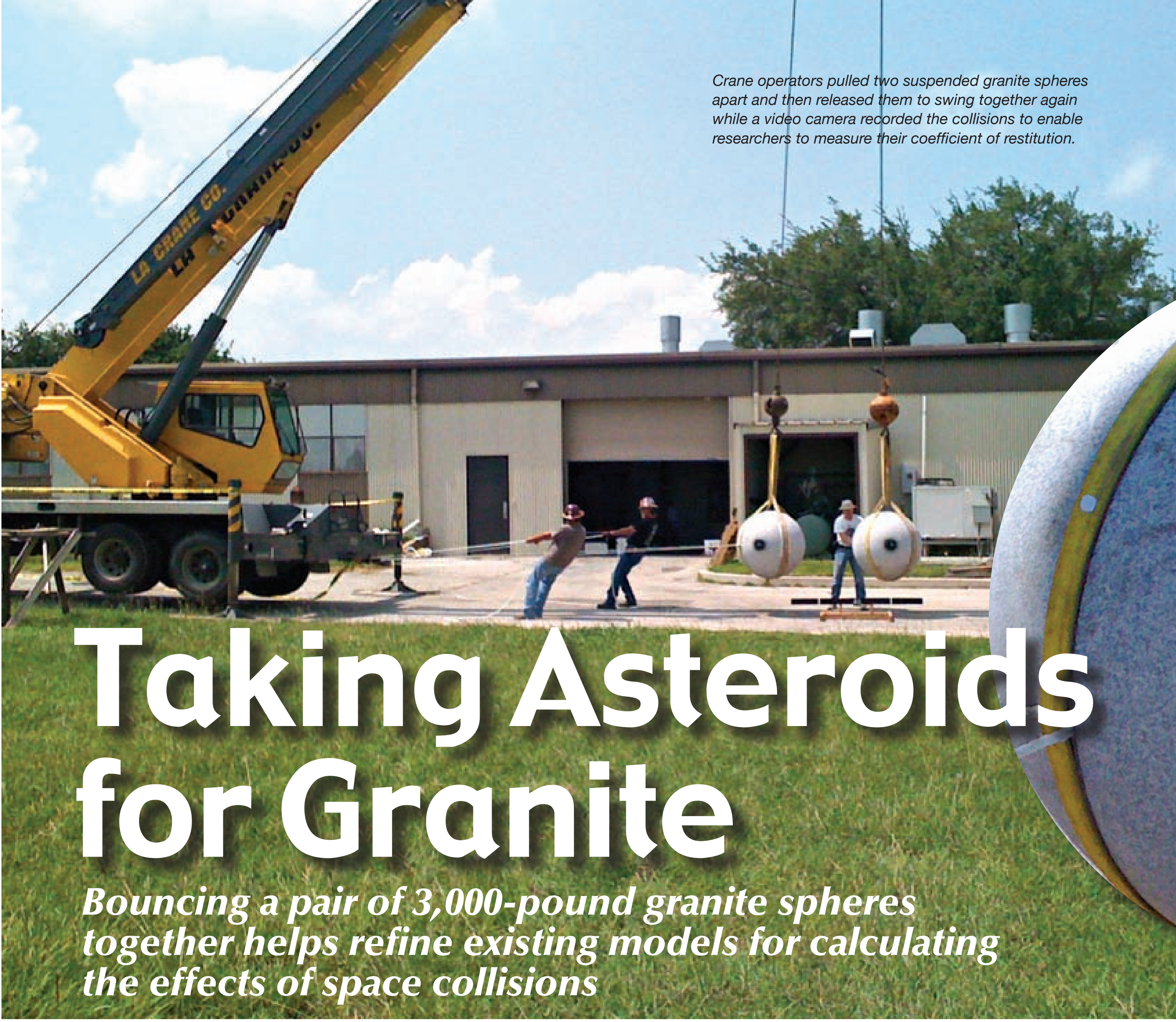


Crane operators pulled two suspended granite spheres apart and then released them to swing together again while a video camera recorded the collisions to enable researchers to measure their coefficient of restitution.

Taking Asteroids for Granite

Bouncing a pair of 3,000-pound granite spheres together helps refine existing models for calculating the effects of space collisions

By Daniel D. Durda, Ph.D.

