EFFECTS OF STAND-OFF BURSTS ON RUBBLE-PILE TARGETS: EVALUATION OF A HAZARDOUS ASTEROID MITIGATION STRATEGY. D. G. Korycansky, C. S. Plesko, *CODEP, Department of Earth and Planetary Sciences, University of California, Santa Cruz CA 95064, Los Alamos National Laboratories,Los Alamos, NM* .

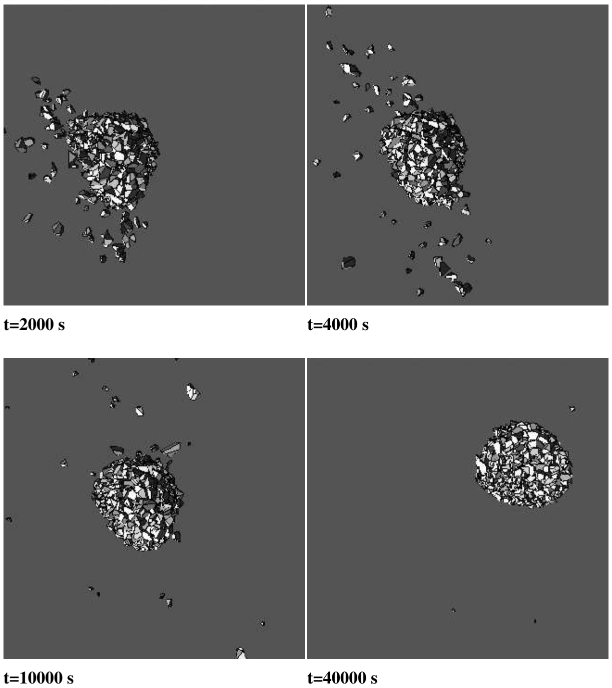

Figure 1: Simulation of the after-effects of a stand-off burst on a Voronoi rubble pile with 1000 blocks and mass 3.5×10^{12} kg. Burst and material parameters are (X-ray) yield $Y = 4.2\times10^{15}$ J, stand-off radius $R = 10^3$ m, vaporization energy $e_v = 6\times10^6$ J kg^{-1}, X-ray opacity $\sigma = 0.06$ m^2 kg^{-1}. The calculation is shown at the indicated times after the momentum input.

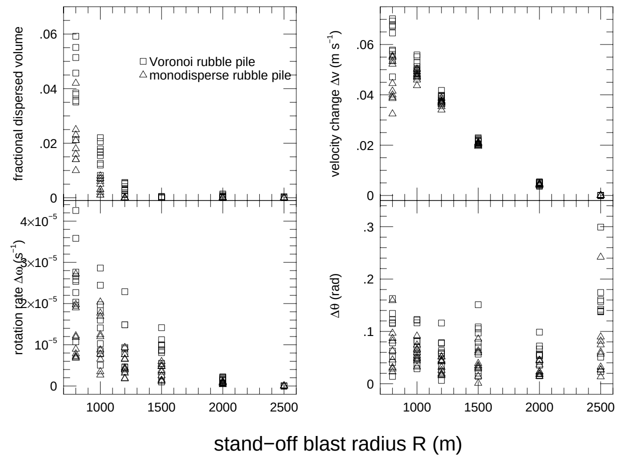

Figure 2: Results from 1 Mt stand-off bursts against the Voronoi and monodisperse rubble piles, as a function of the stand-off burst radius R from the center of mass of the target. Top left: Fractional volume loss of dispersed material after stand-off bursts. Top right: velocity change Δv. Bottom left: spin change $\Delta\omega$. Bottom right: deviation $\Delta\theta$ of the imparted velocity change Δv from the z-axis.

It has been realized for several decades that asteroid and comet impacts are a prime threat to human civilization. Only a century ago, a multi-megaton airburst took place just above Earth's surface in the remote Tunguska region of Siberia, an event that would have been devastating had it taken place over a densely populated area. Current best estimates of the population of potentially hazardous objects (PHOs) suggest that the most substantial risks occur for objects of 800 m to 1 km in diameter. Recent overviews of the topic can be found in [1,2]. A number of candidate strategies for preventing the impact of a PHO have been identified; detailed discussions of mitigation strategies are provided by [3,4,5].

We have carried out a number of simulations of the effects of stand-off bursts on models of km-scale asteroids, as an assessment of one possible consequence of the use of such bursts as a mitigation strategy for hazardous asteroids. Stand-off bursts work as a mitigation effort by means of irradiating the target with the energy of a nuclear device; in space this energy comes primarily in the form of thermal X-rays from the fireball after the nuclear energy release. The X-rays strike the portion of the surface of the target, are absorbed, and vaporize a thin layer (some centimeters deep) on the surface. The resulting vapor expands hypersonically away from the surface and the resulting rocket effect delivers an impulse to the object, changing its velocity by a small amount and thus its orbit from an impact trajectory. We addressed two questions our study: 1) what is the velocity change that can be expected from a stand-off burst? 2) Do bursts lead to significant dispersion of target objects?

