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NEOShield Study on Asteroid Mitigation: Simulation of Impacts into Hazardous Bodies Modeled as Collections of Grains

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Asteroids and comets have been colliding with the Earth since its formation, profoundly influencing the geology and life on the planet. It has been estimated that about every year, asteroids measuring 4 meters across enter Earth's atmosphere and detonate [1], and that asteroids of 100 meters tend to impact the Earth every 5,000 years. On average, collisions with 4-kilometer asteroids are occurring about every 13 million years [2]. In 2005, a United States Congressional mandate called for NASA to detect, by 2020, 90 percent of Near-Earth Objects (NEOs) with diameters of 140 meters or greater [3].

Any discussion of hazardous Near-Earth Object (NEO) mitigation strategies must incorporate an analysis of the makeup of the body. The rationale in the assumption that asteroid surfaces consist of granular material is based on the results of several observations, including confirmation by space missions that have visited asteroids in the last few decades [5,6]. It appears that all encountered asteroids thus far are covered with some sort of granular material, usually referred to as "regolith." To date, this includes a large range in asteroid sizes, from the largest one visited, by the Dawn spacecraft, the main belt asteroid (4) Vesta, which measures about 500 kilometers across, to the smallest one, sampled by the Hayabusa mission, the NEO (25143) Itokawa, which measures about 500 meters across [7,8]. Thermal infrared observations support the idea that most asteroids are covered with regolith, given their preferentially low thermal inertia [9].

One of the four main types of mitigation strategies explored by the United States' National Research Council's "Committee to Review Near-Earth Object Surveys and Mitigation Strategies" involves using an impactor spacecraft to deflect an NEO from its path by crashing into it at speeds of up to 10 km/s or more [9]. In addition to plans based on the 3 other strategies, which include detonations on or beneath the asteroid surface (nuclear and non-nuclear), gravitational tractors, and broad civil defense approaches, NEOShield aims to design a general NEO defense strategy based upon momentum transfer via kinetic impact [10]. Here we study the details of such an approach numerically.

We perform the majority of a given impact simulation using `PKDGRAV`, a parallel N-body gravity tree code [11] adapted for particle collisions [12,13]. A soft-sphere collisional routine was added recently [14]; with this option, particle contacts can last many timesteps, with reaction forces dependent on the degree of overlap (a proxy for surface deformation) and contact history—this is appropriate for dense and/or near-static granular systems. The code uses a 2nd-order leapfrog integrator, with accelerations due to gravity and contact forces recomputed each step. In the spring/dash-pot model used in `PKDGRAV`'s soft-sphere implementation, described fully in [14], a (spherical) particle overlapping with a neighbor feels a reaction force in the normal and tangential directions determined by spring constants (k_n, k_t), with optional damping and effects that impose static, rolling, and/or twisting friction. Plausible values for these various parameters are obtained through comparison with laboratory experiments. The numerical approach has been validated through comparison with laboratory experiments; e.g., [14] demonstrated that `PKDGRAV` correctly reproduces experiments of granular flow through cylindrical hoppers, specifically the flow rate as a function of aperture size, and found that the material properties of the grains also affect the flow rate. Also successfully simulated in `PKDGRAV` were laboratory impact experiments into: sintered glass beads [15], regolith in support of asteroid sampling mechanism design [16].

To carry out the initial phase of an impact, we generally use smoothed particle hydrodynamics (SPH) coding software [17]. The computed positions and velocities of the simulated material are then ported into `PKDGRAV`, taking advantage of its gravity tree solver, to find neighbors and to resolve gravitational forces, and its soft-sphere collisional routine to resolve contact forces. The momentum imparted to the model NEO and the fate of the impact ejecta are analyzed. Results will be discussed.

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