# Tool-soil interaction & granular material dynamics modeling for low gravity surface sampling in planetary exploration


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## Introduction

A potential future in-situ lander mission to the surface of Saturn's moon Enceladus could be the lowest cost mission to determine if life exists beyond Earth since material from the subsurface ocean, where the presence of hydrothermal activity has been strongly suggested by the Cassini mission, is available on its surface after being ejected by plumes and then settling on the surface (Fig. 1). In addition, the low radiation environment of Enceladus would not significantly alter the chemical makeup of samples recently deposited on the surface. A study was conducted to explore various sampling devices (i.e. percussive/ultrasonic scoops, rotary/percussive drills, impactors, rasps) that could be used by an in-situ lander mission to provide 1 to 5 cm$^3$ volume samples to the scientific instruments. It is desired to acquire surface plume material that has accumulated in the top 1 cm to ensure acquisition of the least processed material. In addition to extreme temperature and vacuum environmental conditions, the very low surface gravity of Enceladus (1% of Earth's gravity) represents a new challenge for surface sampling that is not met by sampling systems developed for microgravity (e.g. comets and asteroids) or higher gravity (e.g. Europa, Moon, or Mars) environments.

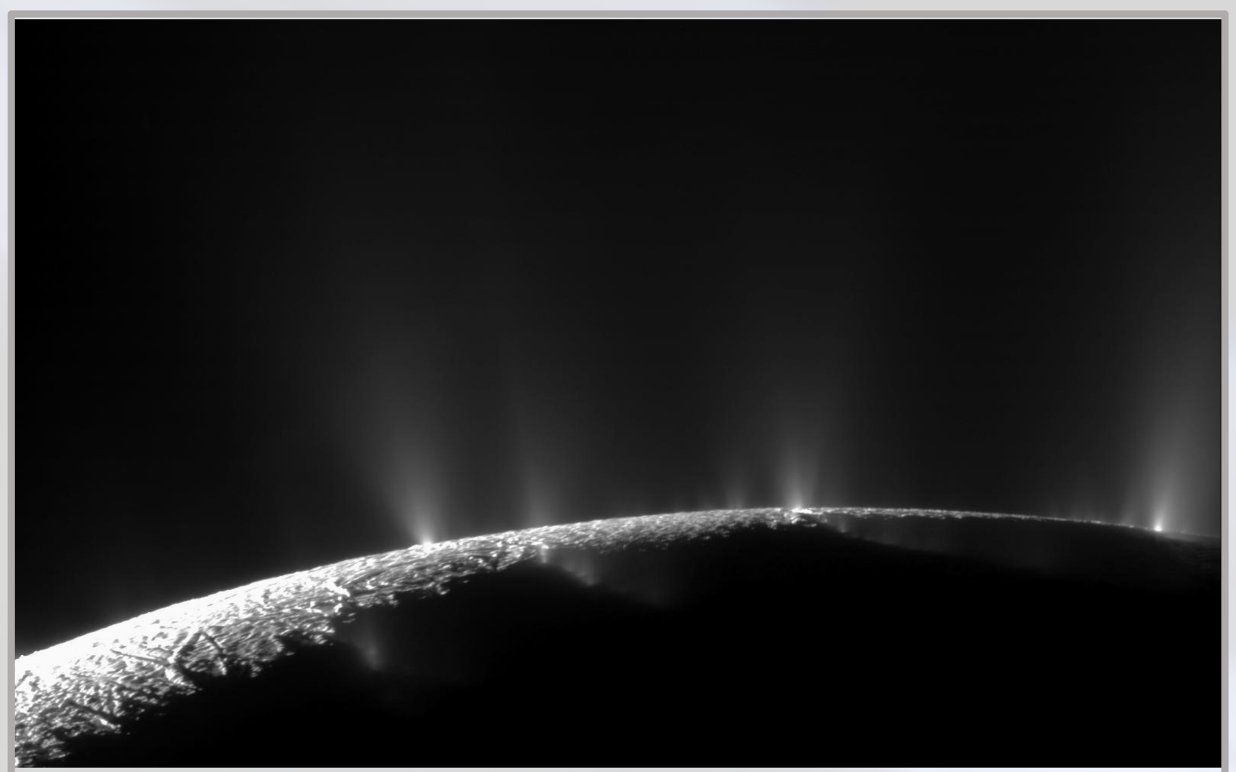

*Fig. 1 – Plumes arise above the surface of the Enceladus' South Polar Region. Picture captured by the Cassini spacecraft. Image credit: NASA/JPL/Caltech*

## Motivation

A percussive, scoop-shaped sampling tool is being considered for a potential future Enceladus surface sampling mission. The sampling operation performed by using such a tool in a very low gravity environment might cause the ejection of aggregates of the surface granular material that could eventually bring to the undesired loss of the sample. The modeling of the tool-material interaction, as well as the dynamics of the granular material's aggregates in a microgravity environment are crucial to design a tool which is efficient in both performing the sampling operation and minimizing the sample loss.

## Objectives

- To develop an analytical model of the tool-soil interaction to identify the main parameters affecting the granular material's dynamics in a microgravity environment and assess their sensitivity.
- To develop a numerical simulation framework to:
  - Reproduce the granular behavior of unconsolidated surface material analogues.
  - Reproduce the tool-material interaction.
  - Characterize the simulated sample collection method.