The simulations consisted of solving the dynamical equations for the individual members (blocks) of aggregates in which blocks at the surface facing the blast location point were given initial velocities derived from our energy deposition/impulse model, using the ODE physics engine [6] that we have used in previous dynamical modeling of rubble piles [7,8,9]. The targets were modeled as loosely-consolidated aggregates of polyhedral blocks ("rubble piles") in line with current views of asteroid internal structure. We also ran tests of close-packed targets ("brick piles"). We studied the response of two types of rubble pile structure: 1) a "monodisperse" pile in which the blocks all have a single volume equal to $0.001\times$ total solid volume, and 2) a "Voronoi rubble pile", composed of polyhedral blocks derived from the Voronoi decomposition of an polyhedral volume. The blocks were dispersed, randomly re-oriented, and allowed to re-accrete. The resulting rubble piles were approximately spherical objects with $\sim 30\%$ void space. Objects consisted of 10^3 blocks. Due to the random nature of the packing, for each parameter combination we ran ten cases with the object in randomly chosen orientations to sample the distribution of results. Our standard case was a target object of mass 3.5×10^{12} kg and radius $\sim 7\times 10^2$ m, typical of the scale of a civilization-threatening object. We took for our standard case a burst with an X-ray yield of 1 Mt (4.2×10^{15} J), with stand-off radii R from the target center of mass ranging from 0.8 to ~ 2.5 km. The other important parameters were the energy of vaporization e_v taken to be 6×10^6 J m^{-1} [10], and the the X-ray opacity σ. Our standard value for σ was 0.06 m^2 kg^{-1} as derived from integration of X-ray cross-sections for the Rosseland mean opacity for a temperature $\sim 8\times 10^7$ K, [11,12], but we also ran a few cases with values σ up to 60 m^2 kg^{-1}.

We did not simulate the actual burst or ablation phase of the mitigation strategy. Instead we applied a simple model of energy deposition into a surface [13] to determine the applied impulse $\tilde{I}$ to surface blocks of our model targets: $d\tilde{I} = \rho V dx, \quad V^2/2 = e - e_v, \quad e = \sigma F, \quad F = F_0 \exp(-\sigma\rho x/\cos\theta)$, where $F_0 = Y/(4\pi R^2)$ is the fluence (energy per unit area) of a burst with yield Y at stand-off distance R, σ is the X-ray absorption cross-section, e_v is the vaporization energy of the target material, ρ is the target density, and x is the distance into the block from the surface. The impulse $\boldsymbol{I}_i$ on a block i is a vector sum of the specific impulses $\tilde{I}_{ij}$ from each face j of i that is visible from the burst location point; $\tilde{I}_{ij}$ is calculated using the formulation described above. We have $\boldsymbol{I}_i = \sum_j \tilde{I}_{ij}\boldsymbol{A}_{ij}\cos\theta_{ij}$, where $\boldsymbol{A}_{ij} = A_{ij}\hat{\boldsymbol{n}}_{ij}$ is the area-weighted normal of face j and $\cos\theta_{ij} = \hat{\boldsymbol{n}}_{ij}\cdot\hat{\boldsymbol{r}}_{ij}$, where $\hat{\boldsymbol{r}}_{ij}$ is the unit vector from the centroid of face j to the detonation point. Likewise the angular momentum of the block $\boldsymbol{L}_i = \sum_j \tilde{I}_{ij}\boldsymbol{x}_c \times \boldsymbol{A}_{ij}$. Having calculated $\boldsymbol{I}_i$ for each block, $\boldsymbol{V}_i = \boldsymbol{I}_i/m_i$ and angular velocity $\boldsymbol{\omega}_i$ is found from $\boldsymbol{L}_i = \boldsymbol{J}_i\boldsymbol{\omega}_i$, where $\boldsymbol{J}_i$ is the inertia tensor of block i.

We subjected our models to impulses large enough to generate velocity changes of ~ 0.05 m s^{-1}, consistent with the magnitude of changes needed to implement a hazard avoidance strategy on timescales of years to decades. We followed the dynamical evolution of the models for periods of $\sim 10^2$ gravitational timescales ($10^2\tau = (G\rho)^{-1/2} \sim 2\times 10^5$ s) to determine answers to the questions listed above.

The behavior of a typical simulation is shown in Fig. 1. In general, we find that rubble piles are surprisingly robust to stand-off bursts of significant magnitude, where by “significant” we mean large enough to induce a velocity change of several cm s^{-1}. Approximately 25% of a target's mass would quickly disaggregate from the main body after the application of the impulse, but almost all of the dispersed mass quickly re-accreted in a few multiples of the gravitational timescale τ. For the “severest” tests ($R = 0.8$ km), approximately 95% of the mass remained of the target; at $R = 1.0$ km, the final mass was $\sim 98-99\%$ of the original. Any dispersed shards of the post-impulse target would themselves require tracking to determine what if any hazards might be posed by them.

The impulse applied to the objects, and internal mass distribution of our models, were not necessarily symmetric, and off-center components thereof generate both torques (spins) and off-axis velocity changes. The induced spins were small (corresponding to rotation periods of tens to hundreds of hours) and are not likely to cause dynamical effects on the targets' internal structures. On the other hand, off-axis velocity changes amounting $\sim 0.05-0.1$ radian deviation from the nominal desired direction of the velocity change. The possibility of such deviations might be a significant factor in the design of a mitigation strategy and would need to be taken into account. Results for disruption, velocity, spin, and off-axis components of the impulse are shown in Fig. 2.

We have assumed plausible but so-far unverified target structures, namely weakly-held-together blocks of uniform density. It is certainly the case that real asteroids will have more complex structures. The few objects for which we have close-up surface imagery (e.g. Eros and Itokawa) exhibit more-or-less finely divided regolith of unknown depth. It is possible, for example, that surface regolith may be graded with depth to larger blocks of the sort we have assumed in our model, and other structures are possible. (For instance, the internal structure may be fine grains through the interior, or there may be a few (or even only one) large but fractured coherent masses under the surface. Both models have been suggested for Eros.) Our information, based as it is on a few gross properties such as bulk densities and spin rates, is insufficient to tell.

Acknowledgments

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