New material model for simulating large impacts on rocky bodies

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Large impact craters on an asteroid can provide insights into its internal structure. These craters can expose material from the interior of the body at the impact site [e.g., 1]; additionally, the impact sends stress waves throughout the body, which interrogate the asteroid's interior. Through a complex interplay of processes, such impacts can result in a variety of motions, the consequence of which may appear as lineaments that are exposed over all or portions of the asteroid's surface [e.g., 2,3]. While analytic, scaling, and heuristic arguments can provide some insight into general phenomena on asteroids, interpreting the results of a specific impact event, or series of events, on a specific asteroid geometry generally necessitates the use of computational approaches that can solve for the stress and displacement history resulting from an impact event.

These computational approaches require a constitutive model for the material, which relates the deformation history of a small material volume to the average force on the boundary of that material volume. In this work, we present a new material model that is suitable for simulating the failure of rocky materials during impact events. This material model is similar to the model discussed in [4]. The new material model incorporates dynamic sub-scale crack interactions through a micro-mechanics-based damage model, thermodynamic effects through the use of a Mie-Gruneisen equation of state, and granular flow of the fully damaged material. The granular flow model includes dilatation resulting from the mutual interaction of small fragments of material (grains) as they are forced to slide and roll over each other and includes a P-α type porosity model to account for compaction of the granular material in a subsequent impact event.

The micro-mechanics-based damage model provides a direct connection between the flaw (crack) distribution in the material and the rate-dependent strength. By connecting the rate-dependent failure behavior to the sub-scale flaw distribution in the material, we are able to investigate the effect of changing the assumed initial flaw population on an asteroid. Additionally, by simulating the naturally variable local flaw population in a body, we introduce macroscopic variability that is both physical and improves the numerical stability.

We have implemented this material model using the Generalized Interpolated Material Point method (GIMP) within the Uintah computational framework [5]. GIMP is an updated Lagrangian formulation, which uses material points to track field quantities in the simulation and a background grid to solve the equations of motion. Since nodal quantities on the grid are mapped from the material points, the grid can be reset at the end of each timestep avoiding mesh entanglement errors associated with Lagrangian finite-element approaches. Since the material points always stay with the same block of material, this method is ideal for history-dependent damage models that are difficult to solve using Eulerian approaches. Finally, using a background grid simplifies the computation of gradients in the material and specifically eliminates the costly neighbor search step in pure particle methods such as SPH. The disadvantage of a background grid is that it must cover the entire simulation domain, not just the location where there is material. This is an acceptable trade-off, because, in our material model, most of the cost of the calculation is confined to the particles and updating the constitutive model.

In this work, we demonstrate the strength of our modeling approach by simulating the impact history of Eros. We assume that Eros began as a solid shard of material, consistent with [3], and then simulate the series of impacts that could have formed the three major craters Himeros, Psyche, and Shoemaker. Work presented by Tonge et al. [6] demonstrated that this material model was able to explain the 20 percent porosity of (433) Eros from porosity produced during the formation of Himeros. Additionally, they showed that initial impacts into solid targets are more effective at creating porosity than later impacts into targets that have been significantly damaged. This modeling work suggests that the first large impact on a body like Eros is the most important impact for setting up the observed structure, and the subsequent impacts can make local modifications to the structure, but will not significantly alter the network of cracks developed by the initial impact event. Additional implications of the modeling work for our understanding of the tectonic history of Eros are discussed in the talk by O.S. Barnouin et al., "The Tectonic Evolution of (433) Eros".

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