MATERIAL PROPERTY AND PARTICLE DISTRIBUTION EFFECTS ON UNCONFINED INERTIAL DILATION.

E. S. Frizzell[1] and C. M. Hartzell[1], [1]U. of Maryland – Aero. Eng., College Park, MD (efrizz@umd.edu)

Introduction: Lunar Cold Spots (LCS) are halos of low thermal inertia regolith surrounding source craters on the Moon [1]. Although LCS are a common feature of young craters [2] and occur across all terrains, their formation mechanism remains unknown. In our prior work, we have demonstrated that surface dilation occurs when a laterally propagating shock wave triggers inertial dilation at the vacuum-grain interface of an assembly filled with cohesive, deformable particles [3]. Both the tendency for the bed to undergo dilation even at moderate initial packing fraction (ϕ_0) as well as the lateral extent of dilation suggest that shock-induced-granular-dilation is a possible explanation for LCS. However, our initial findings come from an idealized monodisperse granular assembly. In this work we determine the sensitivity of shock induced granular dilation to material properties (cohesion, friction, strength, etc.) and different particle size distributions to guide construction of granular assemblies representative of surface Lunar regolith. We give preliminary results showing material property effects on dilation.

Background: The reduced thermal inertia of the LCS is due to a reduction in bulk volume (compared to background regolith) of 1-10% in the first 40 cm of the surface that can persist in a halo around a source crater up to 100 crater radii in distance [1]. We found in [3] that surface dilation occurs as the result of a single passing granular shockwave in a long channel and that the magnitude of dilation was consistent over the shock's entire path (up to 4 meters). The force generated by the shock went through a period of rapid exponential decay before attaining a steady value that was suggestive of the inverse decay regime of an elasto-plastic wave [4], where shocks persist over long distances. We found that the shock induced inertial dilation [5] was on the order of the difference between background and LCS regolith (>2% dilated) in the most densely packed bed. Figure 1 shows the result of shock induced dilation for various ϕ_0. We see that the bed becomes more dilated as ϕ_0 increases. The lower limit ϕ_0 for the compaction-dilation crossover is lower than the $\phi_0 = 0.58$ seen in normal impacts under vacuum in [6] – even our loosest bed ($\phi_0 \approx 0.55$) dilates. The observed dilation could be consistent with LCS if it can occur over large distances and in a granular assembly that more closely resembles Lunar regolith.

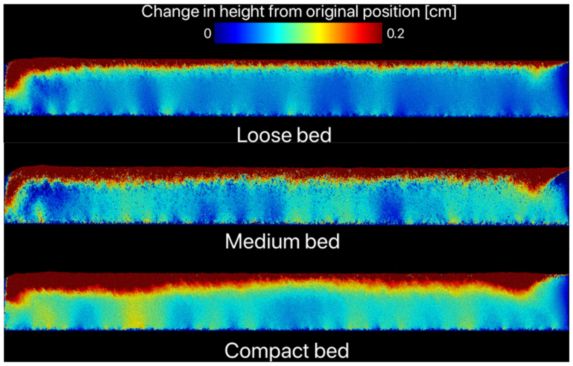

Figure 1. Change in bed height for varied ϕ_0. Particles are colored by their change in height from initial position on a scale of 0 (blue) to 0.2 cm (dark red). The assembly is a 2 meter channel filled 20 cm with particles of loose, medium, and compact packings (average ϕ_0= 54.72, 58.65, 61.96, respectively) which have been shocked. The compact case corresponds to a uniform ~2% dilation across the entire assembly. Visualization produced using [7].

The Lunar regolith has a roughly fixed grain size distribution as a result of impact gardening over the lifetime of the moon [8]. The distribution is known thanks to Apollo measurements and has a mean particle size around 100 μm [9]. The results in [3] come from a monodisperse assembly with particle size 2.5 mm, about one order of magnitude greater. Increasing polydispersity leads in a greater ability for grain reengagement leading to dilation [10] and decreasing particle size will increase the depths to which the shear band that enables the inertial dilation can exist [11]. The material properties of the Lunar regolith are more variable. [8] reports a range of friction coefficients (0.87 – 1.28) and cohesion energy density (15.6 to 29 kPa) for surface regolith. Predicted values for the Poisson ratio (ν) range from 0.23 [12] to 0.41 [13]. We did not come across a reported in-situ value for surface regolith strength, but JSC-1A regolith simulant has a Young's modulus (E) on the order of 10 MPa [14] which is orders of magnitude stronger than used in [3]. Understanding if inertial dilation plays a role in the formation of LCS will require tests conducted with a granular assembly that is more representative of the Lunar regolith.

