Landing on an asteroid: Simulations of the OSIRIS-REx spacecraft touching down on (101955) Bennu.

R.-L. Ballouz1, K.J. Walsh2, P. Michel2, Y. Zhang3, P. Sánchez4, D.J. Scheeres5, M.C. Nolan1, S.R. Schwartz1, D.C. Richardson3, O.S. Barnouin6, E.B. Bierhaus5, H.C. Connolly Jr.,1,6 and D.S. Lauretta1. 1Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA, 2Southwest Research Institute, Boulder, CO, USA, 3Université Côte d’Azur, Observatoire de la Côte d’Azur, CNRS, Laboratoire Lagrange, Nice, France, 4University of Colorado Boulder, CO, USA, 5University of Maryland, College Park, MD, USA, 6The Johns Hopkins University Applied Physics Laboratory, Laurel, MD, USA, 7Lockheed Martin Space, Littleton, CO, USA, 8Dept. of Geology, Rowan University, Glassboro, NJ, USA

Introduction: Granular material, in the form of regolith, is found in the uppermost layer of small bodies in the Solar System. Spacecraft exploration of near-Earth asteroids (NEAs; e.g., [1, 2]) has shown that NEA surfaces are composed of both fine regolith and larger meter-scale boulders. For asteroid sample-return missions, characterizing the geotechnical properties of the surface is critical for ensuring spacecraft safety and sampling success. Constraints on these geotechnical properties from remote observations can provide insight into their expected response from an interaction with a spacecraft; however, there is still a poor understanding of the behavior of granular materials in the low-gravity environment of NEAs. Here, we show direct simulations of the OSIRIS-REx spacecraft touching down on the NEA (101955) Bennu. We discuss how these simulations, combined with observations of the surface and telemetry from spacecraft proximity operations, can provide new insights into the behavior of granular materials in low gravity.

Low-speed impacts: Historically, our knowledge of the response of planetary surfaces to an impact has been driven by a desire to understand the cratering process [3]. Compared to impact cratering, landing on an asteroid is an extremely low-energy event. For example, a 50-m radius asteroid striking the Moon at 10 km/s has a kinetic energy of ~10^{17} J; the OSIRIS-REx spacecraft touching down on Bennu had a kinetic energy that was lower by 16 orders of magnitude. Therefore, the physics involved in these low-energy events are different to that of impact cratering, and our ability to predict their outcomes is, in contrast, immature, lacking the effort put into experimental and numerical work devoted to cratering events.

Low-speed interactions with regolith surfaces have been studied mainly through laboratory experiments of impacts into granular matter in both Earth gravity [4] and in environments that can simulate low-gravity interactions for a limited time [5]. Numerical simulations of granular material have been an invaluable tool for exploring these low-energy impact regimes as we are able to simulate the low-gravity environment of NEAs easily, and recreate the detailed design characteristics of the spacecraft or lander [6].

Simulation Method: We use the code pkdgrav, a parallel N-body gravity tree code adapted for particle collisions and further developed to explore centimeter-to-meter scale granular physics processes [7,8]. Collisions between particles are treated using a soft-sphere discrete element method (SSDEM), widely used in the context of asteroid geophysics studies [9], and implemented in pkdgrav [10].

In addition to particle-to-particle collisions, ref. [7] introduced particle-to-wall collisions, and ref. [8] introduced particle-to-inertial-wall collisions, whereby a complex structure made up of geometric primitives (e.g., cylinders, spheres, squares) can be perturbed by collisions with spherical particles. The complex structures typically behave as a rigid body [6]; however, for the simulations presented here, a set of rules for the behavior of a constant-force spring in the articulated arm connecting the OSIRIS-REx Touch-and-Go Sample Acquisition Mechanism (TAGSAM, [11]) to the main bus of the spacecraft was coded into the software. The constant-force spring activates only when a force threshold, on the order of ~ 50 N, is reached.

