Using a Discrete Element Method with Realistic Packing and Irregular Particle Shapes to Investigate Seismic Response of 99942 Apophis During its 2029 Tidal Encounter with Earth

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Background

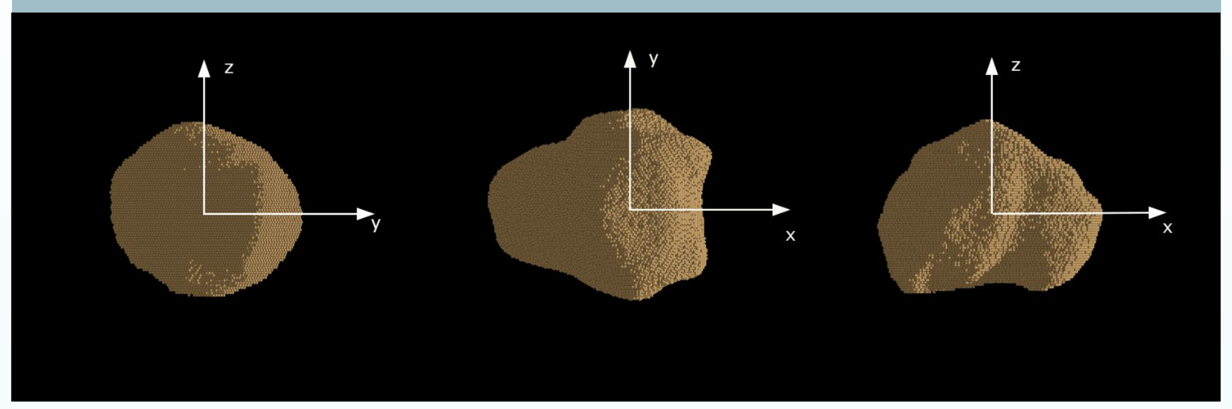

Fig.1: (From [1]) 3 Views of the best-fit shape model of Apophis derived in [2] filled with homogeneous spheres in a hexagonal close pack (HCP) configuration.

99942 Apophis will pass within ~6 Earth radii of our planet on Friday, April 13th, 2029 [2, 3]. Results of radar observations of the body in previous close passes indicate Apophis is likely a bilobate, Sq-type asteroid with a diameter around 400 m [2, 4] and is a suspected rubble pile (Fig. 1). The spin state of Apophis is understood to be tumbling, with a 262 hr rotation period and a 27.38 hr precession period, making for an averaged rotation period of 30.56 hrs [5]. There is currently no measurement of bulk density for Apophis, and the uncertainties in the complex tumbling state of the body mean that the orientation at the time of the 2029 close approach is uncertain, but both bulk porosity and encounter orientation may play a large role in the response of the assumed regolith surface to tidal forces from the Earth in the encounter [1]. Here we show an extension of the work of our 2019 paper regarding the seismic response of Apophis during its close encounter and argue that the passive seismic experiment of the Earth-Apophis 2029 tidal encounter represents a significant opportunity for understanding rubble pile interiors and should be considered a prime target for a future space mission focusing on in-situ seismic measurements of near-Earth objects.

Numerical Model & Approach

We model Apophis as a gravitational aggregate of discrete spherical particles using the parallelized *N*-body gravity tree code *pkdgrav* [6]. Particle contacts are modeled by a soft-sphere discrete element method [7] which allows particles to overlap at the point of contact, with the degree of interpenetration mediated by a Hooke's Law restoring spring force with spring constant (analogous to Young's Modulus), friction, and energy damping chosen to mimic gravel- or silt-like material with friction angle ~35 degrees [1, 8].

To produce our models of Apophis, we use the best fit shape model derived by Brozovic *et al.* [2] and fill it with 10^4 spheres in two different ways: a hexagonal close pack configuration (HCP; the most efficient packing for monodisperse spheres) with particles of radius ~7 m, and a random polydisperse packing (RPP) configuration with particles of radii ~2 to ~7 m following a power law size frequency distribution with slope -3 [Itokawa reference]. We then choose 32 initial orientations from a sample following the nominal solution in [5] and allow the particles to settle under self-gravity and the average 30.56 hr retrograde rotation period before sending the body along the nominal orbital path by the Earth (modeled as a single sphere) from the 2018 ephemeris starting ~5 hrs. before perigee and continuing for ~5 hrs after.

