Title: RAGE Hydrocode Modeling of Asteroid Mitigation: Surface and Subsurface Explosions in Porous PHO Objects

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ABSTRACT
Disruption of a potentially hazardous object (PHO) by an energetic surface or subsurface burst is considered as one possible method of impact-hazard mitigation. This technique of employing surface or subsurface explosions has been popularized in the media but is probably one of the lower priority deflection/disruption methods, unless the warning time is short. In all of our current simulation we use realistic RADAR shape models for the initial geometry, not merely spherical objects. The non-sphericity of the geometry is very important in the resultant shock hydrodynamic evolution. There are two potential scenario’s for the use of interior explosions to mitigate PHOs. First, if the source explosion is emplaced at or near the surface of the object. An explosion energy of ~500 kt then results in strong shocks that will preferentially eject material from the surface near the explosion and by conservation of momentum the remainder to the body as a significant force in the opposite direction. Any porosity of the object will reduce the momentum imparted. The goal of this type of intercept would be to impart a large enough velocity to the remaining object/fragments so that they would miss the earth orbit by a significant margin. The second subsurface method of mitigation would be to emplace the explosive source below the surface of the object and independent of the composition of the PHO the explosion would have enough power to significantly disrupt the entire body, leading to ejection velocities well above the escape velocity. Given a large enough explosion [here we consider energies of 100 kilotons (kt) – 10 megatons (Mt) TNT equivalent] the PHO would be fractured into smaller fragments with sufficient velocity to again miss the Earth’s orbit by a significant margin. First we considered the second option – a centrally located explosion, which we used the RAGE hydrocode to simulate the imparted momentum as a function of depth-of-burial (DOB). Next, we built our computational models from simple to more complex by first considering uniform composition non-spherical objects and then non-uniform, or “rubble pile” initial geometries. These rubble piles can have a very large range of actual internal compositions for which we have no actual data. We consider various rubble pile geometries as shown below. In this work we do not consider any political nor engineering issues with obtaining the initial conditions assumed in these model hydrocode simulations. It is shown that the results of these simulations are very robust at mitigating the PHO hazard, seemingly independent of the internal composition. Most work here was performed with a 500 kt energy source and from surface bursts to central explosions the majority of the PHO fragments have velocities above ~5 m/s; well above the escape velocity for a 500 m object.
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INTRODUCTION

We have performed detailed hydrodynamic simulations of the shock interaction from a strong surface or subsurface explosion with sample asteroid objects. The purpose of these simulations is to apply modern hydrodynamic codes that have been well verified and validated (V&V) to the problem of mitigating the hazard from a potentially hazardous object (PHO), an asteroid or comet that is on an Earth crossing orbit. The code we use for these simulations is the RAGE code from Los Alamos National Laboratory [1, 2, 3, 4, 5]. Ref. 1 contains many of the V&V reports for the code that were completed prior to publication. It should be noted for those not familiar with the RAGE code that it has been extensively V&V'd for shock physics and shock interactions with multiple materials. So we feel confident that the shock physics simulations presented here represent realistic hydrodynamics of the complex shock interactions; including the effect of the shock on the rocks themselves (assumed to be spherically shaped objects).

Initial runs were performed using a spherical object. We next ran simulations using the shape form from a known asteroid: 25143 Itokawa [5, 6]. This particular asteroid is not a PHO but we use its shape to consider the consequences of non-spherical objects. The initial work was performed using 2D cylindrically symmetric simulations and simple geometries (solid non-spherical objects). Next we progressed to Itokawa shaped models filled with uniform size “rocks” composed of granite and a solid background material (alluvium). These models had no porosity and were mainly done as a test of the code hydrodynamics. The first runs used a spherical energy source at the center of the object (typically 1 Mt), both with and without a “drill hole” which would be necessary to emplace an explosive at this location. Since the escape velocity of this object is very low, the disruption and bulk velocities indicated from these simulations is sufficient completely mitigate a PHO threat. That is to say, that is to say, the velocities calculated were so large as to preclude re-assembly of the fragments and moreover ensure that with even modest lead times that all fragments would be pushed well beyond an Earth crossing orbit if the parent body was a PHO.