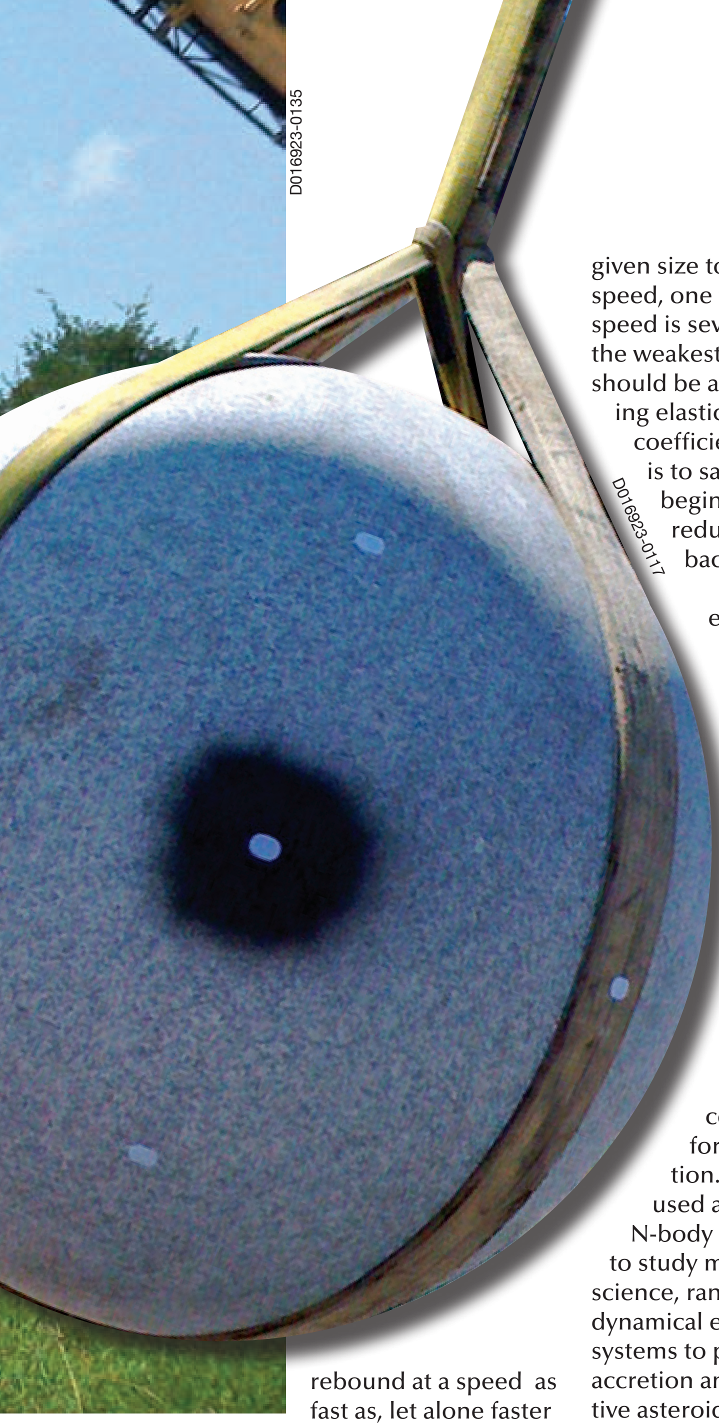
Observations of the rocky asteroid Itokawa revealed that this small body of space debris is actually composed of what amounts to a pile of rocks, with dimensions ranging from pebble-size to office building-size. Given the considerable interest among scientists and governments in determining what might happen if an asteroid collides with the Earth — or if a defensive projectile fired from Earth were to collide with an Earth-threatening asteroid — the physics of space collisions takes on new importance.

A common technique for modeling the outcomes of collisions between small solid bodies in the solar system involves granular physics codes in which the "granules" are rocks with diameters in the tens of meters. This is partly because of the limits of numerical resolution in modeling larger, kilometer-sized bodies. However, as in the case of the rubble-pile asteroid Itokawa, it also is partly rooted in reality.

Extremely high-speed impacts, which would vaporize both of the colliding bodies, would render moot the elastic rebound effect exhibited by bodies that collide at speeds low enough as to not disintegrate on impact. It is this elastic rebound, however, that is of great interest to planetary scientists.

