Simulation and Analysis of Mass Movement Events on Asteroid Bennu. Y. Tang[1], D.S. Lauretta[1], R.-L. Ballouz[2], D.N. DellaGiustina[1], C.A. Bennett[1], and K.J. Walsh[3], [1]Lunar and Planetary Laboratory, University of Arizona (tangy14@lpl.arizona.edu), [2]Applied Physics Laboratory, Johns Hopkins University, [3]Department of Space Studies, Southwest Research Institute.

Introduction: Surface processes dictate the evolution of planetary surfaces into their current state. NASA's OSIRIS-REx sample return mission investigated the near-Earth asteroid (101955) Bennu [1], revealing a boulder-dominated surface with diverse morphologies [2]. Past space missions to asteroids have found evidence that seismic shaking and mass movement could be major contributors to surface evolution on small, airless bodies [3,4]. Evidences of similar mass movement events have been shown to be globally distributed on Bennu [5]. We conducted simulations of both sloping and seismic-shaking-induced granular flow to better understand their mechanisms in mass movement events on Bennu. Additionally, we surveyed in detail one potential mass movement site on Bennu to have ground truth for comparison.

Methodology: The simulations of granular flow used the N-body code PKDGRAV [6,7], which uses a soft-sphere discrete element method [8] to simulate particle-particle and particle boundary interactions. This code has been used previously, for example, in analysis of grain motion on Phobos [9], and on Bennu for simulations of the OSIRIS-REx sample collection event [10,11]. Surface objects can be simulated as both simple spheres or as conglomerations of spheres. Conglomeration allows studies of non-spherical shapes such as ellipsoids, which provide more realistic representations of boulders but add computational complexity and increase run times. Because the boulder survey for the area of interest has a size cut-off of 1.5 m diameter, we used a distribution of spheres that ranges from 2–6 m in diameter, and aggregates with a distribution from 1–4.86m, both following the Bennu global size frequency distribution [12]. The PKDGRAV code provides the locations, orientation, and velocities of boulders throughout the run, allowing detailed analysis of the dynamics of mass movement events.

Mass movements are induced either by the gradual sloping of the surface, simulating the Yarkovsky-O'Keefe-Radzievskii-Paddack effect increasing the rotation rate [13–15], or through oscillation of the base layer of a simulated regolith bed, similar to a seismic shaking event. For seismic shaking simulations, the parameters of the oscillation are varied for each run, and the oscillations provide a maximum force that is described by a parameter (Γ) that relates it to the gravitational force on the surface of Bennu.

$$\Gamma = \frac{A_{osc}\omega_{osc}^2}{g}$$

where A_{osc} is the amplitude of oscillation, ω_{osc} is the angular frequency of oscillation, and g is the local gravity.

To provide ground data for comparisons with simulation data, we selected an area located between 290º to 340º E longitude and 25º to 75º N latitude as a site of interest. We conducted a census of all boulders larger than 1.5 m in this area, documenting the length of their long axis, orientation, location, and albedos. We accomplished this using the Small Body Mapping Tool (SBMT) [16], which can project a ~5-cm-resolution global mosaic created using OCAMS images [17–19] onto a shape model using pointing knowledge gained from stereophotoclinometry (SPC) image processing [20–21]. Morphological data and geophysical context of the areas of interest were also compiled using the extensive data collected by the OSIRIS-REx spacecraft. The elevation was extracted using the geopotential calculated at each facet of a 3,000,000-facet SPC-derived shape model (v42, sbmt.jhuapl.edu) onto which the basemap was projected [20-21].

Results: Simulations of the mass movement reveal a considerable change in the average particle depth for different-sized particles, with the smaller particles migrating downward into the regolith bed over the course of the simulation and larger particles migrating upward slightly (Fig. 2c). This is consistent with conventional understandings of the Brazil nut effect and may help to explain the rough, boulder-dominated surface of Bennu [2]. In addition, the relatively young small craters contain finer-grained materials [22], which indicates that those materials are available but gradually removed from the top surface layer over time, and this is further supported by the large volume of finer-grained materials that was excavated from the subsurface during the sampling event [11]. These observations are consistent with the relationship between particle size and changes in average depth that are demonstrated in the PKDGRAV simulations.

