THE SENSITIVITY OF APOPHIS' NECK TO RESURFACING DURING THE 2029 EARTH FLYBY. Y. Kim[1], M. Hirabayashi[1], R. P. Binzel[2], and M. Brozović[3], [1]Auburn University, Department of Aerospace Engineering, Auburn, AL 36849 (yzk0056@auburn.edu), [2]Massachusetts Institute of Technology, Cambridge, MA 02139, [3]NASA/JPL Caltech, Pasadena, Ca 99190.

Introduction: Surface modification processes derived by solar wind irradiation [1] and micro-meteorite bombardments [2], which are known as space weathering, cause optical variations in an asteroid's surface. On the other hand, resurfacing processes expose fresh (unweathered) materials located beneath the weathered surface layers, inducing their spectral alterations. While studies have explored these processes for decades, the detailed mechanism of resurfacing is still not well understood.

Expected to have the closest Earth flyby within 6 Earth radii on April 13, 2029, (99942) Apophis is considered to be a key opportunity for investigating this unknown geophysical process. It has been proposed that tidal effects from the Earth may contribute to the resurfacing process on asteroids, resulting in either shape modification or landslides or both, which may expose fresh surface materials [3-6]. To evaluate this process acting on Apophis during the Earth encounter in 2029, we develop two types of numerical models that can analyze the surface evolution and structural failures on rubble-pile asteroids that are affected by tidal effects.

These techniques can be directly applicable to geophysical assessments of the resurfacing process on Apophis by providing possible resurfaced and structurally failed regions. This analysis will help suggest more accurate physical properties, i.e., cohesive strength and design Earth-based and possible in-situ missions. Furthermore, by providing further understanding of the surface and structure evolution that affect the dynamic motion of Apophis during the tidal encounter, this study will eventually assist in proposing suitable guidelines for planetary defense technologies and strategies for mitigating the asteroid impact risk.

Methodology: We first use a dynamic model [7] for computing the surface slope evolution of Apophis during the flyby with the radar-derived shape model [8]. Second, we employ a finite-element model (FEM) approach [9] to estimate its structurally failed regions based on the structural strength.

Dynamic model. This model computes the surface slope evolution during the 2029 flyby by simulating the orbital and spin evolution of Apophis. The surface slope describes how the surface element is tilted from the direction of gravity, depicting a surface topography. In the analysis, the orbital information of Apophis is obtained from NASA/JPL's Horizons web interface [https://ssd.jpl.nasa.gov/horizons.cgi] within six days during the encounter with a time step of 30 min. To define the initial conditions of the spin state of Apophis in the simulation, its attitude is evolved by using the Euler equation with a torque driven by the tidal effect from the Earth. Then, the surface slope of Apophis is computed based on the direction of the gravity force, the tidal force from the Earth, and the rotation-driven force on each facet. This model uses a 4th order Runge-Kutta integrator implemented in MATLAB.

The shape model has a contact binary shape with an equivalent diameter of 335.80 m and has 2,000 vertices and 3,996 facets. The bulk density is assumed to be 2.0 g cm^{-3}, considering the material density of chondrites having 40% porosity [10], and the material distribution to be uniform. We note that this model only considers Apophis' top-surface layer, not its structural strength (i.e., cohesion). Considering earlier analyses that asteroids' surfaces are covered with a structurally weak layer that consists of non-cohesive grains within tens of micrometers [10-12] and a space-weathered rim on (25143) Itokawa is very thin (~80 nm) [13], we can expect that even mass movement in this thin layer removes the space-weathered layer, leading to the exposure of fresh materials. The dynamic model reasonably provides the locations of resurfacing in top-surface layers.

FEM approach. This model estimates the conditions of structural failure on Apophis by the tidal force during the 2029 Earth flyby. The FEM analysis predicts how the surface and sub-surface regions that may have low cohesion [14,15] are structurally failed, leading to additional resurfacing. In simulations, we set the cohesive strength manually as the lowest value, causing structural failures. Based on the earlier studies for the FEM approach [9,16], the friction angle, Young's modulus, and Poisson ratio are set to be 35 deg, 10^7 Pa, and 0.25, respectively [17]. The applied FEM mesh is a three-dimensional 10-node mesh that is generated from the radar-driven shape model [8] using Tetgen [18], which includes triangular 17,186 elements and 27,590 nodes. The ANSYS FEM solver gives elastic-plastic solutions by applying loadings acting on each node in the FEM mesh. The elastic condition is described to be linear elasticity, while the plastic condition is based on perfect plasticity. The yield condition is defined by The Drucker-Prager yield condition [19].