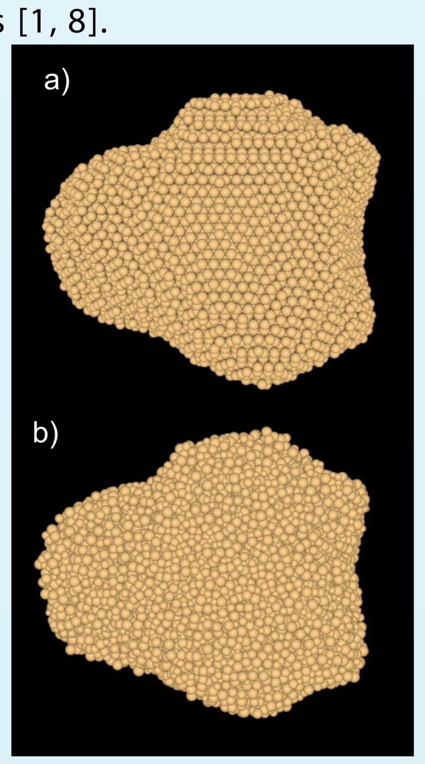

Fig.2: a) HCP Apophis model (as in [1]). b) RPP Apophis model. Note that porosity differs in these models (~26% in HCP and ~45% in RPP) while bulk density remains the same (nominal value: 2.7 g/cc)

Previous Work: HCP, Influence of Body Orientation & Young's Modulus

Analysis

We measure the change in separation between particle pairs at the ends of each of the primary body axes (and 10 randomly chosen pairs throughout the body) and plot a histogram of the maximum change in particle separation measured along one of the principal axes for each run (Fig. 3a). We also investigate the influence of our choice of Young's modulus and particle size.

Results:

- The choice of Young's Modulus for the material is inversely proportional to the maximum strain we measure in our simulations, making it the most influential factor.
- The encounter orientation has the second strongest influence on the strain.
- Particle size does not strongly influence the measured strain.

