

Ricochets on Asteroids II: Sensitivity of laboratory experiments of low velocity grazing impacts on substrate grain size.

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Introduction: Laboratory study of impacts of marbles into sand showed that low velocity (a few m/s) projectiles can ricochet off granular materials, such as sand, at grazing angles (from the surface) up to 40° [1]. These laboratory experiments were done at 1g, however these and normal impact experiments can be scaled to low surface gravity conditions on astronomical bodies using dimensionless parameters [2,3]. This suggestion builds upon a related body of work that has developed scaling relations for impact craters [4]. The dimensionless Froude number ($Fr = v_{imp}/\sqrt{g R_p}$) was used to predict the outcome of oblique impacts into sand [1]. The Froude number is the inverse of the π_2 parameter in the impact literature.

Laboratory studies have carried out normal impact experiments into a variety of granular media, however, differences in the force laws or penetration depth are usually attributed to variations in velocity, gravitational acceleration and projectile and substrate densities, rather than to the substrate grain properties such as grain size, shape, or friction coefficients (e.g. [5], [2], [6]), with an exception being [7].

The heterogeneity of rubble found on astronomical objects and differences in size distributions on different

regions of astronomical bodies motivates understanding how oblique impacts are sensitive to the properties of the granular substrate. For example, impactors have been observed to ricochet on the surface of (101955) Bennu [8].

Oblique impact experiments: We compare low velocity impacts that ricochet with the same impact velocity and impact angle into granular media with similar bulk density, porosity, and friction coefficient, but different mean grain size. To characterize the grain size, we define a ratio of projectile diameter to mean grain length, $\pi_{\text{grain}} \equiv R_p / \bar{a}_g$, where R_p is the projectile radius and \bar{a}_g is the mean semi-major axis of the grains. This ratio has a value of 4 for our coarse gravel, 5 for the finer gravel, 17 for the dark sand, and 51 in our finest sand (Figure 1).

Using high speed video and fluorescent markers, we track the trajectory of the projectile before, during, and after impact. Example of a trajectory on the coarsest substrate is shown in Figure 2. We can measure the spin of the projectile by tracking painted green dots.

Coefficients of restitution: From the trajectories, we measure the ratio of pre- to post-impact velocity components, which we refer to as coefficients of restitution. We do this for both the horizontal and vertical directions. Coefficients of restitution are



Figure 1: Images of the four different granular substrates and the marble projectile for comparison (diameter 16.15 mm). A dimensionless parameter π_{grain} is defined as the ratio of projectile to grain size. From top to bottom, there is a coarse gravel, finer gravel, dark beach sand, and light playground sand. The substrate and impactor were chosen to match their densities.

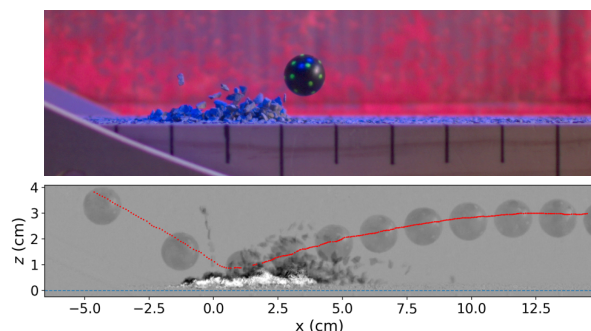


Figure 2: Upper – Single frame from a high-speed video of a ricocheting impact into the coarsest substrate. Lower – A summed greyscale image of multiple frames separated by 33 ms. Trajectory of the tracked projectile is in red. The blue dashed line is the surface. All experiments had an impact angle of 30° and impact velocities of ~3.8 m/s.

sensitive to mean grain size with the horizontal restitution about twice as large for the coarsest gravel as that for the finest sand. This implies that coefficients for hydro-static-like, drag-like and lift-like forces, used in empirical force laws, are sensitive to mean grain size. We also estimate an effective friction coefficient for our impacts. Figure 3 shows our measured values for the restitution coefficients.

