



Quantifying the effect of asteroid structure on hypervelocity impact outcomes with the Material Point Method

Xiaoran Yan¹, Wenhan Zhou², Yan Liu¹, Patrick Michel^{2,3}, and Junfeng Li¹

¹Tsinghua University, School of Aerospace Engineering, Lab of Astrodynamics, Beijing, China (yxr17@mails.tsinghua.edu.cn)

²Observatory Cote d'Azur, University Cote d'Azur, CNRS, Nice, France

³Department of Systems Innovation, School of Engineering, University of Tokyo, Tokyo, Japan

Introduction Recent advancements in computational power and model sophistication have revolutionized the study of hypervelocity impacts on asteroids, enabling the exploration of broader parameter spaces and more intricate asteroid structures [1, 2]. The outcome of such collisions, including crater formation and catastrophic disruption, is intricately linked to the internal structure of asteroids. However, the nature of this relationship remains an open question, necessitating further investigation. The Material Point Method (MPM), renowned for its ability to accurately track interfaces and resolve contact problems, emerges as a powerful tool for numerical simulations in this context [3]. By harnessing the capabilities of MPM, we aim to shed light on the correlation between an asteroid's structural composition and its response to hypervelocity impacts, ultimately contributing to a deeper understanding of the underlying physical processes.

Method Developed from the particle-in-cell numerical method, the Material Point Method (MPM) combines Eulerian and Lagrangian descriptions, making it well-suited for handling boundary conditions and interface problems. By utilizing a dynamic background grid that only creates nodes with mapped material points for efficient computation, we further implement a contact algorithm in our MPM framework that could accurately calculate the real contact and friction force on each interface, and novelly extend the contact correction from two-object to multi-object scenarios.

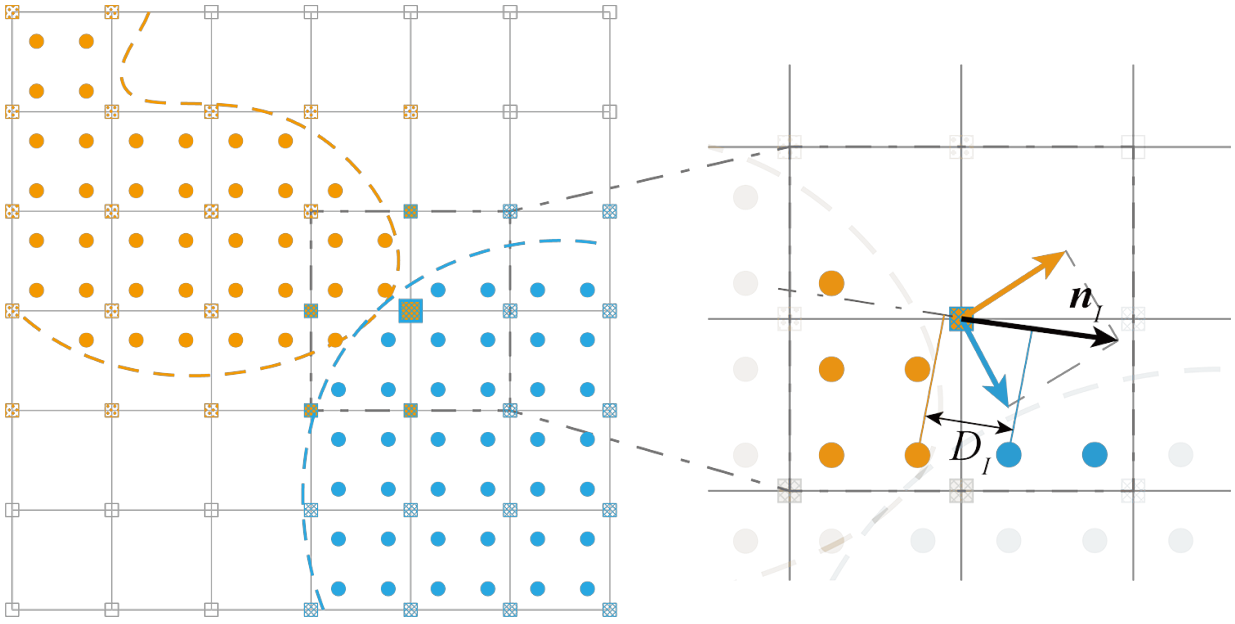


Fig. 1. Multi-object dynamic background grid and the detection of contact on a grid node.