Coefficient of restitution

The notion of modeling relatively low-speed collisions between bodies is based on determining their coefficient of restitution; that is, the ratio of an object's post-collision outgoing speed, to its speed prior to the collision. No object is perfectly elastic; even a Superball® dropped onto a solid surface will not



rebound at a speed as fast as, let alone faster than, that with which it was dropped. Its coefficient of restitution, then, is necessarily some value less than 1. This is confirmed in experimental laboratory-scale measurements of the coefficient of restitution for low-speed rock-on-rock collisions, which yield values around 0.8-0.9. However, are the values observed from collisions of small objects in a laboratory an adequate description for blocks of material with diameters measured in meters to tens of meters, which comprise the bulk of the mass of small asteroids and planetesimals?

Balancing size-dependent failure strength against the elastic stress accrued during deceleration of an object of a given size to a full stop from a given speed, one finds that when the impact speed is several meters per second, the weakest flaws in a rock's volume should be activated, thereby releasing elastic energy and lowering the coefficient of restitution. (That is to say, its internal structure begins to crack or crumble, reducing its ability to bounce back.)

On the other hand, the existence of intact decameter boulders within landslide deposits on Earth indicates that at least some very large rocks are perhaps not so fragile after all, and that an elastic collisional approach, parameterized by a single coefficient of restitution, might apply for a wide variety of regimes of collisional, tidal or any other kinds of evolution.

Several granular physics codes rely on assumed values for the coefficient of restitution. One of the most widely used among these is the fast N-body code *pkdgrav,* which is used to study many problems in planetary science, ranging from the collisional and dynamical evolution of planetary ring systems to problems of planetesimal accretion and the outcomes of disruptive asteroid collisions. Within the code is the assumption of a coefficient of restitution characterizing the outcomes of low-speed collisions between bodies up to about 200 meters in diameter. Since few experimental data exist from which to extrapolate for the value of the coefficient of restitution appropriate to rocky and icy bodies in this size and speed range, most *pkdgrav* simulations assume values of about 0.5 for both types of bodies. How representative this value is for the size and impact speed range typically used within the various simulations, or how variable it may be, is simply not well known. It is a significant roadblock to a better understanding of these and other problems in planetary science.

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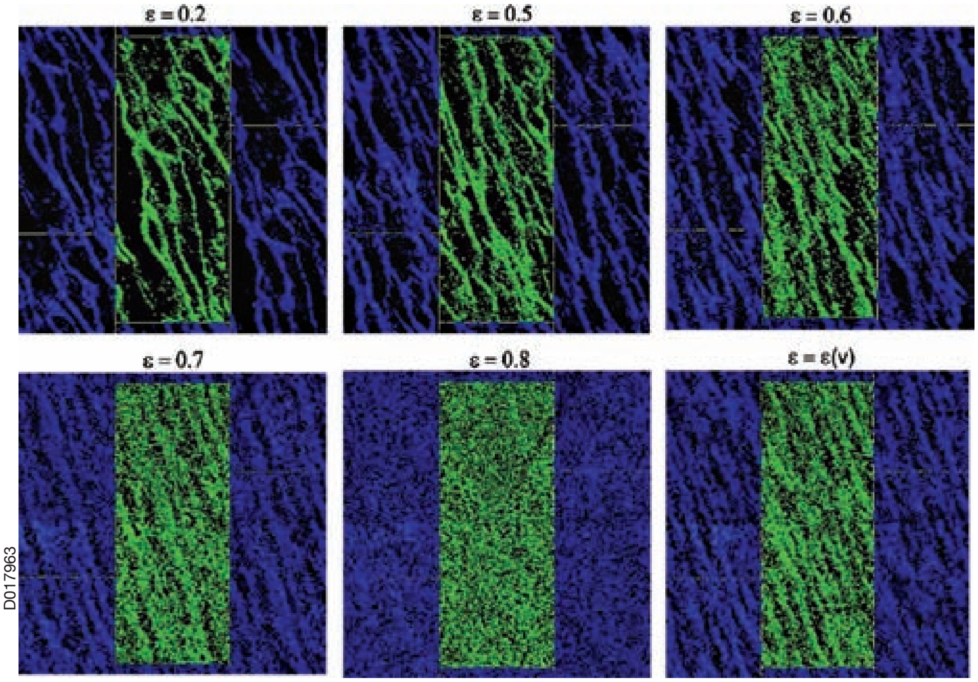
Scaling up the model