Hydrodynamic coefficients: To test our interpretation of the dimensional empirical force law coefficients we developed a phenomenological model to relate them to dimensionless lift and drag hydrodynamic coefficients C_L and C_{Dx} , respectively. We relate the dimensional coefficients α_L and α_x to the dimensionless coefficients with the time it takes the projectile to impact and then exit the granular media. This exit time t_e was measured for each substrate with the smallest grain size having an exit time of about four times longer than the coarsest grain size. The coefficient that is most strongly sensitive to grain size is the lift coefficient C_L that decreases by a factor of four between our coarsest and finest media. The drag coefficient by comparison only varied by a factor of two. The hydrodynamic coefficients are plotted in Figure 4.

Conclusion: At lower π_{grain} , dynamics is essentially only impacts between two objects, the projectile and a single grain. At higher π_{grain} we expect dynamics to become independent of grain size as the grains are small compared to the projectile and act more fluid like. The range of projectile to grain sizes ratio of our experiments covers a range where the impacts dynamics would be sensitive to grain size. The dependence of impact mechanics on the mean substrate particle size should be considered in future impact models for populations of objects that impact granular asteroid surfaces.

Acknowledgments: This material is based upon work supported in part by NASA grants 80NSSC21K0143 and 80NSSC17K0771. We thank Jim Alkins for helpful discussions regarding machining. We are grateful to Tony Dimino for lent equipment. This study was initiated in collaboration with Randal C. Nelson who is sorely missed.

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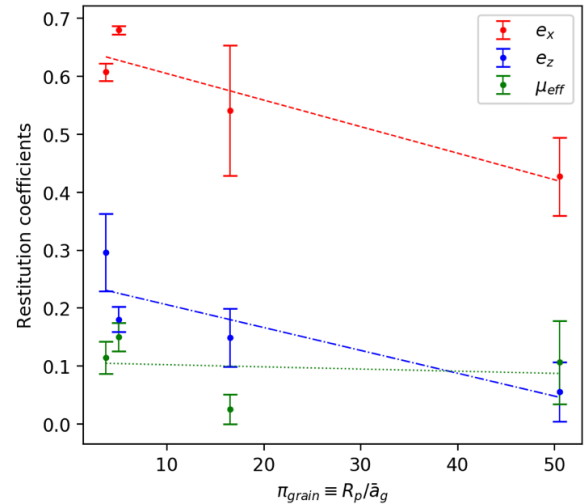


Figure 3: Restitution coefficients with errors of one standard deviation plotted as functions of projectile to mean grain size ratio π_{grain} . Larger grain sizes are on the left; coefficients of restitution are larger in larger grain size substrates. The dashed lines correspond to a linear fit of the coefficients. The effective friction coefficient μ_{eff} is insensitive to grain size.

Additional Information: If you have any questions regarding this abstract you contact the lead author at ewrig15@ur.rochester.edu. Work presented here is published in the journal *Icarus* 114868, January 7, 2022. High speed videos can be found at <https://www.youtube.com/playlist?list=PLYnpHw29go3pCWwm554fwR6jNFvB5qVQn>.

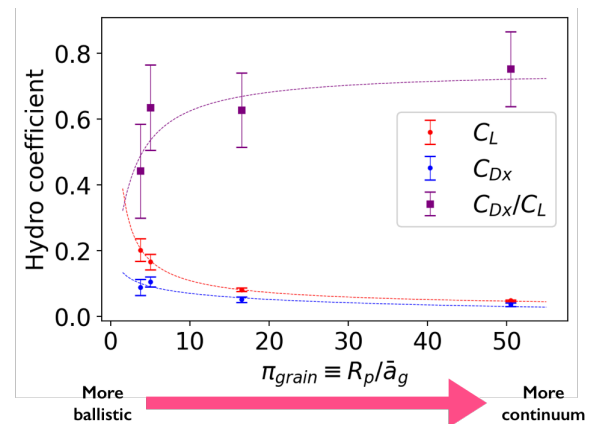


Figure 4: Lift and drag coefficients as a function of size ratio π_{grain} from oblique impact model. Red dots are the lift coefficients. The drag coefficients are in blue dots. The ratio of the two coefficients are shown in purple squares. Dotted lines correspond to fitted lines for the lift, drag, and ratio of the coefficients.