In this work we seek to determine how changes to material properties and particle size distribution influence the expression of unconfined inertial surface dilation. We will conduct a campaign of shock simulations on granular assemblies of varied material properties and size distributions. Simulation parameters are selected to form assemblies that have bulk properties similar to Lunar surface regolith.

Methodology: We begin with a sensitivity analysis of surface dilation to the mechanical parameters of our granular assembly using Soft Sphere Discrete Element Modeling (SSDEM) as described in [3]. We use a 2 meter channel filled to 20 cm with particles and induce a lateral shock using a single compressive impulse from a virtual piston (sheet of particles given an initial velocity, [15]). We measure resultant dilation as the result of varied particle-particle material properties: strength, cohesion, friction, rolling friction, rolling viscous damping, coefficient of restitution, and Poisson ratio. We will then prepare new beds with varied particle sizes and introduce polydisperse particle distributions. We will characterize the resultant bulk properties through shear cell analysis [16] which can be compared to bulk properties derived through the sound speed for validation. We are also interested in what effect the material make-up of the regolith has on surface dilation. Given that dilation occurs to form the LCS across both maria and highlands we expect to find that surface dilation occurs for a wide range of particle stiffness and masses inspected. We can use the material properties of the regolith [17] to set varied spring and mass ratios between particles in our polydisperse distribution to see if dilation can be tuned to occur in some instances and not in others as was done with solitary waves in [18].

Initial Results: We varied cohesion from 0-10 kJ/m3, which bounds the predicted lunar cohesion values from [8] and includes a no cohesion case. Dilation is fairly insensitive to cohesion for low values ([0,1 kJ/m3]) and decreased slightly for the highest case considered (10 kJ/m3). We see the additional pull of neighbor particles reduces the total height particles attain. High cohesion is therefore not necessary for surface dilation to occur as the result of a shock, exposure to vacuum is the enabling condition. The range of static fiction coefficient considered (0-1.8) includes a no friction case, the range laid out in [8], and larger values that are used in SSDEM to simulate gravel [19]. Friction had the greatest influence on surface dilation, the results are shown in Figure 2. Dilation is most pronounced for the roughest particles and in the case of no friction there is a slight compaction that occurs throughout the channel. Inertial dilation was insensitive to the coefficient of restitution (0.35-0.85) which was varied according to the range consider in other modeling efforts [20]. Similarly, coefficient of rolling friction (0-1.2) included the a no rolling friction case as well as values used by others modeling low gravity regolith [21]. Dilation showed a slight inverse proportionality to rolling friction.

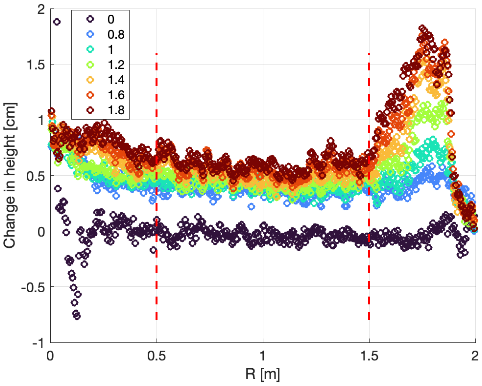

Figure 2. Change in bed height vs radial position for varied friction. We show average height increase experienced by particles initially resting on the top of a 2 meter channel filled 20 cm deep with particles. Color legend shows static friction coefficient. The dashed red lines show the measurement region, disregarding ejected sensor particles located at the end wall.

Conclusions + Future Work: We are currently finishing out the material parameter sensitivity analyses (E, ν) and preparation of beds with different particle sizes and distributions is underway. We will present the results of these simulations and use them to guide our initial analysis of the scaling properties of shock-induced-granular-dilation.

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