## Materials and methods

A prototype of the percussive scoop was realized by using a motor-driven, helical cam percussive system (Fig. 2, top). The scoop is 63 mm long and 42 mm wide. The percussive system is composed by a spring-driven impactor cyclically striking the scoop. The percussion cycle has a frequency of 40 Hz and an amplitude of 3 mm. A first approximation analytical model was developed to catch the essence of both the working principle of the percussive system, the tool-particle interaction and the particle's dynamics (Fig. 2, bottom). The percussive system was modeled by a double mass-spring system dependent on the impactor-scoop Coefficient of Restitution (COR). The tool-particle interaction was modeled as an inelastic collision, also dependent on the tool-particle COR. Finally, a cohesionless loose material made of distinct particles was assumed to be representative of the sample. A sensitivity analysis was performed to explore the influence the tool/sample parameters would have on the dynamics of the granular material's ejection. Moreover, a comparison between Earth's and Enceladus' gravity was made.

From the numerical standpoint, the Discrete Element Method (DEM) implemented by the open source LIGGGTHS was adopted to simulate the tool-particle interaction and the granular material's dynamics. DEM features modeling of soils on grain scale, thus the macroscopic soil deformation is based on inter-particle contact reactions. The real scale CAD model of the scoop was imported into software, then the prescribed motion (i.e. the percussive action) of the scoop was implemented. The granular material reproduced is a cohesionless loose sand (Fig. 4, bottom). The Hertz-Mindlin contact model was adopted to simulate the particle-particle interaction as well as the tool-particle interaction in the normal and tangential contact directions. The sample material was simulated by using spherical particles scaled up to 1 mm in diameter to significantly reduce the computational cost. Since spherical particles do not experience any geometrical rotational resistance, an additional elastic-plastic spring-dashpot (EPSD) model was implemented to include the rotational resistance deriving from real causes such as the friction and the inter-locking between particles. The simulation requires some input parameters related with the contact models chosen. Some of those parameters are bulk properties (e.g. Young's modulus or Poisson's ratio of the scoop's material). Other parameters are grain-scale properties (e.g. Young's modulus, Poisson's ratio or density of the granular material's particles). Moreover, some grain-scale properties are paired, meaning that those are properties associated with a particle-particle pair or a particle-tool pair (e.g. coefficient of friction, COR, coefficient of rolling friction). Finally, a comparison between Earth's and Enceladus' gravity was made.