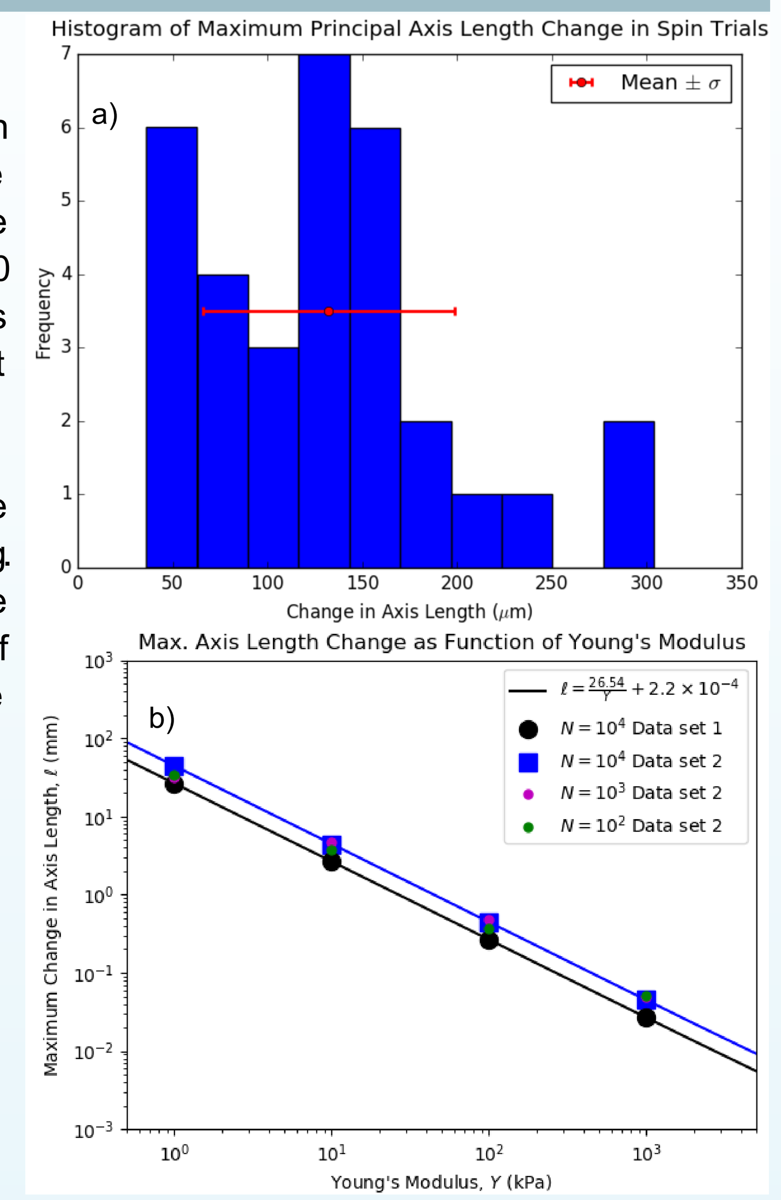

Fig. 3: (From [1]) a) Maximum change in separation between particles located at the ends of the principal axis of Apophis which felt the most change over the encounter for trials over 32 encounter orientations. Typical change in axis length is 0.13 mm. b) Scaling of axis length change as a function of Young's modulus (showing an inverse relationship) and relative unimportance of particle resolution.

New Work: RPP, Influence of Body Orientation, Comparison of Change in Spin Period

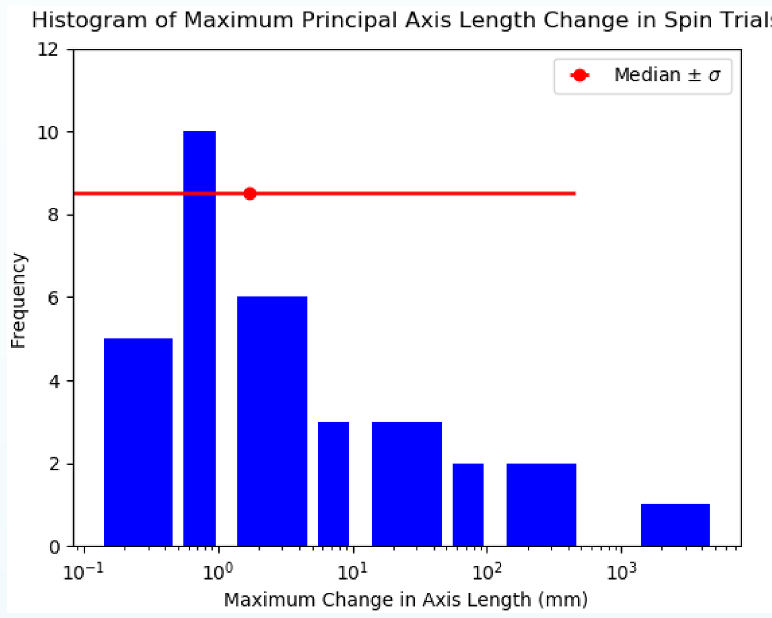

Fig. 4: Maximum change in separation between particles located at the ends of the principal axis of Apophis which felt the most change over the encounters with RPP Apophis model, for comparison to Fig.. 3a. Note x-axis in log-scale and with units in mm.

Results:

Analysis was performed as in the HCP encounters. Figures shown side-by-side for comparison.

- Encounter orientation now has the strongest influence on measured strain
- Maximum strain is on the order of a particle radius: meter-scale boulders along the primary axes may come out of contact with neighbors.
- Little change to results regarding change in spin state (see Fig. 5).