To begin to answer some of these questions, scientists at Southwest Research Institute (SwRI) conducted an extensive series of large-scale experiments to measure the coefficient of restitution for impacts between a pair of 1-meter diameter granite spheres with collision speeds up to about 1.5 meters per second (ms^{-1}). The experiments were intended to evaluate the size dependence of the coefficient of restitution of this silicate material. The two spheres were obtained from a commercial supplier of large, natural stone spheres for landscapes. They were milled from large blocks, and their surfaces were



Energy loss during inter-particle collisions in ring systems plays a key role in determining mean free paths, velocity dispersions, viscosity, spreading rates and ring thickness. Here, a numerical simulation of a patch of Saturn's rings compares the effect of varying values for the coefficient of restitution. The illustration shows how differences in coefficient of restitution can affect the equilibrium state of ring material and cause asymmetry in the brightness exhibited within the ring.

smoothed but not polished. To suspend the spheres and allow for pendulum-like motion, the SwRI team contracted two 40-ton cranes and secured each sphere using lifting straps. The straps were slung under each sphere perpendicular to each other, so that the spheres were securely cradled while still showing enough open rock face for unobstructed rock-on-rock contact during the experiments.

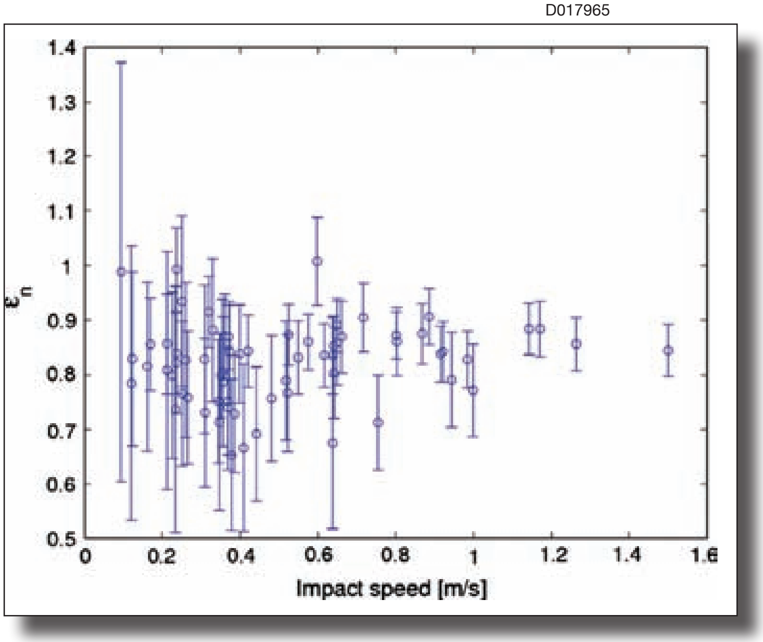
Before the experiment runs began, basic characterization and calibration data were obtained. The spheres were weighed using onboard crane sensors. One measured 3,000 pounds (1,361 kg) and the other was 2,700 lbs. (1,225 kg). The scientists then displaced one of the spheres about 1 meter from its equilibrium position and allowed it to swing for several cycles to verify that energy losses inherent in the suspension system were small compared to the energy losses in the collisions.

How the ball bounces

The SwRI team began the experiment series with small displacements of just one sphere, using ropes to pull it to the side before releasing it and letting it impact its motionless companion sphere, yielding impact speeds of about 1 m/s. For higher impact speeds, greater displacement was needed. This was achieved by displacing both spheres from their rest positions and allowing them to impact at their natural point of contact at the bottom of the pendulum arc. Pulling and holding the spheres for these higher speeds required great mechanical advantage, which was achieved through the use of ratcheting cable pullers. The SwRI team thus pulled the spheres up and away from each other and secured them in place with cable ties. The ties to both spheres were then cut on cue, releasing the spheres to swing back down and collide. This arrangement had the advantages of allowing greater displacement and thus greater impact speed, and establishing much more stabilized initial conditions before release. In all, 108 data runs were conducted, of which 90 were head-on collisions, to measure the normal-incidence coefficient of restitution. (The other 18 runs, exploring the effects of rotation and off-center impacts, were "bonus" data gathered because the planned operations proceeded so successfully.) All runs were imaged with high-definition video to record raw data including the ratio of initial sphere displacement, speed before impact, and displacement and speed after impact.

