RIGID-BODY DYNAMICS AND SECONDARY IMPACT EJECTA ON ASTEROIDS. D. G. Korycansky, E. Asphaug, *CODEP, Department of Earth Sciences, University of California, Santa Cruz CA 95064 USA (kory@pmc.ucsc.edu, asphaug@pmc.ucsc.edu).*

We report results of modeling rigid-body dynamics applied to asteroids, in particular, the dynamics of ejecta from impacts onto asteroids. In previous work we have modeled the effects of impacts on asteroid shapes (Korycansky and Asphaug 2003, *Icarus* **163**, 374) and simulated impacts and regolith accumulation on Eros (Korycansky and Asphaug 2004, *Icarus* **171**, 110) using test-particle dynamics around accurately calculated gravitational fields of non-spherical objects. We have extended the methods to incorporate the dynamics of polyhedral bodies in a general (mutual) gravitational field (Korycansky 2004, *Astron. Space Sci*, **291**, 57, corrigendum **293**, 363) and studied the dynamics of collisions of rubble piles at low speeds (Korycansky and Asphaug 2006, *Icarus* in press).

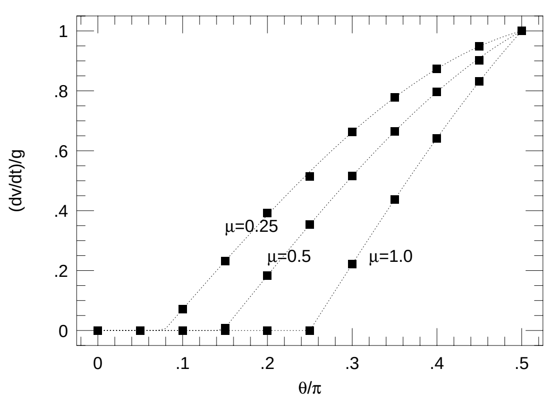

Figure 1: Acceleration dv/dt of a block on a plane inclined at angle θ. Dashed lines: Analytic value of $(dv/dt)/g = \mu\cos\theta - \sin\theta$ for $\mu = 0.25$, 0.5, and 1.0. Points: simulation results for a parallelipiped computed using our methods.

In this work we revisit the question of ejecta from impacts onto asteroids using our newly extended methods. We model the dynamics of arbitrary rigid polyhedra that represent boulder-like ejecta like those visible in NEAR and Hayabusa images. We include full gravitational dynamics including torques. We also include collision dynamics with a model of inelastic and frictional collisions. Polyhedra have triangular faces and may take general (arbitrary) shapes. Full dynamics including rotational degrees of freedom are simulated. Collisions are detected via comparison of the positions (interpenetration) of vertices, edges, and faces. Collisions are resolved by calculation of the impulse **P** of the collision: $\mathbf{P} = (1+\varepsilon_n)P_n\hat{n} + (1-\varepsilon_t)\tilde{P}_t\hat{t}$, where ε_n is the normal coefficient of restitution, ε_t is the tangential coefficient of restitution, and

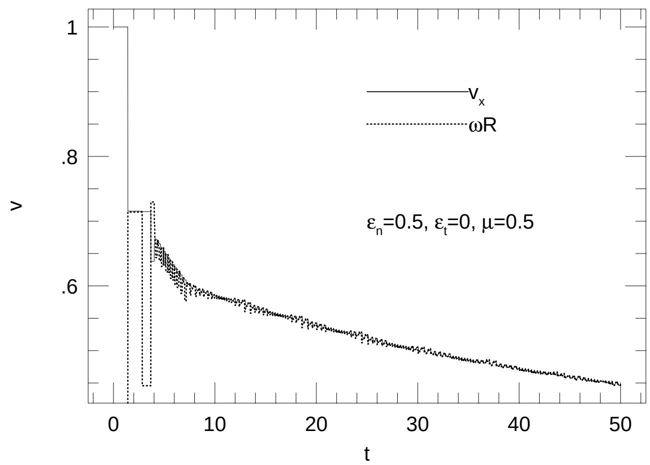

Figure 2: Comparison of forward velocity v_x with rotational velocity ωR for a unit-radius "sphere" (1280-face polyhedron) rolling on a horizontal plane. Coefficients for normal and tangential coefficients of restitution and friction as given in the figure.