Results and Applications: As Apophis closely passes the Earth, the body is affected by time-varying forces, inducing the surface slope variation. To analyze the possible regions for resurfacing due to the slope

variation, we consider two types of material flows depending on the analytical theory and numerical analysis of erosion for transport-limited downslope flow. First, when the surface slope reaches its critical slope, fast material flows start to occur [20]. We define the critical slope as the angle of repose of 35 deg for a typical geological material without cohesion [17]. Second, even if the surface is not in the critical state, slow material flows happen when the slope variation is considerable enough to cause surface mobility [21]. Ballouz et al. (2019) numerically showed that the surface slope variation of ~2 deg causes the slow material flows on the Martian moon, Phobos [21].

We simulated 1000 cases that have different initial settings for the spin orientation within the plausible range because Apophis' spin state uncertainty is still very large [8]. The following results show a specific case that has the most considerable surface slope variation during the close encounter. Fig. 1 describes the maximum surface slope on each element, while Fig. 2 depicts the maximum slope variation. In the current shape model, some regions initially have high surface slopes, in which around or exceed the angle of repose. We note that the initially high-slope regions and the surrounding areas are likely to experience material flows. The red regions in Fig. 1 would have the fast material flows, while the surrounding areas (the black dotted regions in Fig. 2) would experience slow material flows because of the large surface slope variation of ~2 deg. In the proximity of Apophis, we also found that locations of resurfaced regions would be more affected by its shape than spin orientation.

Our FEM analysis shows structurally failed regions in the surface and sub-surface (Fig. 3). The cohesive strength to cause structural failure during the close encounter is estimated to be 0.3 Pa, which is very weak. The failed regions (the yellow regions in Fig. 3) approximately match the possible resurfaced regions from the dynamic model and specifically show that the neck regions would become structurally unstable.

Although the resurfacing is correlated with Apophis' shape, the used shape model has high uncertainties due to the weak radar signals. Thus, we expect the future radar observation in March 2021 will improve Apophis' shape and spin estimates, allowing us to provide further constraints on resurfacing.

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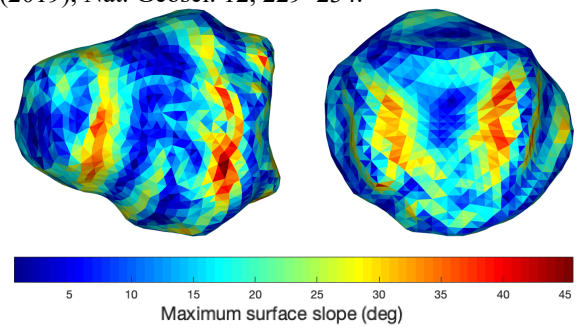

Fig. 1. Apophis' maximum surface slope during the 2029 Earth flyby. If the angle of repose is higher than 35 deg, fast flows may occur.

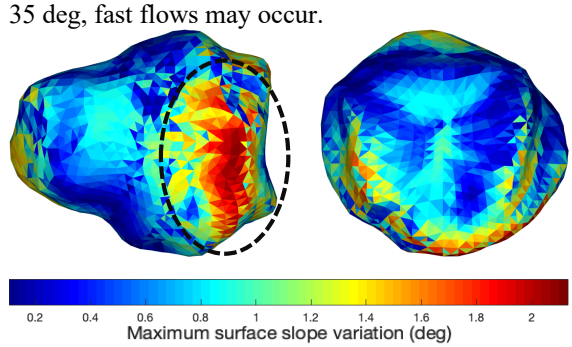

Fig. 2. Apophis' maximum surface slope variation during the 2029 Earth flyby. The black dotted line represents regions that have high slope variations.

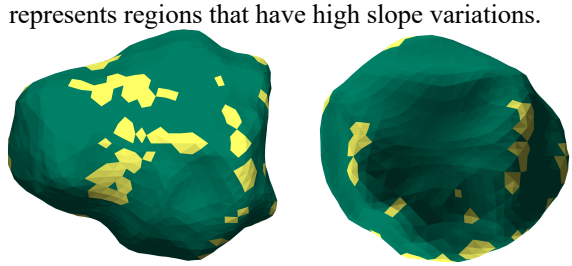

Fig. 3. Apophis' structural failures at the closest approach. The yellow regions describe failed regions where the current stress exceeds the yield condition.