## Results

The results of the analytical model showed that the high sensitivity parameters are the impactor spring stiffness, the scoop's mass and the kinetic energy loss (Fig. 3). The medium sensitivity parameters were found being the impactor's mass, the tool-impactor COR, the tool-particle COR. The low sensitivity parameters were found being the tool's angle with respect to ground and the particle's mass. The results suggest that a particle's range of few centimeters in Earth's gravity easily shifts in the order of magnitude of the meters in Enceladus' gravity. This suggests that a careful balance of the aforementioned parameters is crucial to effectively sample the surface material while minimizing the entity of the ejecta.

The numerical simulation framework was qualitatively tested by using the simulation parameters inherited from previous DEM studies conducted by using a similar granular material. The qualitative results showed the expected general behavior of the granular material under different gravity environment conditions. No ejecta have been observed in Earth's gravity (Fig. 4, middle), while some ejecta can be seen in Enceladus' gravity (Fig. 4, top).

## Future work

The next research steps will include:

- The refinement of the numerical simulation framework, as well as the development of a second approximation analytical model by including second order phenomena (i.e. structural dynamics of the scoop subjected to high frequency excitation) which might be relevant to the granular material's dynamics.
- The simulation of more realistic Enceladus' surface analogue materials (e.g. super-cooled, highly porous ice).
- The simulation of the other phases of the sampling chain (i.e. sample collection, sample transport, sample transfer to the scientific instruments).
- The simulation of the sampling operations performed by using an ultrasonic scoop.
- An extensive test campaign to validate the numerical simulation framework, as well as the analytical model. A first qualitative example is represented in Fig. 4, bottom. The sampling operation performed by an ultrasonic scoop running at 17 kHz was recorded by using a high-speed camera at 30000 frames-per-second.

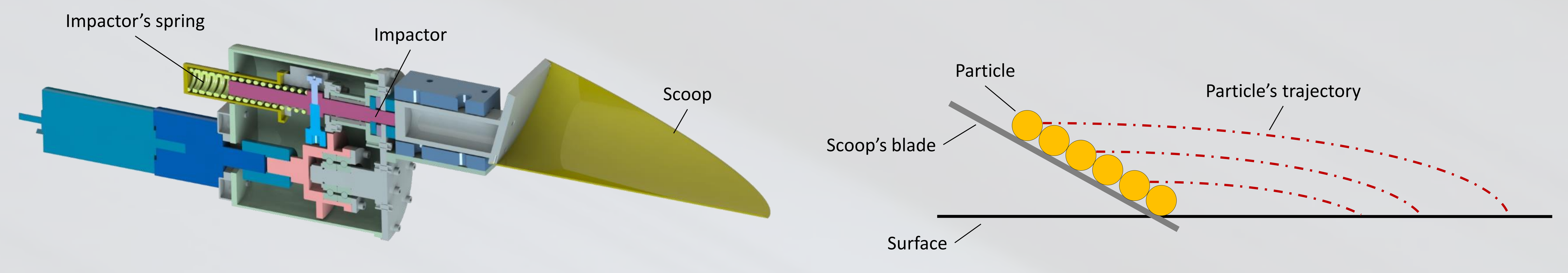


*Fig. 2 – Section of the percussive scoop (left). Qualitative scheme of the material's particles sitting on the scoop and their ejection trajectories relatively to the height along the scoop's blade (right).*