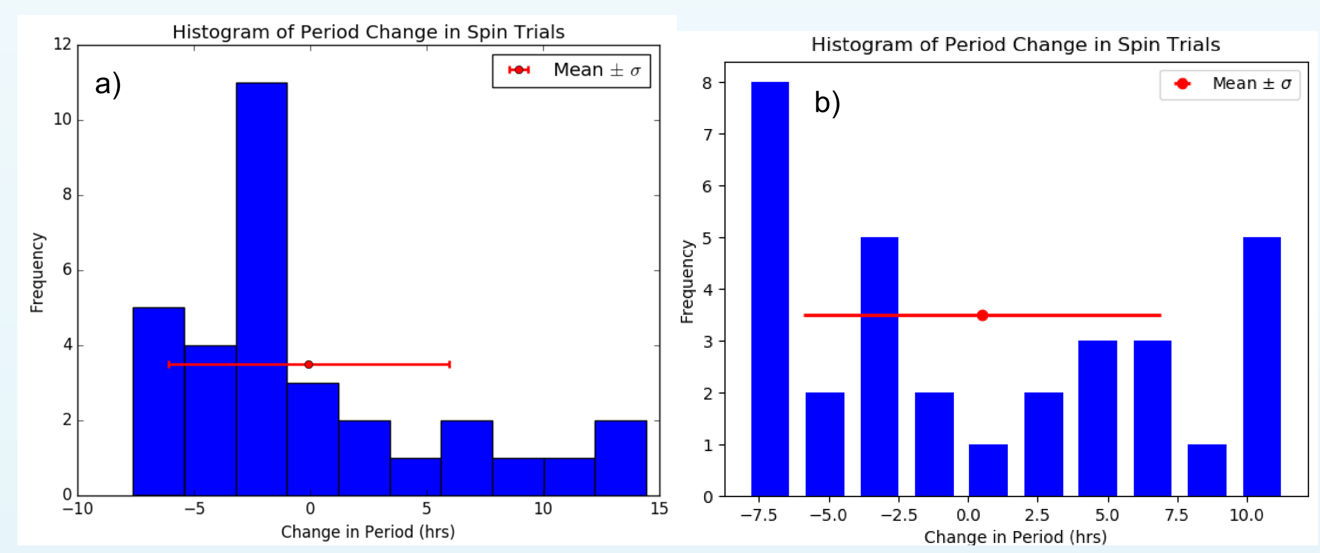

Fig. 5: Change in bulk spin of the body (hrs) from the start to the end of the simulation for HCP spin orientation trials (a) and RPP spin orientation trials (b). Relative agreement between the results indicates that changes to rotational properties are unlikely to be strongly influenced by the packing structure of the regolith making up the body.