When the contact algorithm is activated, if a background grid node is shared by multiple objects, separate node information will be created for each object, along with the associated material point indices, as illustrated in Fig. 1. The execution of contact correction is triggered by assessing both the distance between objects and their relative motion based on non-penetration constraints. It is implemented by applying contact forces to eliminate penetration and enforce suitable friction conditions. Multi-body contact is resolved by solving a linear system of equations for the unknown contact forces between each pair of interacting objects. This algorithmic enhancement bolsters the capability of our MPM code to precisely simulate hypervelocity impacts on asteroids with intricate internal structures.

Simulation and Discussion In this study, we conduct numerical simulations of artificial hypervelocity impacts on asteroids to quantitatively investigate the distinct dynamic responses of rubble-pile asteroids compared to monolithic, homogeneous ones. We employ material parameters of typical basaltic rocks in our simulations [4]. The impact scenarios and results for rubble-pile asteroids are illustrated in Fig. 2. Considering the crucial role of the catastrophic disruption threshold in understanding the evolutionary history of small celestial bodies and designing asteroid impact defense missions, as well as the availability of numerical values for specific asteroid sizes from previous research [5], we aim to quantify the influence of porosity and internal interfaces on impact disruption mechanisms by calculating the catastrophic disruption threshold for rubble-pile asteroids with various configurations.

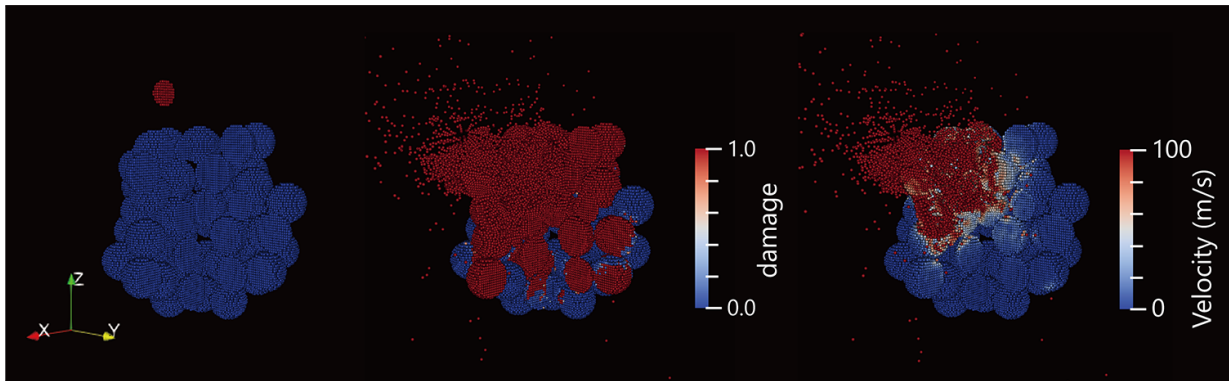


Fig. 2. Artificial hypervelocity impact on a rubble-pile asteroid: initial collision, damage distribution, and velocity field from numerical simulations.

Our simulation results demonstrate the significant impedance effect of internal interfaces on shock wave propagation, leading to a substantially higher catastrophic disruption threshold for rubble-pile asteroids compared to monolithic asteroids of the same strength. This finding suggests that the presence of a rubble-pile structure enhances the resistance of asteroids to catastrophic disruption, which has important implications for understanding their fragmentation and reassembly processes throughout their evolutionary history.

Furthermore, the quantitative analysis of the catastrophic disruption threshold for different rubble-pile configurations provides valuable insights into the role of porosity and internal structure in the impact response of asteroids. These findings contribute to the development of more accurate models for asteroid evolution and can inform the design of future asteroid impact defense strategies. Additionally, the results of this study have the potential to facilitate the calibration of asteroid ages based on their structural properties and impact history, enhancing our understanding of the chronology of asteroids in the solar system.

Acknowledgment X.Y. and J.L. acknowledge support from the National Natural Science Foundation of China under Grant 12372047. X.Y. acknowledges support from the National Natural Science Foundation of China under Grant 62227901. P.M. acknowledges support from the French space agency CNES and from the French National Centre for Scientific Research (CNRS) through the exploratory research program of the Mission for Transversal and Interdisciplinary Initiatives.

References [1] Raducan, S. D. et al. (2024). *PSJ*. 5(3). [2] Jutzi, M. et al. (2022) *Nat. Commun.* 13(1), 7134. [3] Yan, X. et al. (2023) *ACM Conference*. [4] Jutzi, M. (2015) *P&SS*. 107(1), 3–9. [5] Benz, W. et al. (1999) *Icar*. 142, 5–20.