Momentum Transfer via Direct Impact: Experimental Measurements

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Introduction/Test Setup

Deflection of potentially hazardous objects of 100's meter size can be achieved by direct spacecraft impact. The effectiveness of this method depends on the efficiency with which the spacecraft momentum is transferred to the asteroid. The question of how the momentum exchange depends on the size scale of the impacting bodies, their target properties and relative speed is largely unknown. Is it just the momentum of the impactor, as in a "perfectly-plastic" impact? Or is it many times more, because of a great amount of material ejected from the body?

To answer this question, we define the momentum multiplication factor:

$$\beta = \frac{\text{Change in asteroid momentum}}{\text{Impactor momentum}}$$

and perform experiments to measure β. Experiments are performed at the NASA Ames gun and in the Boeing Shock Physics Lab. The material of interest is in a container suspended from springs. After impact, the momentum of the projectile and from the ejecta cause the target to oscillate. The frequency and magnitude of the oscillations allow us to calculate β.

The key questions we address are:

(1) How does β depend on the mechanical properties of the target body?

(2) How does β depend on the conditions of the impact, such as the speed?

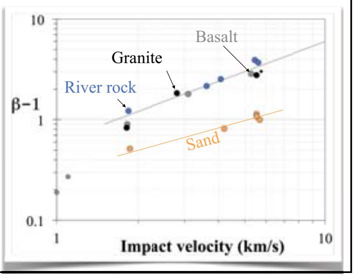
(3) How are small-scale lab experiments properly "scaled" to the conditions of a deflection mission?

This study combines experimental, numerical and theoretical techniques to understand momentum transfer in hypervelocity collisions. Here we summarize our progress in the experimental part of the study.

Baseline data for sand and rock

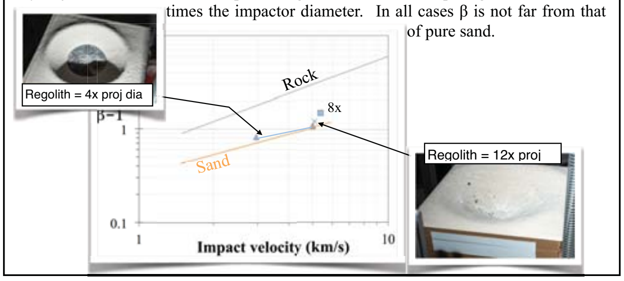
Our initial experiments were on rock and sand targets, two prototypical materials that may bound the behavior of a bare stony asteroid and a rubble-pile, or regolith-covered object. The plot below shows β-1 as a function of impact velocity. We plot β-1 because that represents the contribution of the ejecta only (if there are no escaping ejecta, β=1 and the ejecta contribution is zero).

Our experiments show similar results for three types of rock, all of which are significantly above those for dry sand. Even though sand generates more ejecta than an impact into rock, the ejecta in rock are much faster than for sand. Thus an impact into a rocky body would transfer much more momentum than one into a rubble-pile.



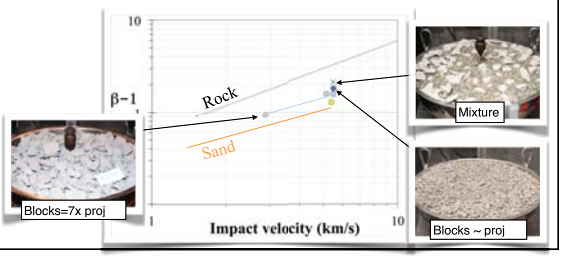
β is insensitive to regolith depth

Many asteroids are likely covered with a layer of regolith. Given that sand exhibits much lower values of β than rock, an important question to answer is "How does a regolith layer affect the value of β when attempting to deflect a regolith-covered body"? We conducted experiments with various depths of sand layers on top of a rock layer. β is insensitive to the depth of regolith, at least for depths greater than a few times the impactor diameter. In all cases β is not far from that of pure sand.