Potential Measurable Seismic Signal

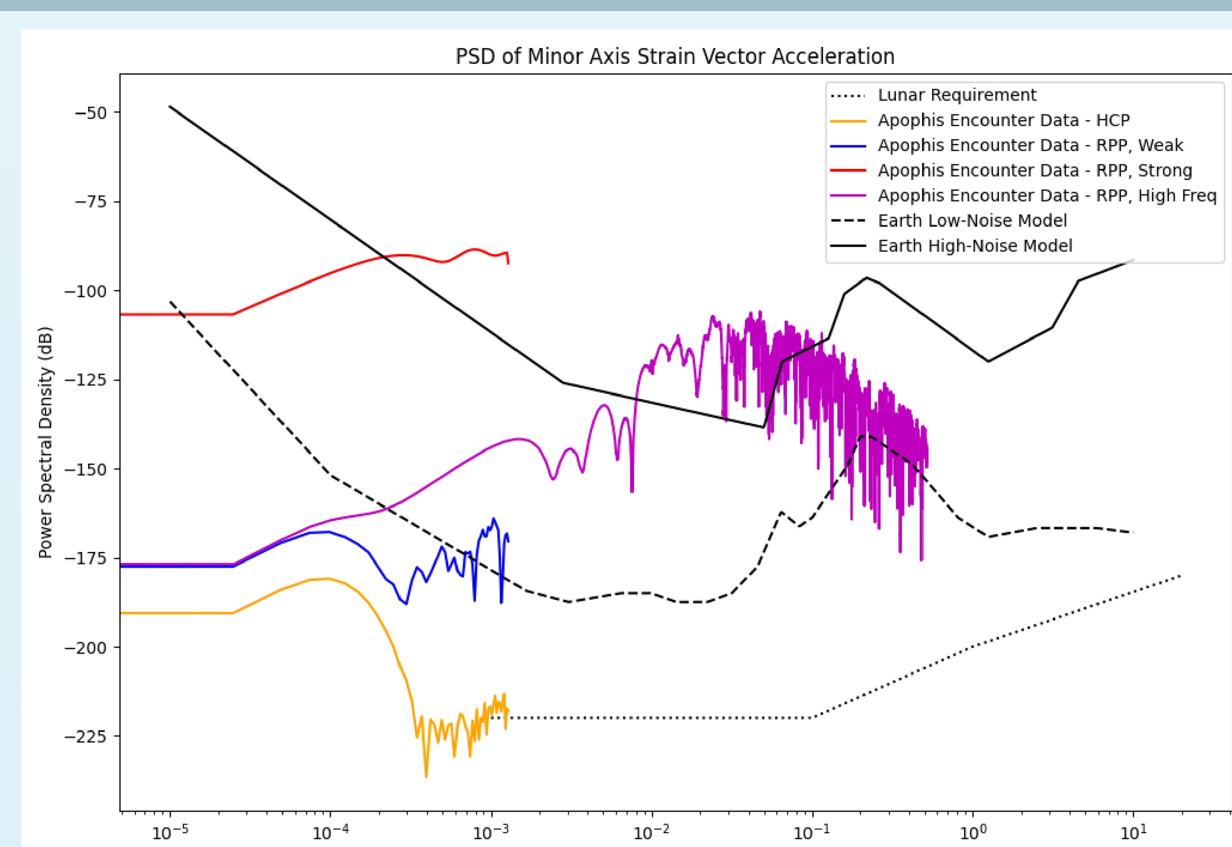

Fig. 6: Power spectral density for curves for the Apophis encounter plotted against Earth noise models for the Earth and the requirements for a lunar seismometer. HCP result in orange, strongest and weakest RPP results in red and blue, respectively, and a relatively weak RPP result modeled to higher frequencies in magenta. An in-situ seismometer with a low enough sampling frequency should be able to measure the signal induced during the tidal encounter.

Approach:

We create Fig. 6 by determining the Welch power spectral density from the acceleration of the maximum strain vector along one of the primary body axes for: the most typical HCP encounter (green), the strongest RPP encounter (red), and one of the weaker RPP encounters (blue). These are plotted alongside typical Earth noise floors for comparison.

Results:

- HCP typical result shows much weaker seismic signal than even a weak RPP encounter
- Strongest RPP encounter should be measurable (at mid-range frequencies) by seismometers capable of making Earth-based measurements
- High porosity regolith structure can mean a much stronger seismic response for an otherwise identical encounter

Conclusions & Ongoing Work

Conclusions:

- Expected change in the bulk spin of Apophis as a result of the encounter is ±20% of the current average spin period.
- Motion of meter-scale surface boulders over distances similar to their radii is a possible result of the tidal encounter, but a typical result indicates motion on the order of millimeters across the entire body.
- Regolith porosity, bulk Young's modulus (stiffness), and body orientation at the time of encounter are the largest factors in determining the strength of the seismic influence of the tidal forces.

Ongoing Work: Modeling with Irregular Particle Shapes

Particles in real granular media are non-spherical, and thus pack less efficiently, creating higher-porosity regolith structures than media containing only spheres. We are able to model irregular shapes by "gluing" spherical particles together [9] (see Fig. 7). Our models of irregularly shaped grains packing naturally under low gravity have reached porosities approaching 70%, which is in the range expected for the regolith layers of S-type asteroids [10]. We expect further increase in the measured strains when we use models of Apophis made from irregularly shaped particles with realistic porosity, leading to even stronger seismic signals from the tidal encounter.

