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A model for impact-induced lineament formation and porosity growth on Eros

Andrew L. Tonge [a,*], K.T. Ramesh [a], Olivier Barnouin [b]

[a] Department of Mechanical Engineering, The Johns Hopkins University, 3400 N. Charles St., Baltimore, MD 21218, USA
[b] The Johns Hopkins University Applied Physics Laboratory (JHUAPL), 11100 Johns Hopkins Road, Laurel, MD 20723, USA

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ABSTRACT

We investigate the impact history of the Near Earth Asteroid (NEA) Eros 433 using a new material model for brittle materials such as rocks, where initial flaw distributions within the rock are explicitly defined to match what is known about flaw size distributions in rocks. These simulations are limited to the initial impact phase of the crater formation process and use a very crude approximation for the effect of the gravitational overburden pressure. Given these approximations, our simulations of this numerical approximation of Eros suggest that the current observed bulk porosity of about 25% could be consistent with the porosity generated by the formation of the three largest craters observed on Eros indicating that Eros could have started as an intact shard from a prior impact event. Further, we investigate the consequences of two possible internal flaw distributions for the asteroid: a "strong" flaw distribution with shorter crack lengths, that are more difficult to activate during cratering; and a "weak" flaw distribution with longer flaws. The "strong" distribution produces localized deformation regions (lineaments) that are resolved by the simulations, while the "weak" distribution does not produce resolved localized features. For either distribution of internal flaws the initial impact (assumed to be the Himeros forming impact) shatters but does not disrupt the body implying that simulations of asteroid mitigation approaches should assume that asteroids will behave like rubble piles. Subsequent impact events activate linear features created by prior impacts but only change the orientation of the lineament structure near the impact site.

1. Introduction

The internal structure of asteroids is important for determining an asteroid's origin (Richardson et al., 2002), its subsequent evolution, and when considering possible asteroid mitigation strategies. For example, the collisional evolution of an asteroid depends on its internal strength and on how effectively waves travel through the body during a cratering event. Similarly, mitigation strategies require understanding how the internal structure of an asteroid might affect any attempts to displace it. Little is known about the internal structure of asteroids besides what can be learned from observed lineaments (Buczkowski et al., 2008) and the measured bulk density (Britt et al., 2002). Fortunately, impact events interrogate the interior of asteroids through the production of stress waves that travel through the body. Since a coherent body will transmit waves more efficiently than a rubble pile, the extent of the area of influence of an impact event can be used to assess the nature of the target body, either through the observed distribution of surface lineaments or by the consequence impact-derived seismic processes (Thomas and Robinson, 2005).

1.1. Eros as a model NEO (ordinary chondrite)

One of the best studied Near Earth Objects (NEOs) is the Asteroid 433 Eros. The Near Earth Asteroid Rendezvous (NEAR–Shoemaker) mission obtained detailed measurements of the surface of Eros and its bulk density. Spectral data collected during the rendezvous mission indicate that Eros is an S type asteroid best represented by LL ordinary chondrite (McCoy et al., 2001). Most ordinary chondrites in the recovered meteorite collection that closely resemble Eros possess a density near 3400 kg/m^3 while the bulk density of Eros measured from gravity is 2670 kg/m^3 (Wilkison et al., 2002). This measured density, in light of Eros' best spectral match, suggests that this asteroid is not structurally heterogeneous. Eros most likely possesses a porosity between 21% and 33% (Wilkison et al., 2002). Such a porosity is small

* Corresponding author.
E-mail addresses: andy.tonge@jhu.edu (A.L. Tonge), ramesh@jhu.edu (K.T. Ramesh), olivier.barnouin@jhuapl.edu (O. Barnouin).

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compared to the typical porosity of a loose sand or gravel, which is near 40%, and suggests that Eros cannot be a loosely bound aggregate or rubble pile, but may more closely resembles a tightly bound aggregate or fractured shard. Such a hypothesis that Eros is a heavily interlocked body capable of transmitting seismic waves over significant distances is supported by the abundance of global lineament structures associated with individual impact events (Buczkowski et al., 2008), and the paucity of craters attributed to crater destruction by seismic shaking near Shoemaker (Thomas and Robinson, 2005).

1.2. Impact history of Eros from NEAR data

The craters on Eros provide a record of the order of impact events. There are three major craters on the surface of Eros: Himeros, Psyche, and Shoemaker (this latter crater is named Charlois Regio by the IAU; however, to be consistent with previous literature, we will use the name Shoemaker in this work) (Veverka et al., 2000b). For an illustration of these three craters relative to the rest of Eros see Fig. 1 in Buczkowski et al. (2008). The distribution of the largest blocks on Eros correlates with the expected location of ejecta from Shoemaker crater, suggesting that the youngest of these three craters is Shoemaker (Thomas and Robinson, 2005). There is some debate about whether Himeros or Psyche is younger; however, Himeros appears more degraded than Psyche and so, for the purposes of this paper, we assume that Himeros occurred first. Investigations of the orbital evolution of Eros indicate that it evolved for some time in the main belt, before it became a Near-Earth orbiter (Michel et al., 1998). Due to the greater cratering flux in the asteroid belt near the source of many impactors (Bottke, 2001), it is likely that the bulk of Eros' cratering history occurred in the main belt. We, therefore, assume that all of these impacts occurred prior to Eros leaving the asteroid belt. In this region, typical impact velocities are around 5 km/s (Bottke et al., 1994).

