on sediment transport rates.[2] A bulk property of natural sand is the angle of repose, or the angle at which a pile of sand will avalanche. Beach sands typically have an angle of repose around 33°. Similarly, glass spheres have an angle of repose around 26°. Using spheres to represent sand grains in the DPM will therefore result in behaviors inconsistent with natural grains. To alleviate this discrepancy, we constructed composite particles by overlapping two spheres (with different radii) to form a particle shape that possesses an angle of repose near that of typical beach sand. The simulations with composite particles do a much better job of reproducing sediment transport rates from laboratory experiments[3] (using beach sand) than do the simulations with spherical particles (Fig. 7).

A modified version of the DPM is being used to study large-scale morphodynamics in the swash zone. We are investigating the processes driving bed level changes at the shoreline of a beach. In this implementation, the fluid portion of the DPM has been replaced with a 2D Navier-Stokes solver. Here, the fluids exhibit vertical motions as the free surface moves up and down, while some portion of the beach face is repeatedly submerged and exposed. The first implementation of the model allows one-way coupling between fluid and particles, where particles feel the force from the fluid but do not exert any reaction force back onto the fluid. Figure 8 is an example from this version of the DPM. Here we model a thin strip of grains (~3 m long) running perpendicular to the shoreline. The grains are spherical and represent gravel

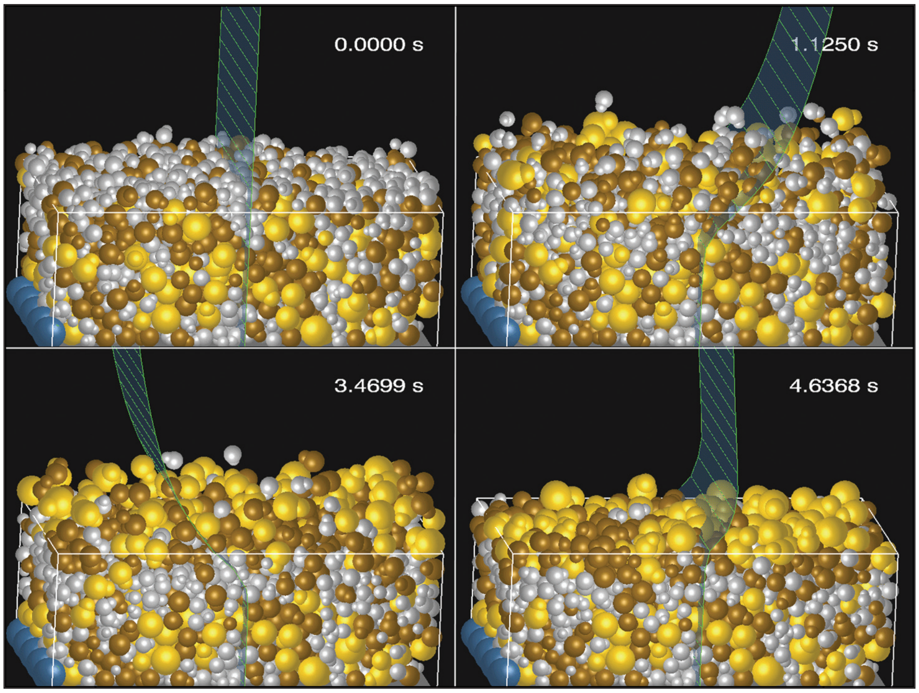


FIGURE 6
Four successive snapshots from a simulation with composite particles driven by a single oscillating wave. The fluid is represented with the green sheet. The grains are colored by size where the smallest particles are grey and the largest are yellow. The median particle diameter is 0.001 m. There is a hard bottom with a row of particles attached to the left of the plane to avoid wholesale sliding. The boundaries are periodic in the horizontal directions (0.02 m by 0.01 m), such that a particle exiting on one side is immediately inserted on the opposite side. The volume of particles is outlined with a white box. At time 0 s, the particles and fluid are at rest. At time 1.125 s, the fluid and particles have begun motion to the right. Notice that the bed has dilated in response to particle motion. At time 3.4699 s, the wave has reversed direction and motion is to the left. At time 4.6368 s, the particles have come back to rest and the fluid is beginning to accelerate back to the right again. Notice that many particles deep in the bed never experience any motion. As well, the particles that have moved near the top of the bed have sorted by size, with larger grains (yellow) above smaller grains (gray).

