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Resistance forces during boulder extraction from an asteroid

Anton V. Kulchitsky [a,*], Jerome B. Johnson [a], David M. Reeves [b]

[a] University of Alaska Fairbanks, Institute of Northern Engineering, P.O. Box 755910, Fairbanks, AK 99775-5910, United States
[b] NASA Langley Research Center, Space Mission Analysis Branch, 1 N. Dryden St. Mail Stop 462, Hampton, VA 23681, United States

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ABSTRACT

Planning for NASA's Asteroid Redirect Mission (ARM) requires estimating the forces that appear during extraction of a boulder from the surface of an asteroid with unknown surface regolith properties. These forces are estimated for a vertical constant force or acceleration pull and a rolling, constant force, torque (peel) on a 4-m diameter spherical boulder using both analytic and discrete element method (DEM) models considering the effects of microgravity and regolith cohesion using Johnson–Kendall–Roberts (JKR) model. Estimates of the bulk asteroid regolith cohesion strength derived from lunar and asteroid regolith studies ranged from 25 Pa to 250 Pa. JKR cohesive forces at particle contacts depend on particle surface energy and effective curvature radius (particle size). DEM particle size dependent cohesion parameters are linked to estimated regolith cohesion strength by simulating shear and tension tests over a range of DEM particle surface energies resulting in the formulation of the dependence of particle surface energy as a function of cohesion strength and particle size. Maximum extraction forces occur for a vertical pull through the boulder center of mass with constant acceleration. Extraction force decreases for a constant force pull to $0.62 p_c S$ where S is the boulder surface area embedded in the regolith and p_c is the cohesion strength of the regolith. Boulder extraction by peeling produces the smallest forces by up to more than a factor of 2, as the failure across the boulder surface increases progressively rather than being fully engaged as occurs during a vertical pull extraction. Variations between DEM and analytic results differed from 9% to 17% over the range of regolith cohesion values and peel extraction leverage.

1. Introduction

NASA's Asteroid Redirect Mission (ARM) is based on the concept of redirecting asteroidal material to the Earth–Moon vicinity [3]. The robotic portion of the mission, would rendezvous with a 100–1000 m diameter near-Earth asteroid (NEA) and retrieve a 1–5 m boulder from the surface and return it to a lunar orbit for astronauts to explore [17].

To inform mission design parameters, it is important to identify the forces required to separate the boulder from the surface of the asteroid. The magnitude of the forces depends on the size and shape of the boulder, the strength of the regolith, the depth the boulder is buried, the acceleration imparted to the boulder during extraction, the method of extraction, the mass forces of gravitational attraction, and apparent centrifugal force due to asteroid rotation.

The goal of this work is to estimate the reaction forces acting on a boulder from the regolith in microgravity conditions during the extraction process based on the assumption that these forces are mainly due to adhesion between regolith grains and the boulder and cohesion between regolith grains. The boulder extraction method is also investigated by looking at a vertical pull, as well as a pull with rolling torque applied (peeling). The boulder shape is chosen to be a sphere to eliminate shape as a variable and to have results that can be readily compared to results from any future experiments.

These forces are first theoretically estimated and then modeled using the COUPi (Controlled Objects Unbound Particles interaction) discrete element method (DEM) model [19,14]. A fully implemented Johnson–Kendall–Roberts (JKR) adhesion model is used to calculate particle-to-particle regolith cohesion and regolith to asteroid adhesion. The JKR model is the most widely used contact mechanics adhesion forces model [10,11,20]. DEM simulations are used to estimate regolith cohesion parameters for the theoretical model approach and to directly perform simulations of boulder retrieval in the asteroid surface reference frame and calculate the reaction forces.

Two methods of extracting a boulder were examined: (1) constant acceleration and (2) constant force applied to the boulder. Constant acceleration and constant force represent two different control modes for applying force to separate the boulder and lift it

* Corresponding author.
E-mail addresses: anton.kulchitsky@alaska.edu (A.V. Kulchitsky), jbjohnson5@alaska.edu (J.B. Johnson), david.m.reeves@nasa.gov (D.M. Reeves).

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off the surface of the asteroid. A constant force control mode will simply apply a constant force through the actuators. While this mode is simple and does not require any feedback, it might result in a failed attempt in cases where the attempt does not exceed the maximum cohesive force and could also result in a wide range of final velocities since the exact cohesive force profile will be unknown. The constant acceleration control mode will require feedback, but will allow the vehicle to adjust to a cohesive force that is stronger, or weaker, than expected to ensure separation and will also result in consistent final velocities. However this could result in higher than expected forces and require force monitoring to ensure limits are not exceeded.

2. Asteroid regolith strength

The strength of regolith, and other granular materials, is typically defined by the maximum stress that the material can support in compression, shear, or tension [6]. Compression strength can depend on regolith initial packing density and shear strength. At present, no direct measurements of strength for asteroid regolith exist. Estimates of strength for tension and shear are based on values determined for near-surface low packing density lunar regolith [18,25,26,4] or from theoretical analysis of the relationship between asteroid size/spin rate curves [22].

