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Numerical modeling of Bennu's structural stability and implications for its internal and surface properties

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- **Introduction**

Previous studies have shown that material strength and density heterogeneity play important roles in asteroid reshaping processes through YORP spin-up (Holsapple 2010). The final shapes are also dependent on the magnitude and distribution of these intrinsic properties. In turn, material properties as well as the reshaping history of an asteroid could be revealed by examining its detailed morphology. The high-resolution shape, detailed surface characteristics, and internal density distribution of (101955) Bennu measured by the OSIRIS-REx mission (Barnouin et al. 2019; Walsh et al. 2019; Scheeres et al. 2019; Lauretta et al. 2019) now grant us an opportunity to decipher its material properties from its current state.

- **Methodology**

We use the Bennu shape model with a resolution of 1.68 m per facet derived from the data collected by the OSIRIS-REx Laser Altimeter (Seabrook et al. 2019; Barnouin et al. 2020) to construct rubble-pile models consisting of ~10,000 to ~100,000 spheres with different particle size distributions. The soft-sphere discrete element method is applied to simulate the spin-up process of these rubble piles (Schwartz et al., 2012; Zhang et al., 2017, 2018). The contact interactions between the constituent spheres are used to control the material shear and cohesive strengths. We study the behaviors of our simulated rubble piles against rotation as a function of frictional and cohesive properties.

- **Results**

In response to the rotational acceleration, we find that the contact-force networks adjust themselves to maintain the overall stability. The stress distributions in the Bennu rubble-pile models change with the spin rate. When no cohesion is included, the local regions subject to the highest shear stress are located near the surface at the slow spin state and shift to the interior during the subsequent spin-up. The critical spin period value of this transition decreases with a larger friction angle of the asteroid. For example, with a friction angle of ~20°, this transition occurs before achieving a spin period of ~ 5 hr and the Bennu rubble-pile model begins to fail internally and deform before achieving the current spin period of ~4.276 hr (Barnouin et al. 2019). With a friction angle of 30°, the rubble-pile Bennu is able to marginally keep its structure stable at 4.276 hr with an internal region subject to the highest shear stress. When the friction angle is larger than ~37°, the most sensitive region subject to the highest shear stress occurs at the surface at Bennu's current spin rate. Since some recent surface mass movement is evidenced on Bennu (Jawin et al. 2020), Bennu's material may have a high friction angle larger than 37° to promote surface movement. This friction-angle magnitude is common for terrestrial granular materials and is comparable to the maximum surface slope of Bennu (~40°).

The critical spin period to induce structural failure for Bennu modeled as a rubble pile with a friction angle of ~37° is ~3.4 hr, which is notably faster than its current spin period. If this is the case, Bennu might have been spun up to a spin period smaller than 3.4 hr in the past to induce some macroscopic reshaping effects. The critical spin period decreases to 2.6 hr if the rubble-pile material contains a small amount of cohesion ~ 3 Pa that is homogenously distributed. This fast critical spin state would lift any surface material that is not cohesively attached to the surface. This is inconsistent with the recent surface mass movement observed on Bennu. Furthermore, the structural failure is induced by surface cracking, preventing surface shedding from occurring. Therefore, our study suggests that Bennu should not have an overall cohesion larger than ~3 Pa.

However, if the cohesion distribution is highly heterogeneous, it is possible that some regions have a large material cohesion and some other regions are cohesionless. This inhomogeneous cohesion distribution is consistent with the estimated porosity and boulder distribution on Bennu, and could account for the formation of the observed features such as longitudinal ridges and internal heterogeneity.

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