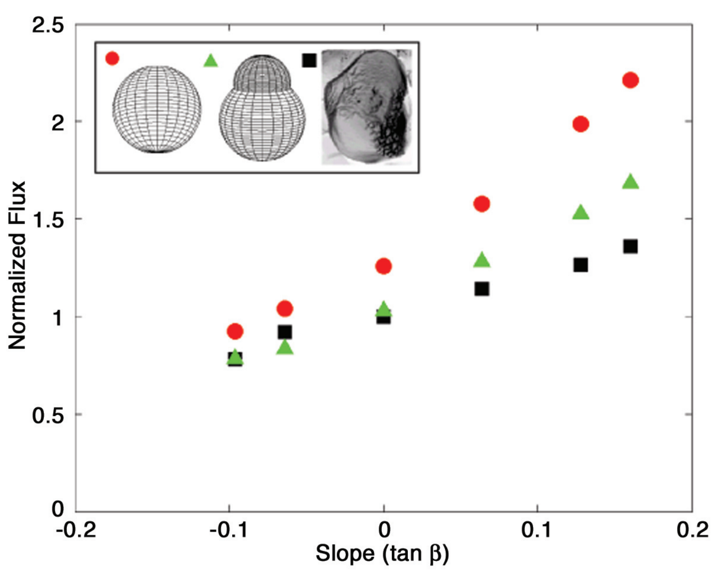
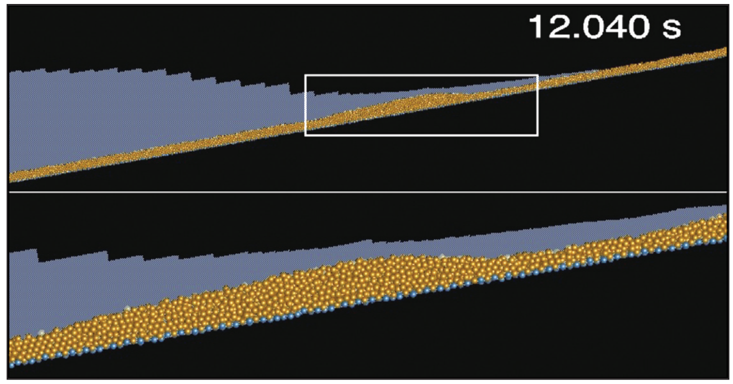


FIGURE 7
The influence of grain shape is tested. The normalized flux, representing the amount of sediment displaced, is plotted against the local bed slope for simulations with spheres (red circles), simulations with composite particles (green triangles), and laboratory experiments with beach sand (black squares). For all points, the wave simulated was constant while the bed slope is varied. The range of values for each point typically does not exceed the size of the symbol. The graphic inset shows the representative particle shape for each of the symbols used in the plot. The median particle is 0.001 m for all cases.

FIGURE 8
Snapshot from a DPM simulation of swash zone morphology. The domain in the upper panel is over 3 m in length and just 0.03 m into the page (boundary is periodic into the page). The median particle diameter is 0.01 m. The simulation uses more than 5,000 particles. The white box outlines the area shown in the bottom panel. The blue particles are fixed to the plane to prevent particles from simply rolling down the hill. The blue shading represents the position of the water.



with 0.01-m diameter. The bed was initially planar and has begun to form a step after a couple swash cycles. Similar morphology has been observed in the laboratory under similar conditions.

Summary: Despite the accessibility of the phenomena of interest, namely the motion of sand under waves on the beach, traditional approaches to modeling beach evolution are not robust, mainly because of our failure to understand the fundamental interaction forces driving sediment transport under waves. The DPM described here is a research tool that puts NRL at the forefront of small-scale sediment transport modeling. We are not trying to model every grain of sand on the beach. Instead, we model small but relevant collections of grains where results obtained at fundamental length and time scales are parameterized into simple formulae for use at larger length and time scales. Our ability to model large-scale morphodynamics (meters to kilometers and hours to days) will directly benefit Naval operations such as mine warfare, amphibious landings, and special operations.

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