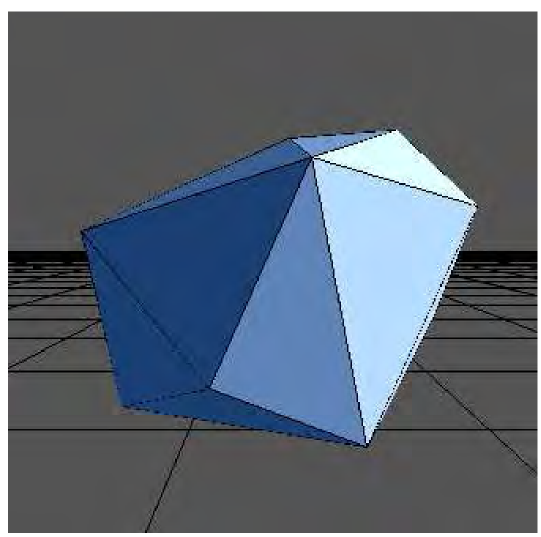

Figure 3: 20-sided irregular icosahedron model for ejecta boulder.

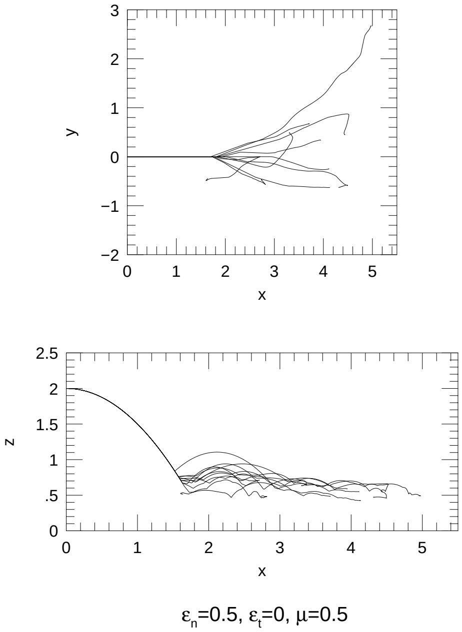

Figure 4: Center-of-mass positions of 10 “boulders”like that shown in Fig. 3, tossed onto the horizontal plane ($z = 0$) in a vertical gravitational field $g = 1.0\hat{z}$. Initial conditions $x = y = 0$, $z = 2$, $v_x = 1$. Left: $x - y$ tracks. Right; z vs. x. Initial ground impact at $x \approx 1.6$, followed by bounces. Restitution and frictional coefficients as given in the figure.

we limit the magnitude of the tangential impulse to be no larger than μ times the normal impulse by setting $\tilde{P}_t = \max(P_t, \mu P_n)$. The impulse magnitudes P_n, P_t, result from enforcing conservation of linear and angular momentum in the collision.

We have conducted simple but non-trivial tests of the dynamics, such as the acceleration of a block on an inclined plane (Fig. 1) and a “sphere” (a 1280-face polyhedron) rolling on a plane (Fig. 2). In both cases, results closely matched the expected results from elementary physics: the sliding block accelerated at $dv/dt = g(\mu \cos\theta - \sin\theta)$ and the rolling sphere matched angular and translational velocities $v_x = \omega R$ to a high degree. (For the former case, however, long-term integrations of a static block on an inclined plane reveal a very slow slippage with velocity proportional to the square of the timestep, showing that mimicry of static friction is not exact due to numerical effects.) In neither case do the bodies involved “know” about the constraints: the calculations are carried out in terms of elementary collisions and impulses affecting body vertices and faces.

For asteroid dynamics, we model ejecta as many-sided polyhedra (“boulders”), as seen in Fig. 3 as an example. We model various dynamical scenarios, starting with simple calculations of the flight and bounce of boulders on a horizontal plane to gain a sense of the degree to which bouncing, rolling, and sliding after the initial impact will affect the distribution of a sample of test cases. An example of the impact and bouncing of 10 sample boulders is shown in Fig. 4. For this particular combination of restitution and frictional coefficients, the boulders continue to move after initial impact for several body diameters. Depending on the coefficients similar effects on asteroid ejecta may be significant. The values of friction and restitution coefficients will play a large role in determining the dynamics. These parameters are not well known, but studies such as the one by Hartmann (1978, *Icarus*, **33**, 50) will help constrain them.

Subsequent calculations will be done with gradually increasing realism with respect to asteroid physical conditions, including the replacement of horizontal plane and vertical gravity field with the shape and gravitational field of representative bodies like asteroid 433 Eros. Our aim is to determine whether post-impact motion makes a significant difference in the expected distribution of impact ejecta on asteroid surfaces. Similar work has been done in the context of design of a target marker system for asteroid missions (Sawai and Scheeres 2001, *J. Spacecraft Rockets*, **38**, 601). Additional calculations will be done of “clusters” or small rubble-piles of boulders to model aspects of the expected breakup of some ejecta on impact. Ultimately, we aim to incorporate the effects of post-impact motion as a kind of diffusive process that takes its place with other processes like seismic shaking from impacts, and tidal or thermal effects (cf. Scheeres *et al.* 2002, in *Asteroids III*, eds. W. F. Bottke *et al.*). At the time of writing, work is ongoing, but we expect to report on results as a function of physical parameters (restitution and friction coefficients).

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