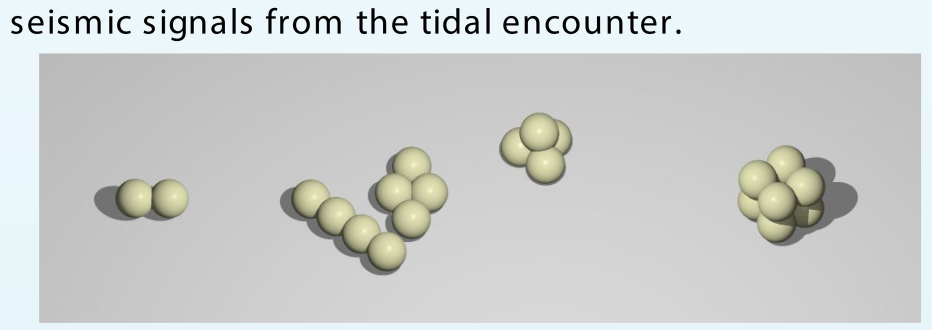

Fig.7: Irregularly shaped rigid "aggregates" made by "gluing" together spherical particles in *pkdgrav*. Aggregates provide shape effects to simulations and account for both gravitational and contact torques.

References

[1] J. V. DeMartini, D. C. Richardson, O. S. Barnouin, N. C. Schmerr, J. B. Plescia, P. Scheirich, P. Pravec. Using a discrete element method to investigate seismic response and spin change of 99942 Apophis during its 2029 tidal encounter with Earth, Icarus 328 (2019), pp. 93-103.

[2] M. Brozović, L.A.M. Benner, J.G. McMichael, J.D. Giorgini, P. Pravec, P. Scheirich, C. Magri, M.W. Busch, J.S. Jao, C.G. Lee, L.G. Snedeker, M.A. Silva, M.A. Slade, B. Semenov, M.C. Nolan, P.A. Taylor, E.S. HOwell, K.J. Lawrence. Goldstone and Arecibo radar observations of (99942) Apophis in 2012–2013, Icarus 300 (2018), pp. 115-128.

[3] D. Farnocchia, S.R. Chesley, P.W. Chodas, M. Micheli, D.J. Tholen, A. MIlani, G.T. Elliott, F. Bernardi. Yarkovsky-driven impact risk analysis for asteroid (99942) Apophis, Icarus, 224 (2013), pp. 192-200.

[4] R.P. Binzel, A.S. Rivkin, C.A. Thomas, P. Vernazza, H.T. Burbine, F.E. DeMeo, S.J. Bus, A.T. Tokunaga, M. Birlan. Spectral properties and composition of potentially hazardous asteroid (99942) Apophis, Icarus, 200 (2009), pp. 480-485.

[5] P. Pravec, P. Scheirich, J. Durech, J. Pollock, P. Kusnirák, K. Hornoch, A. Galád, D. Vokrouhlický, A.W. Harris, E. Jehin, J. Manfroid, C. Opitom, M. Gillon, F. Colas, J. Oey, J. Vrastil, D. Reichart, K. Ivarsen, J. Haislip, A. LaCluyze. The tumbling spin state of (99942) Apophis, Icarus, 233 (2014), pp. 48-60.

[6] D.C. Richardon, T. Quinn, J. Stadel, G. Lake. Direct large-scale n-body simulations of planetesimal dynamics, Icarus, 143 (2000), pp. 45-59.

[7] Schwartz, S.R., P. M., Richardson, D.C., 2013. Numerically simulating impact disruptions of cohesive glass bead agglomerates using the soft-sphere discrete element method. Icarus 226, 67–76.

[8] Y. Zhang, D.C. Richardson, O.S. Barnouin, C. Maurel, P. Michel, S.R. Schwartz, R.L. Ballouz, L.A.M. Benner, S.P. Naidu, J. Li. Creep stability of the proposed Aida mission target 65803 Didymos: I. Discrete cohesionless granular physics model, Icarus, 294 (2017), pp. 98-123,

[9] J. V. DeMartini, D. C. Richardson, An efficient algorithm for operating on large numbers of aggregate particles with applications to simulating the dynamics of irregularly shaped grains, 14TH Europlanet Science Congress (2020).

[10] D. L. Domingue, M. Robinson, B. Carcich, J. Joseph, P. Thomas, B. E. Clark, Disk-Integrated Photometry of 433 Eros, Icarus 155 (2002) 205-219.