METHODS

All of the simulations presented in this paper were performed with the RAGE hydrodynamic code from Los Alamos National Laboratory [1]. This code features a well verified and validated continuous adaptive mesh refinement (CAMR) described in [1] as well as the extensive validation done prior to the publication of that paper. We ran 2D cylindrically symmetric and 3D models of the shock interaction of a strong explosion with the asteroid material. Most of the results shown here are 2D simulations for ease of parametric studies and savings on computer time. Models were done for several parametric studies, including the effect of solid (no-porous) models; the effect of non-spherical models; the effect of similar strength explosions at various depths from the asteroid surface to the center of the object; long-side versus short side surface explosions as finally full 3D models. These models used source energies from 500 kt to 1 Mt; with most models run at 500 kt. The main physics employed in the multi-physics, multi-material RAGE code were the detailed CAMR Eulerian...
hydrodynamics and the material strength package, the Steinburg-Guinan (SG) model for the “rock” strength. Radiation is available in the code but was not used for these simulations. For simulations with radiation transport included, the effect of momentum transfer from the energy source to the asteroid will only increased, so these results represent lower limits to the momentum transferred to the model objects.

MODELS

The models used for these studies transitioned from simple to more complex. The models shown in this paper are:

1) a non-spherical asteroid 25143 Itokawa shape with a uniform iron composition and a central explosion site. This model was done first to test the code for reasonable results and assess the effects of non-spherical models.

2) Next we wrote a simple program to fill the non-spherical outer shape of the asteroid with a random distribution of rocks. These rocks could be of arbitrary size between size 1 and size 2 and were spherical in shape with the centroids within the asteroid surface. These models represent what we call “rubble pile” compositions, which is considered to be more realistic on average than uniform or spherical compositions.

The first runs of this type were done with single size “rocks” (really torus’s in 2D) composed of granite material equation-of-state (EOS) with an alluvium background material. Thus these first runs had no porosity. It is generally believed that typical asteroids have porosities of 30-40% due to multiple collisions and subsequent re-aggregation.

3) Next we simulated porosity by removing the background alluvium and leaving the granite rocks. This resulted in porosities of 25-40 % (in 3D). The main effect of the high porosity is to significantly degrade the shock strength and therefore impart less momentum to the asteroid.

4) We then modeled the effect of the depth-of-burial of the explosion from the center of the object to the surface and also the effect of short-side versus long-side surface bursts.

5) Our final model in this series is running now and is a full 3D porous object filled with three different size rocks from 5 m to 50 m.

2D RESULTS

Work done previously to this meeting included the non-spherical uniform composition central explosion simulation with a energy of 1 Mt. The resulting images from the 2D RAGE simulation are shown in Figure 1. This initial model indicated the importance of non-spherical geometry. The shock from the central explosion clearly reaches the surface of the asteroid along the shortest chord and ultimately ejects the two large end caps at a velocity of ~ 50 m/s due to the enormous pressure inside the explosion cavity at breakout time.

![Image](image.png)

**Fig. 1.** The initial non-spherical uniform composition simulation with the RAGE hydrocode

Next we used a program to fill the shape object with a distribution of rocks. This first simulation was done with a background material of alluvium and rocks composed of granite with SG strength. Thus this run had no porosity. Again dispersion velocities of all the asteroid material and “rocks” were calculated to be ~1m/s, significantly above the escape velocity. These results are shown in Fig. 2.
Fig. 2. The next RAGE simulation had “rubble pile” for a composition with uniform 5 m rocks and an alluvium background material. The velocity imparted to the asteroid material from the central 1 Mt explosion was again > 10 m/s at 0.1 sec.

Next we explored the asteroid mitigation for various depths-of-burial of the explosion from the center to the surface. These results are shown in Fig 3. Significant velocities (much greater than escape velocity) were imparted to all the asteroid material for each depth-of-burial from a surface burst to the centroid position. Given these results, the easiest mission to proceed with is a surface/contact burst mode. This mission could easily be un-manned and no “hollywood style” equipment would be necessary. The main focus from here forward will thus be on surface burst scenarios.