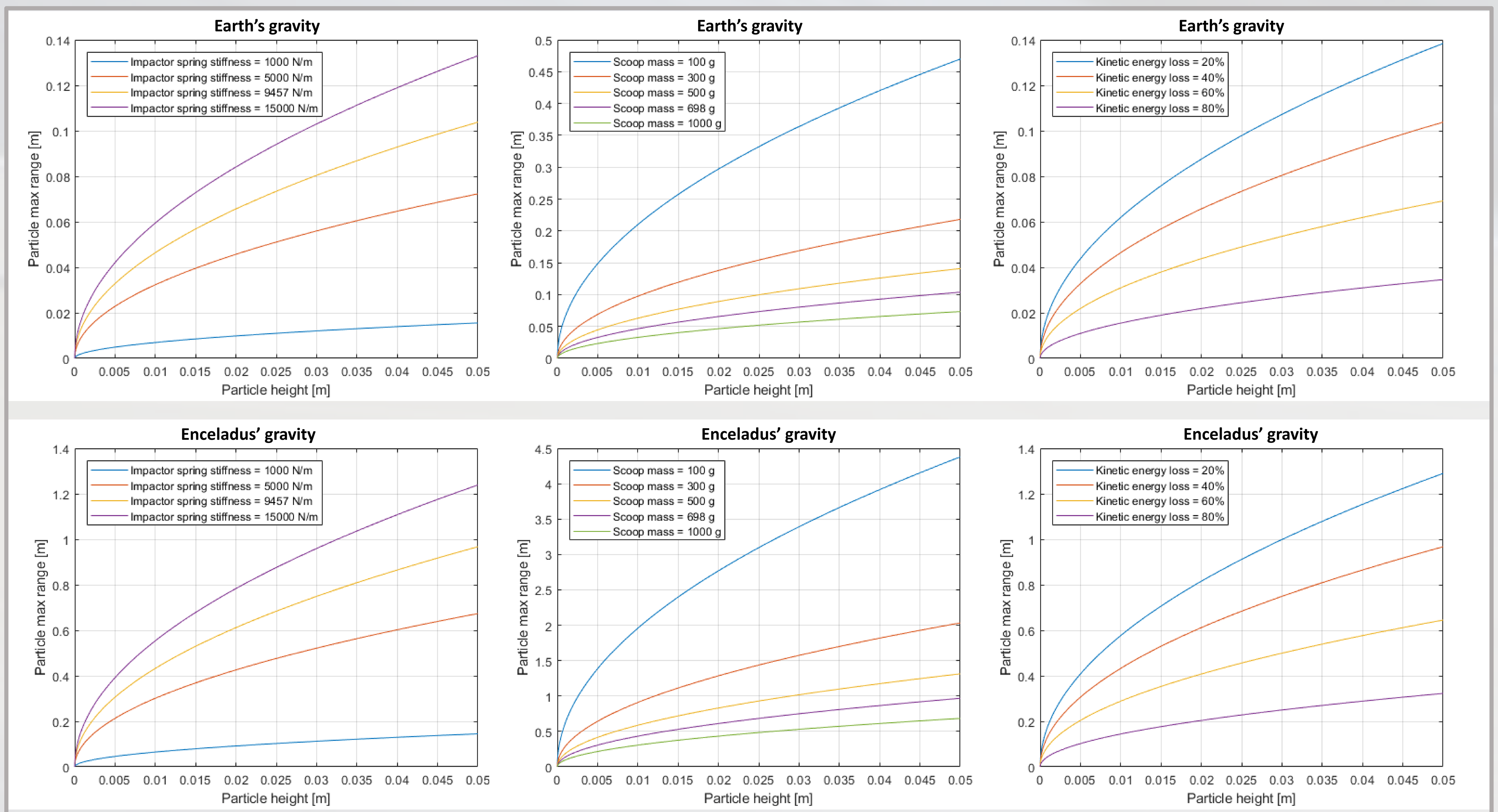


*Fig. 3 – High sensitivity parameters identified by the analytical model. The top row represents the results in Earth's gravity, while the bottom row represents the results in Enceladus' gravity.*