β is insensitive to how blocky the regolith is

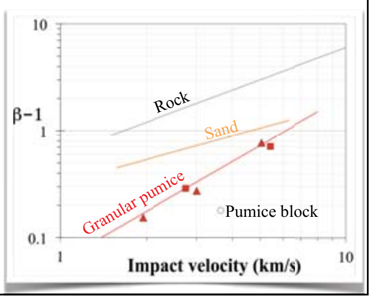
Small objects can be have a range of sizes of blocky material. The blocks on Itokawa range from well below to well above the size of (typically) meter-sized impactor that might be used in a deflection mission. We examined how β depends on the block size in a regolith by using gravel ranging from 1/30th the size of the impactor up to 7x the impactor diameter. Surprisingly, we find that β is quite insensitive to the size of the blocks, with values slightly above those of sand, but not those of rock, even when the gravel particles are several times larger than the impactor.



Porosity reduces β

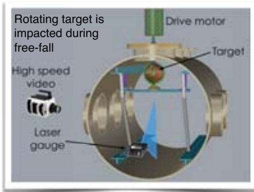
The nature of the craters on the low-density asteroid Mathilde, as well as recent laboratory impact experiments indicate that high target porosity causes a significant reduction in the mass and speed of ejecta. We performed impacts into a cohesive block of pumice (~70% porosity) and cohesion-less granular pumice (85% porosity). We find much lower values of β for these materials than for sand, presumably due to the low ejecta speeds.

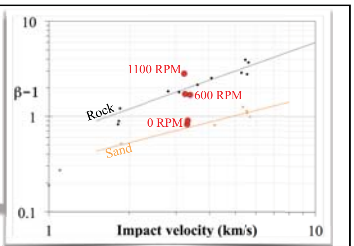
The granular pumice shows an unexpectedly strong dependence on impact velocity. We are currently studying this further. If that steep slope is real,and persists to higher speeds, loose porous materials could have values of β similar to sand at higher velocities.



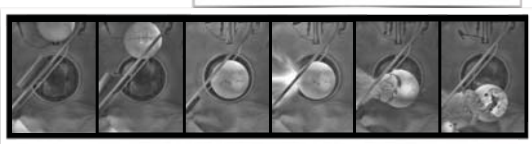
Target rotation matters!

Radiation forces and/or impacts cause many small NEOs to spin rapidly, some near their rotational bursting limit. This turns out to have an important effect on the collisional energy required for shattering. Collision experiments using rotating targets (Housen 2004) showed that rotation *significantly* reduces the energy required for fragmentation. For example, a body rotating a factor of 5 slower than its bursting limit was shattered by only 20% of the energy required by its non-rotating counterpart! The effect of rotation on disruption must be researched further before designing a mission to deflect a rapidly rotating NEO. In addition, rotation might also cause an increase in the mass of ejecta, and the value of β during an impact event.





We are conducting impact experiments on rotating cohesive targets made of plaster and and to simulate the conditions in a rapid rotator. The test setup is shown at the right, as well as a series of frame grabs from a test. While a non-rotating target (0 RPM in the figure) has β close to that of sand, β steadily increases as the spin rate is increased, even exceeding rock at the highest spin rate. The mass of material removed from the target increases with spin rate (because of the effectively lower strength due to pre-existing stresses), which causes β to go up. We are running additional experiments to determine the conditions under which a rotating body might be catastrophically



Summary

1. The momentum multiplication factor, β is significantly larger for nonporous bodies than porous one, because porosity reduces ejecta velocities. It will be much harder to deflect rubble-piles than rocky asteroids
2. Over the range of conditions studied, β is not strongly affected by how blocky a regolith is or by the depth of a regolith layer.
3. Rapid rotators might be easier to deflect (but also possibly to disrupt) since rotation increases the mass of ejected material.
4. β increases with impact speed, in agreement with point-source scaling theory.
5. These experiments provide an upper bound, since they do not account for the amounts of ejecta that would be retained by an asteroid.

Implications

Consider an example of a single 20 km/s deflection mission of a 5-ton spacecraft to a rocky asteroid 300 to 500 m in diameter. Given a decade of warning, the Δv needed for deflection is ~0.01 m/s (Ahrens & Harris 1992). This means β would need to be 3.3 (300m) to 15 (500m).

The experiments indicate β≈12 at 20 km/s. Therefore, under these conditions, a single direct impact would deliver sufficient momentum to deflect a rocky object 400 m in diameter. Regolith-covered asteroids would be restricted to ~250 m and smaller. The viable object sizes drop substantially with lower impact velocity.