Simulation Setup: We simulate the interaction of the OSIRIS-REx TAGSAM with a regolith surface composed of ~ 150,000 spherical particles with radii between 0.5 and 1.5 cm, which have a cumulative size-frequency distribution described by a power law with an exponent of ~3. The particles have a grain density of 2.5 g/cm³ and the bulk density of the granular bed is ~ 1.3 g/cm³. After filling up an empty cylindrical container with grains, the granular bed is then allowed to relax in an environment with a gravity of ~ 7 × 10^{-5} m/s².

The TAGSAM is a cylindrical object with a diameter of ~ 30 cm, and is modeled to the specifications of the actual instrument. The simulated TAGSAM is attached to a simulated spacecraft bus by a cylindrical arm. The total mass of the TAGSAM and spacecraft is ~ 1300 kg. This complex structure impacts the granular surface at a speed of 10 cm/s. The interaction between spacecraft and regolith is simulated for up to 5 seconds after contact. We varied the angle of friction, φ, of the material to better understand how it may control the response of the regolith to the intrusion by a spacecraft. Furthermore, we varied the mass and speed of the spacecraft to better understand the
dynamics of the regolith to obtain a more complete picture of the impact physics in this gravity regime. Throughout the simulations, we measure the dynamical properties of the spacecraft and particles.

Results: Here, we discuss the results of varying the angle of friction as it is most pertinent for interpreting the data returned by OSIRIS-REx during the sampling maneuver. In our simulations, we found that the angle of friction of the material can have a strong influence on its response to an impact by a relatively massive spacecraft (Fig. 1).

![Image](52nd Lunar and Planetary Science Conference 2021 (LPI Contrib. No. 2548) 1349.pdf)

Figure 1. Measured penetrations depths from simulations of the OSIRIS-REx sampling mechanism after 1 s of contact with Bennu’s surface.

We found that for low angles of friction, the TAGSAM is essentially unperturbed by the spacecraft. Past a friction angle of ~ 30 deg, the constant-force spring of TAGSAM engages. There are other geotechnical properties of a regolith, not explored in this study, that contribute to the response of a granular bed. Chief among these are the inter-particle cohesion (explored for the OSIRIS-REx touchdown in [12]), and the porosity of the regolith bed. This latter property can influence the manner in which the regolith can resist the load of a spacecraft by changing the number of grain-to-grain contacts in the medium. These grain-to-grain contacts build a network of contacting particles known as a force chain, which we visualize in Fig. 2.

Discussion: The value of φ for terrestrial granular materials typically ranges between ~ 20–40 deg and is controlled by the physical properties of individual grains such as size, shape, and roughness. We find that, for cases with high φ, the grains more strongly interlock in response to motion-loading from the spacecraft’s intrusion. This allows the regolith to more readily resist penetration, leading to the spacecraft resting at shallower depths. For these same values of φ, a more porous bed may have a different response, as there will be fewer surfaces for particles to develop frictional contacts, allowing the TAGSAM to penetrate deeper into the bed.

![Image](52nd Lunar and Planetary Science Conference 2021 (LPI Contrib. No. 2548) 1349.pdf)

Figure 2. Snapshot of simulations showing the force-chain network for two cases. The color represents the normal force (N) that each particle experiences 0.2 s after contact. a) For regolith with low φ, the force chains are relatively shallow and weak. b) For regolith with high φ, the force chains are relatively deep and strong.

Acknowledgements: This material is based upon work supported by NASA under Contract NNM10AA11C issued through the New Frontiers Program and from Grant no. 80NSSC18K0226 as part of the OSIRIS-REx Participating Scientist Program. P. Michel and Y. Zhang acknowledge support from CNES the UCA IDEX JEDI “individual grants for young researchers” program and the European Union’s Horizon 2020 research and innovation program under grant agreement No. 870377 (project NEO-MAPP). We are grateful to the entire OSIRIS-REx Team for making the encounter with Bennu possible.