Analysis of asteroid size/spin rate curves assume that a spinning asteroid remains a coherent body so long as the tensile strength of the asteroid is greater than the spin generated tensile stresses due to centripetal acceleration acting on the asteroid's body. Once the spin rate induced tensile stresses equals the asteroid's tensile strength, the asteroid undergoes a disaggregation into smaller objects that can include boulders and finer material [22].

Asteroid regolith strength is affected by its packing density, regolith particle size and shape distribution, particle contact friction and degree of particle interlocking, weight due to asteroid gravitational acceleration, electrostatic forces, solar radiation pressure, van der Waals cohesive forces between regolith particles and adhesion between regolith particles and boulders. The strength can also be affected by cold welding and the presence of water or ice in the asteroid as recent observations of water vapors around Ceres [15] may indicate. Van der Waals cohesive forces are considered to be a dominant contributor to regolith strength, competing with regolith weight, but greater than electrostatic and solar radiation pressure forces [18,22,23]. The contribution to regolith strength caused by interlocking of sharp regolith particles has not been examined for the low gravitational field of asteroids, but is considered to be a major source of apparent cohesion for the near-surface lunar regolith [4,24].

While gravitational force can be easily estimated for any particular asteroid, the adhesive force is unknown. Therefore, this work is focused on estimating the adhesive force isolated from gravitational force. Moreover, gravitational force can be estimated to be significantly smaller factor during boulder extraction for the boulders and asteroids that are considered for this mission. For example, an asteroid of a size around 1000 m, which is the largest asteroid we consider, has a free fall acceleration at the surface not exceeding 1 mm/s^2. Therefore, for a 4 m boulder of 2000 kg/m^3 density, the gravitational force would not exceed 40 N. This is significantly less than our low estimate of the adhesion force of more than 100 N even for the smallest considered regolith cohesion strength of 25 Pa and for the best force application method (see Section 7).

By assuming that the dominant source of regolith strength is due to van der Waals cohesion between regolith particles and analyzing the size/spin rate distribution of asteroids, Sanchez and Scheeres estimate a lower bound for asteroid tension cohesion to be 25 Pa [22]. They also examine the effect of higher asteroid cohesion by using weak lunar shear cohesion of 110 Pa and strong lunar shear cohesion of 3000 Pa. Estimates of lunar shear cohesion in the upper 0.15 m of lunar regolith range from 440 Pa to 620 Pa based on in situ physical interactions between astronauts, landers and penetrometers with the lunar surface [4]. Sanchez and Sheers [22] treat both tension cohesion, which is the tensile strength of regolith under tensile normal stress and zero shear stress, and shear cohesion, which is the shear strength of the regolith under zero normal stress, the same. Shear and tension cohesion differ in that shear cohesion is an apparent cohesion that is due to particle interlocking and contact friction as well as van der Waals cohesion between regolith particles while tension cohesion is primarily the result of van der Waals cohesion (see Fig. 1). The difference between shear and tension cohesion is likely too small to affect the overall analysis of regolith strength [1], however, assuming shear cohesion values to represent tension cohesion values may result in overly conservative estimates for regolith tensile strength for the same particle surface energy value.

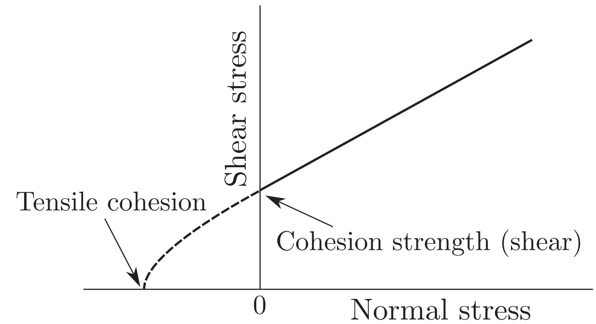

Fig. 1. Mohr–Coulomb soil yield surface. Difference between tensile cohesion and shear cohesion strength.

3. Discrete element method approach

The process of failure of cohesive granular matter during boulder extraction from an asteroid is difficult to simulate continuously as the separation process is not continuous by its nature and involves many particle separations and reconnections. On the other hand, it is also impossible to simulate the actual particle size distribution of regolith in DEM simulations as it would require unrealistically large computational resources. To address both issues, we use the DEM approach with equal particles that are larger than expected regolith particle sizes, but still much smaller than the boulder. The ensemble of particles in the DEM model represent the bulk of the material and the size of the particles can be considered as a “resolution” of the model. In this case, the deformation and failure of the granular matter can be simulated if other parameters are chosen properly and the particle size is sufficiently small compared to the size of the boulder.

Discrete element method models represent the evolution of an ensemble of interacting rigid particles. The key component of the method is determined by the contact model used for describing the particle interactions. In this work, we use a modification of the Hertz–Mindlin model with damping and cohesion terms as described below.

3.1. Hertzian contact

Hertz derived the expression for the force of a contact of two spheres without cohesion as a function of displacement δ. The main assumption of this contact mechanics approach is that the