Video data were reduced and analyzed to derive the coefficient of restitution as a function of impact speed. After analyzing and refining the test data, the scientists determined that the mean coefficient of restitution between one-meter scale spheres at speeds of order 1 m/s^{-1} can be calculated as 0.83 plus or minus 0.06.

This value is significantly higher than the assumed value of 0.5 commonly used in numerical simulations, in the absence of data to suggest otherwise. It also is comfortably in the same range of values for the 1-cm



This graphic records the derived coefficient of restitution as a function of impact speed for 66 experimental runs where two granite balls were swung into each other. The scattering of data suggests that coefficient of restitution is independent of impact speed for the range of speeds tested.

scale granite spheres as measured by Imre *et al* in 2008.

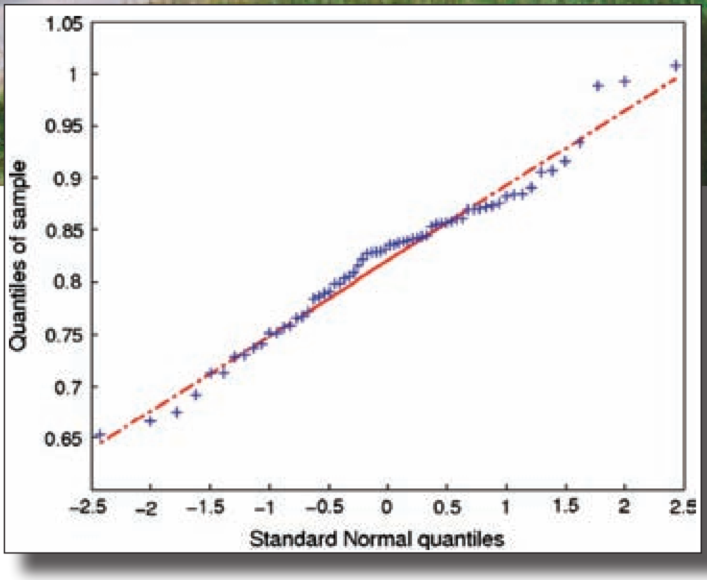
Discussion and applications

Mechanical constraints related to the weight of the spheres, and the difficulty of ratcheting them back far enough to obtain maximum impact speeds, limited the speed range in these experiments and kept speeds below the regime in which one would expect to see material compaction effects that were observed in experiments on some other materials. Also, the fact that the granite from which these spheres were produced had survived intact through the quarrying and milling process meant that they likely represented a natural selection toward a stronger and large-flaw-free, end-member sample of this type of granite. This should be considered when applying these measured values against other rocky materials, and when using these data in contexts where values representing more porous and weaker materials might be more appropriate.

Also, irregular body shapes might cause the effective coefficient of restitution for collisions between real fragments to approach the lower, 0.5 value. Protuberances will tend to get tamped down on impact, lowering the effective coefficient of restitution, and off-axis impacts into irregular surfaces generate more angular momentum transfer than a typical tangential coefficient of restitution would provide. The SwRI experiment results were published in the January 2011 issue of the journal *Icarus*.

The SwRI team plans future experiments using nearly spherical, but still very rough, granite fragments, to measure their effective coefficient of restitution for normal-incidence collisions, checking for moderately increased dissipation or rotational coupling with increased surface irregularity.

Those data can then be compared with the values for spherical bodies to provide appropriate, realistically constrained inputs for numerical codes for which a proper choice of assumed coefficient of restitution appears crucial.



A Q-Q plot of sample collision-experiment data versus values drawn from a standard normal distribution supports the conjecture that coefficient of restitution for the suspended granite spheres was not speed-dependent, but that a coefficient of 0.83 plus or minus 0.06 best represented the results.

Questions about this article? Contact Durda at (303) 546-9670 or daniel.durda@swri.org.

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