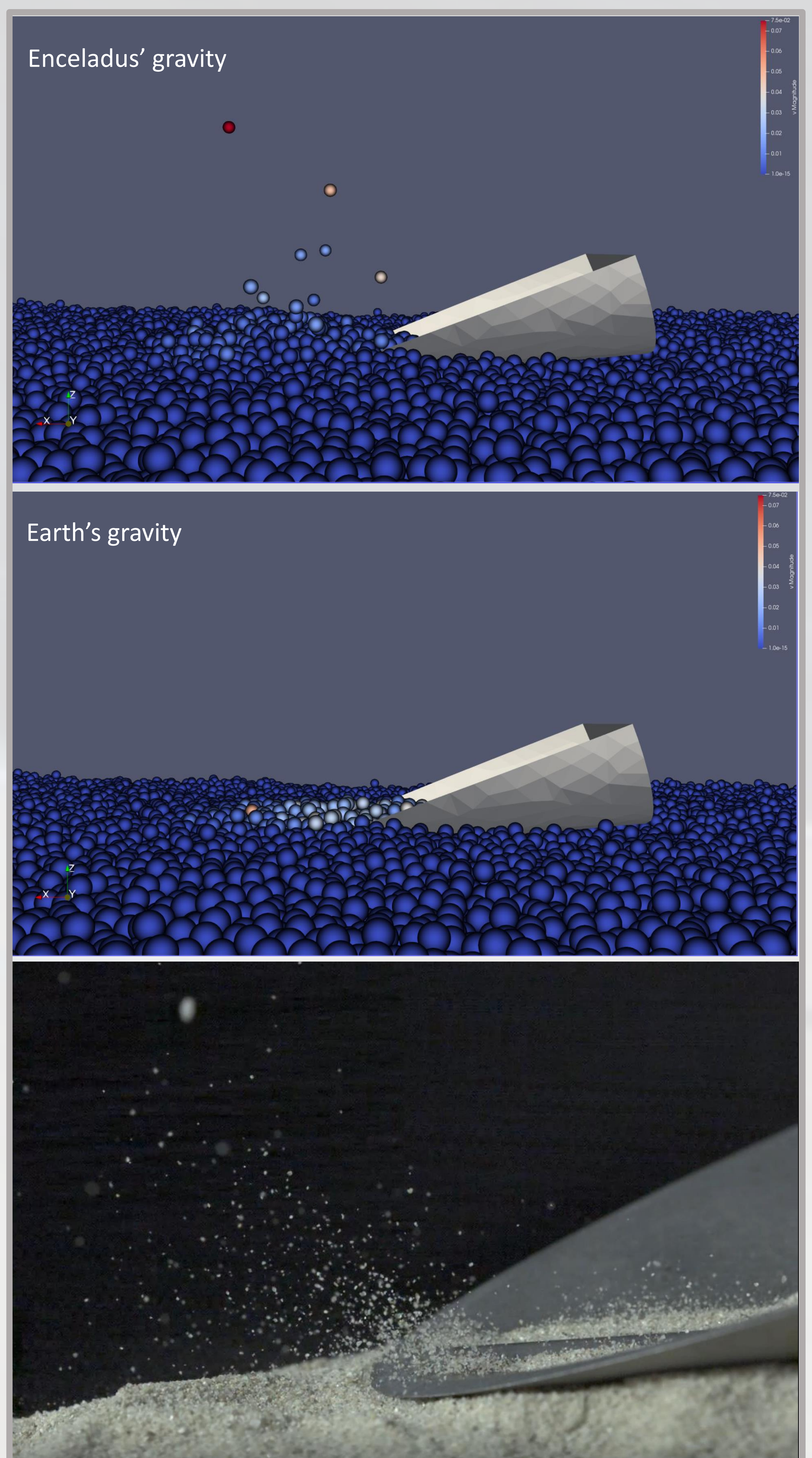


*Fig. 4 – Numerical simulation results in Enceladus' gravity (top) and Earth's gravity (middle). Particles are colored according to velocity magnitude (meters/second units). High-speed recording of the real granular material's behavior by using an ultrasonic scoop (bottom).*