We investigate the impact history of Eros using a new material model (Tonge and Ramesh, 2016) for the dynamic failure of geologic materials. This model explicitly defines a distribution of flaws that are then activated by the impact process. Using this new material model we perform simulations of the impact events on Eros and look for expressions of material failure on the surface of the body that can be compared to observations. We investigate the hypothesis that Eros originated as a fragment from an impact event on a larger parent body and subsequent impact processing has produced the current body. Additionally, we will investigate the evolution of bulk porosity in a numerical approximation of Eros as a result of the impact history to determine the plausibility of generating at least 20% porosity from a fully dense body as a result of impact processes. In this investigation we consider only the effect of the impacts and neglect the effect of gravitational or other long duration processes that occur between impact events.

2. The Tonge–Ramesh model for geomaterials

The material model developed by Tonge and Ramesh (2016) is a mechanism-based material model designed for impact events involving brittle materials (such as rocks). The key features of the new material model are self consistent dynamically interacting crack distributions, pressure dependent granular flow of the highly damaged material, pore compaction through the use of a P–α porosity model, and a Mie–Grüneisen equation of state. The Mie–Grüneisen Equation of state is sufficient for the purposes of this investigation since significant phase changes are not expected for impact velocities near 5 km/s. The mechanics-based model captures the important physical processes (Fig. 1) during impact events. It is useful to think of these processes in terms of both time and length scales. Starting from the green quadrant in Fig. 1 and moving clockwise through the bubbles, the key physical processes are listed in generally increasing length and time scale after an impact event occurs. In the green quadrant labeled thermodynamic response we have the Mie–Grüneisen equation of state and the elastic response (specifically the shear modulus). The orange box contains processes associated with dynamic crack growth. Specifically, the interaction and growth of microcracks leads to rate effects (Kimberley et al., 2013) that limit the rate at which a material point with a given distribution of defects can fail through microcrack growth. These rate effects (Kimberley et al., 2013) are a direct result of the subscale flaw distribution (flaws at a scale below the computational discretization threshold) and the existence of a limiting crack growth speed. Moving from the orange region in Fig. 1 across the dotted line to the yellow[1] region, one moves to slightly larger length scales and later times. This region describes processes that occur within the fully damaged material as it continues to deform. We describe the damaged material using a granular flow model with associative flow. As the material is sheared it dilates and increases the porosity in the body. We include a pore compaction model to account for the evolution of that porosity. The upper left corner of the figure lists physical processes that must be resolved by the computational mechanics framework because they are changes to the initial boundary value problem rather than subscale processes occurring within a representative material volume.

2.1. Key equations in the Tonge–Ramesh material model

The balance of linear momentum within a continuum body is often written using the Cauchy or true stress ($\boldsymbol{\sigma}$) as:

$$\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{b}\rho = \rho \boldsymbol{a}. \tag{1}$$

Here $\boldsymbol{b}$ is the body force per unit mass, $\boldsymbol{a}$ is the acceleration, and ρ is the current density.

The stress can be split into a pressure $\left(p = -\frac{1}{3}\mathrm{tr}(\boldsymbol{\sigma})\right)$ and a deviatoric portion. Within this model we address porosity through the use of a P–α (Carroll and Holt, 1972) porosity model such that the pressure is given by:

$$p(J, J_{GP}) = \frac{p_s(J_e)}{J_{GP}}. \tag{2}$$

Here we have introduced the total volume change ratio $\left(J = \frac{\rho_0}{\rho}\right)$, the volume change ratio in the solid material $\left(J_e = \frac{\rho_0}{\rho_s}\right)$, the distension $\left(J_{GP} = \frac{\rho}{\rho_s}\right)$, and the solid material pressure (p_s), which is computed using a Mie–Grüneisen equation of state (discussed below). From these relationships it follows that $J = J_e J_{GP}$. In developing the model, it is more convenient to define the alternative stress measure $\boldsymbol{\tau} = J\boldsymbol{\sigma}$, where $\boldsymbol{\tau}$ is called the Kirchhoff stress. We assume a decoupled representation of the Kirchhoff stress tensor:

$$\boldsymbol{\tau} = \boldsymbol{\tau}_{dev} - p_s J_e \boldsymbol{I}. \tag{3}$$

Here $\boldsymbol{\tau}_{dev}$ is the deviatoric (or traceless) part of the Kirchhoff stress and $\boldsymbol{I}$ is the second order identity tensor.

2.1.1. Elasticity and the equation of state

The deviatoric stress $\boldsymbol{\tau}_{dev}$ is assumed to be a linear function of the deviatoric part of the volume preserving elastic deformation:

$$\boldsymbol{\tau}_{dev} = G\left(\bar{\boldsymbol{b}}_e - \frac{1}{3}\mathrm{tr}(\bar{\boldsymbol{b}}_e)\boldsymbol{I}\right) \tag{4}$$

[1] For interpretation of color in Fig. 1, the reader is referred to the web version of this article.