The average displacement of particles along the direction of flow also slightly varies by particle size, with the smallest-sized particles moving by roughly 10% less distance over the course of the simulation (Fig. 2). This, combined with the overall depth migration of the particles, help explain the boulder distribution patterns at the site of interest. This site has a relatively even distribution of smaller-sized boulders (<3 m diameter), except for a spike near 57° N latitude and a congregation of larger-sized boulders (>3 m diameter) near 35°–50° N (Fig. 3). These surface-level observations are informed by the simulation data, where the larger boulders become more prominent at the surface as the smaller boulders migrate down.

Conclusion and Future Works: The PKDGRAV simulations have provided insights into mass movement on asteroids such as Bennu that are consistent with the data collected by the OSIRIS-REx spacecraft. Analysis of the variations in mass movement mechanism across different simulation conditions is still proceeding, but these analyses show an increase in volumetric flow with an increase in Γ, initially, but a drop-off towards high Γ (>500). The simulation of aggregates is not yet complete but will provide additional data on the orientation of boulders throughout the mass movement events.

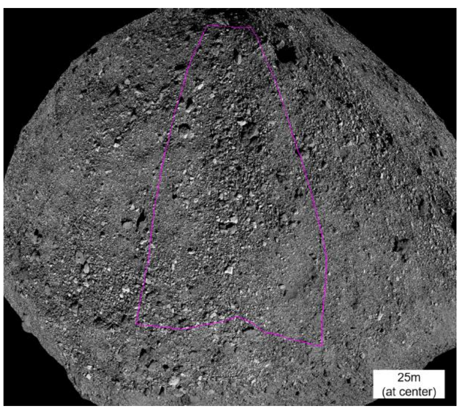

Figure 1: Image of the site of interest, located between 15º - 80º N, and 295º - 340º E

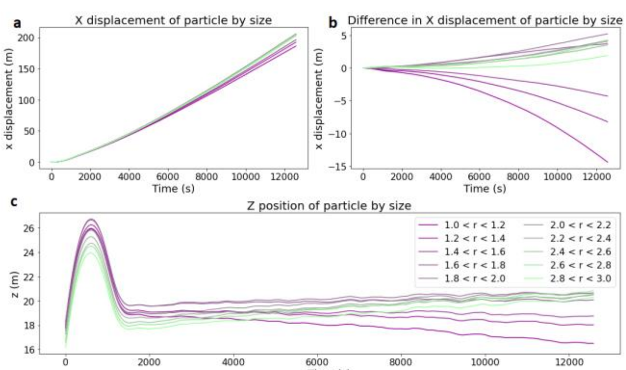

Figure 2: Data from one of the simulations, with a slope of 25°, 10-cm amplitude, and 0.0796-Hz oscillation frequency. More purple lines represent smaller particles, and greener lines represent larger particles. (A) The displacement over time of particles along the downslope direction; (B) differences in the x displacement over time for different bins of particle size; (C) the z position of different bins of particle size, with the jump at beginning due to the initial impulse from the start of shaking.

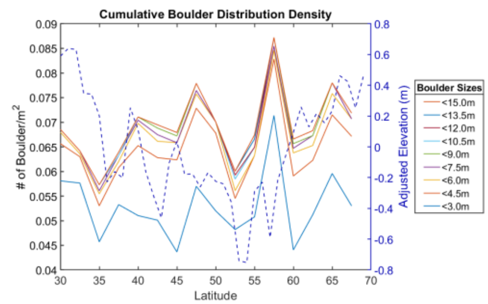

Figure 3: Concentration of boulders across different latitudes at site of interest, with each solid line representing cumulative concentrations below that boulder size. The dashed line indicates the variation of the surface elevation from the overall north-south slope of the area of interest. Although boulder concentration is similar across latitudes, different size regimes have slight latitudinal variance.

Acknowledgments: This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program. We are grateful to the entire OSIRIS-REx Team.

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