RE-AGGREGATION TIMES OF POTENTIALLY HAZARDOUS OBJECT FRAGMENTS AFTER A HAZARD MITIGATION IMPULSE. D. G. Korycansky, *CODEP, Department of Earth and Planetary Sciences, University of California, Santa Cruz CA 95064 (kory@pmc.ucsc.edu)*, C. S. Plesko, *Los Alamos National Laboratory Applied Physics Division.*

Asteroids and comets range in composition from rubble piles to delicate conglomerations of ice and rock to solid objects. They are occasionally found on trajectories that pose an impact hazard to the Earth. There is an ongoing scientific debate about how to best mitigate the risk posed by these potentially hazardous objects (PHOs). Several of the techniques proposed involve applying short-duration impulses to a PHO in order to change its orbit, by means of stand-off blasts, surface detonations, or kinetic impacts. However, such methods have the potential to knock fragments off the parent body or disrupt it completely. The resulting fragments may continue to threaten ground or orbital assets if they have not been dispersed far enough on diverging trajectories, or collectively deflected away from the original Earth-intercepting trajectory to a sufficient degree. Here we explore the question of the time required after an impulse for fragments to re-aggregate or disperse to large radii.

Background

PHOs can be delicate objects. Rubble pile asteroids like near-earth asteroid Itokawa [1] are evidently held together only by gravity and friction; comets are porous conglomerations of ice and rock. Imparting enough momentum to an object to alter its trajectory without disrupting it or breaking pieces off is challenging. Fragments of an otherwise mitigated parent body can still be hazardous. A fragment of 50 m in diameter or larger is comparable to the object that caused the Tunguska airburst [2]. A fragment as small as 1 cm can be hazardous to spacecraft. By studying the dynamics of fragments after a hazard mitigation impulse we can begin to estimate safety tolerances for fragment mobilization.

Fragments that escape the parent body must end up more than one Earth diameter from the original object's point of Earth intercept by the original time of Earth intercept in order to be rendered safe. Fragments that scatter or remain gravitationally bound and on a trajectory close to the original will re-aggregate over time, following complicated paths and interacting with other fragments before re-accretion. The time taken for fragments to re-aggregate depends on the physical properties of the original object and the impulse applied; re-assembly timescales can be used to guide the timing and magnitude of "fast-push" hazard mitigation strategies.

Initial Conditions and Approximations

We have carried out preliminary rigid-body dynamical simulations of rubble-piles as a first study of these issues using the Open Dynamics Engine (ODE, `www.ode.org`). ODE is a simulation package that works with bodies of arbitrary shapes (described by triangular meshes) and uses a sophisticated collision detection method and solver for contact constraint forces, along with a first-order time-stepper for the dynamics equations [3]. ODE has been used to simulate planetesimal collisions of km-scale bodies [4], and the work presented here builds on that.

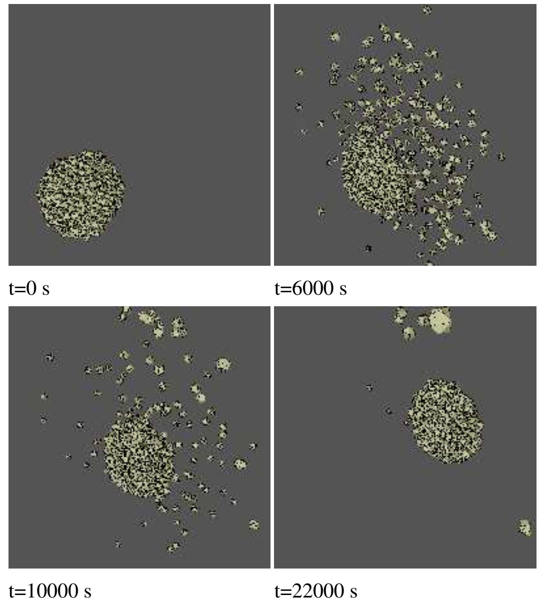

Figure 1: Sample calculation of a sub-catastrophic disruption. Parameters are velocity scale $v/r = 10^{-3}$, opening angle $\theta = \pi/2$, with $n = 1000$ sub-elements.

The simulations are of rubble piles whose fragments have masses, volumes, and shapes that remain constant throughout the calculation. They are given an initial velocity field and are allowed to evolve dynamically. Collisions are dissipative: there is a coefficient of restitution for normal collisions and tangential Coulomb friction is applied as well. For these calculations, we set the coefficients of restitution $\varepsilon = 0.5$ and friction $\mu = 0.5$.

The initial calculations reported here use rubble piles made of elements of the same mass (monodisperse distribution). The initial radius of the pile was ~ 1 km; we tested cases made of $n = 10$, 100, and 1000 sub-elements. All the aggregates have the same total mass $M = 8 \times 10^{15}$ gm, so individual fragments have masses M/n. The velocity field was a simple radial uniform expansion with a rate with rates $v/r = 5 \times 10^{-4}$, 10^{-3}, and 2×10^{-3} s^{-1}, for which the entire body takes part ($\pi < \theta < \pi$) or is confined to a polar opening angle $\pi/2 < \theta < \pi/2$ (a hemisphere), or $\pi/4 < \theta < \pi/4$ (a quarter sphere). The corresponding kinetic energies span the range from mild sub-catastrophic disturbances to complete disruption. An example is shown in Fig. 1. In the future we will extract initial fragment velocity distributions from the results of hydrocode calculations of specific deflection and disruption scenarios. These calculations