Fig. 3. We also explored the effects of the depth-of-burial of the explosion from a central location to the surface along both major directions. This study showed that explosions along the short side of this non-spherical object resulted in the greatest velocities (at 1 sec after explosion). These simulations had no porosity.

This initial set of RAGE simulations was meant to explore the parameter space of using this type of surface/subsurface explosion to totally disrupt an asteroid of ~500 m size. However, these simulations all had no porosity, which we then addressed in a fashion that is well suited to the RAGE code. Not knowing the exact internal composition of such an asteroid, but knowing it’s porosity is likely to be 30-40% and it composition to be made of a distribution of rock materials, we started a new set of simulations. These simulations had two main advances that moved towards more realistic scenarios: 1) we used a distribution of rocks size: typically in a range from ~5 m spherical rocks to ~50 m spherical rocks randomly distributed in the outer shape of the asteroid; and 2) we added porosity to the simulations by removing the background alluvium. This left the initial geometry to be comprised of the rocks separated by porous void regions. This gave a total porosity of the simulated asteroid of ~20 – 40% depending on the random distribution of rocks and on their size distribution. The result of these random size rock distributions with porosity gave the expected result of a weakening of the shock wave that translated into smaller velocities imparted to the asteroid materials. The typical reduction was
about a factor of 5 – 10. Specifically for a surface burst (easiest mission), a 25% porous non-spherical 2D object was given a bulk velocity of ~6 m/s at 10 seconds after a 500 kt explosion (see Fig. 4). In summary the effects of the porosity as modeled in 2D here with the RAGE code indicate that even for at 500 kt explosion (modest energy) and significant porosity (~20%) the asteroid material was given a bulk velocity of ~>5 m/s at 10 seconds, sufficient to mitigate the PHO hazard. Thus for short notice PHO’s one should not consider the nuclear explosive option as “off the table”. There are clearly significant international issues to be resolved:

- which nuclear country will be given the lead on such a mission?
- which international organization will be in charge of such a mission?
- should multiple missions be undertaken (at the same time) to ensure mitigation?

Fig. 4. We included porosity in the next set of simulations by removing the background alluvium material, leaving voids between the rocks. The depth-of-burial study was redone from both the long and short side of the asteroid. At this point we also varied the size distribution of the internal random rocks from ~5m to ~50m radius spheres. Although the bulk velocities were down ~5 times the explosion was still more than adequate to totally disrupt the asteroid.

The answers to these questions should be addressed in an international forum best suited for the salvation of the Earth. The authors do not make light of the fact that these issues are outstanding and of major concern.
3D MODELS

The previous results were based on 2D cylindrically symmetrical simulations ultimately with porosity and credible internal compositions for an actual asteroid. We have recently started full 3D simulations similar to those shown in Fig. 4. These runs are quite expensive with a courant limited shock physics code. However, the initial runs have progressed to ~25 ms and show interesting differences to the 2D results.

The 3D simulation included porosity as described above and had random rock size distributions from 5m to 50 m within the outer shape of asteroid Itokawa. The initial results show that the shock seems to be significantly degraded compared to the 2D results at ~25 ms. Realize that the 3D run needs to run to about 1 -10 seconds to make a fair comparison. However, it appears that the 2D symmetry for a surface burst subtends a much larger solid angle (2D Torus’s) than the 3d simulation resulting in the significant reduction of shock strength in 3D. These 2D to 3D results are very preliminary and should wait for the 3D run to finish. The initial time sequence from the 3D run is shown in Fig 5.

Fig. 5. The first 3D simulation analogous to the 2D porous surface burst shown in Fig. 4 but with a 1 Mt source energy. The shock seems to dissipate more strongly in 3D than 2D. However final conclusions require the 3D run to complete.

SUMMARY

These initial full hydrocode simulations of non-spherical objects including porosity seem to show promise for a late time discovery of a PHO. The 2D bulk velocity imparted to the asteroid material is sufficient to mitigate the PHO hazard. The 3D runs are still in progress and thus the results of the simulations await their completion. The bottom line to these authors is that nuclear explosion options for recently discovered PHOs should not be eliminated and scientific hydrocode results tend to support this option. Radiation effects were not included in these results and will ultimately add to any effect simulated here.

References