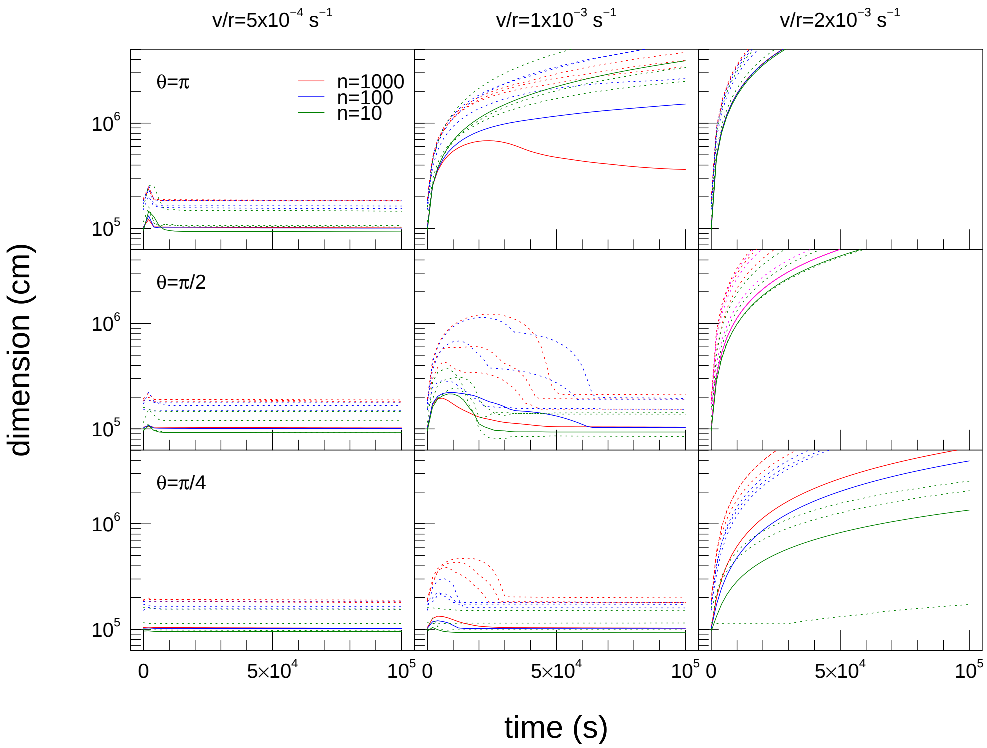

Figure 2: Dimensions vs. time for disrupted rubble-piles. Nine combinations of velocity scale ($v/r = 5\times10^{-4}$ s^{-1}, 10^{-3} s^{-1}, 2×10^{-3} s^{-1}) and opening angle $\theta = \pi$, $\pi/2$, $\pi/4$ are shown for cases with numbers of rubble elements $n = 10$ (green), $n = 100$ (blue), and $n = 1000$, (red). Solid lines show the rms radius $< r^2 >^{1/2}$, dotted lines show the maximum dimensions in x, y, and z.

are currently underway, see Plesko et al. (this conference).

Preliminary Results

The dynamical timescale is $\tau = (G\rho)^{-1/2} \sim 2\times10^3$ s. However, in these cases interest focuses not only on the basic scaling but more particularly on the re-aggregation timescale $T_r = K\tau$, given the critical nature of hazard mitigation. The exact value of T_r (or K) will depend in general on details of the configuration, velocity field, mass spectrum, number of fragments, etc. In turn this will depend on the results of the mitigation strategy employed and the characteristics of the object to which the strategy is applied.

We can distinguish three regimes of results: 1) sub-catastrophic disturbance with complete re-aggregation, 2) sub-catastrophic disturbance with re-aggregation with some fragments escaping to large distances, and 3) complete disruption. The lines between the regimes are somewhat fuzzy, particularly 2) and 3), and depend not only on kinetic energy of the impulse but also its geometry. Thus, plotting the kinetic energy as a function of time is somewhat limited as a diagnostic of the resulting configurations and timescales. Here we present some measures of configuration size, namely the maximum dimensions x_{max} of the assembly of fragments and the rms radius $< r^2 >^{1/2}$ as functions of time as a first step in characterizing the outcomes of the numerical experiments.

Figure 2 shows the outcomes (maximum dimension x_{max}, y_{max}, z_{max}, and rms radius *vs* time) for combinations of initial velocity scale (v/r), velocity opening angle θ, and numbers of elements n. Low-energy runs ($v/r = 5\times10^{-4}$ s^{-1}) settle back to their initial states in $T_r \sim 10^4$ s $\sim 5\tau$. Complete disruption ($v/r = 2\times10^{-3}$ s^{-1}) takes place on similar timescales, after which object dimensions exceed the local Hill radius H at 1 AU $\sim a(m_{obj}/3M_\odot)^{1/3} \sim 2\times10^7$ cm. The middle-velocity cases which we have run ($v/r = 10^{-3}$ s^{-1}), as seen in the center column of panels in Fig. 1, can take as long as 6×10^4 s for the bulk of the object to settle back to its initial state. This case is also one for which geometry of the disturbance matters as well as the number of objects: for $\theta = \pi$, the $n = 1000$ object remains largely impact, but the $n = 10$ and $n = 100$-body objects are disrupted.

References

[1] Fujiwara *et al.* (2006) *Science*, **312**, 1330. [2] Boslough and Crawford (2008), *Int. J. Imp. Eng.*, **35**, 1441. [3] Erleben *et al.* (2005) *Physics-Based Animation*, Charles River Media, Inc. [4] Korycansky and Asphaug 2009, *Icarus*, **204**, 316.