FINITE-DISCRETE ELEMENT MODELING OF IMPACT EXPERIMENTS ON MARS REGOLITH PROXIES.

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Introduction: InSight landed on Mars on November 26, 2018, and has since then placed a seismometer, called SEIS, on the surface of the planet [1,2]. Being able to identify and exploit seismic signals produced by impacts is important to the mission. Fresh craters can potentially be located by satellite imagery and provide strong constraints on the source at origin of the seismic signal [3]. Seismic signals with less uncertainty on their sources may be the key for the scientific objectives which are: (1) to unravel the inner structure of Mars, and (2) to re-evaluate the meteorite flux of Mars. Small impactors are more frequent than larger ones. Current estimates are that there are 10 times more craters in the range of 4.2 to 5.9m created every year compared to craters of 9.24 to 13m [4]. A key for InSight objectives is to understand the generation of seismic waves by impacts. For such small impacts, this process takes place within the Mars regolith, the layer of unconsolidated rocky material covering the bedrock [5]. High-fidelity modeling of the generation of seismic waves from the original shock wave created by the impact is challenging due to the complexity of the response of such material to impacts. Our goal is to develop a model of impacts on Mars regolith and to understand how much variability can be explained by the unconsolidated/porous nature of the target material on future SEIS observations.

Background: High-fidelity modeling of impacts needs to address several regimes: the high strain-rate regime existing near the impact, followed by the plastic regime where significant damage still occurs, followed by a purely elastic regime where shock waves transition to seismic waves [6-7]. Eulerian-based numerical methods have limitations when modelling the first regime where noticeable advection of the material through the mesh is expected.

Only now, thanks to recent developments in numerical methods and the increase of computing power, can high fidelity 3D modeling be achieved and used to simulate impacts in realistic geologic materials [8-10]. For this purpose, the granular nature of the materials has to be taken into account: friction and displacement between grains are important and may lead to strongly localized and non-linear behaviors, as evidenced by “force-chains” [11] and “fairy-castle” structures [12].

Methods: Numerical tool. We use a novel simulation code known as the Hybrid Optimization Software Suite (HOSS) which is an implementation of the combined Finite and Discrete Element Methods (FDEM). It merges continuum solutions for the calculation of stresses as a function of deformation with the discrete element method for the resolution of fracture, fragmentation and contact interaction [13]. Rougier et al. [14] benchmark HOSS with other hydrodynamic codes.

The material is represented by Lagrangian finite elements each containing between 1,000 and 1,000,000 grains of sand. Inside each element, the material model is governed by two equations (Fig. 1): one describing the volumetric response, or Equation of State (EOS), and another describing the deviatoric response, or Strength Equation (SE). The EOS has three regimes. First, the pressure increases linearly with the deformation according to a pure elastic regime with a bulk modulus $K_{el}$. At a limit pressure, called $P_{el}$, the material undergoes a plastic deformation where the grains within the elements are allowed to move relatively to each other and are crushed. In this regime, the relationship between pressure and strain is no longer linear but is represented by a tangent bulk modulus $K_{trans}$ (much lower than $K_{el}$) and increases with deformation [15]. Finally after all the pores are crushed, the pressure continues to evolve linearly with the strain with a bulk modulus $K_{el}$ corresponding to a non-porous rock of the same composition. The SE defines the maximum deviatoric stress that can be sustained for a given mean stress. In this model, the deviatoric stress, which is indicative of damage or grain displacement, increases linearly with mean stress following a model of solid friction and then reaches a limit yield transitioning to a viscous behavior.

![Figure 1. Equation Of State (left) and Strength Equation (right) used in the numerical model of Mars regolith. Main parameters of the model are explicit.]
capturing cratering processes and material being ejected during an impact. A Coulomb friction law with a coefficient of 0.75 is used to describe the interaction of Lagrangian Elements in contact. HOSS is fully parallelized and optimized, with a typical simulation taking 32 hrs. on 290 processors.

**Validation.** The validation of the novel numerical model presented here is done with data from a series of 22 impact experiments conducted in June 2012 at the NASA AVGR facility [16]. The experimental setup is a closed tank, 1 meter in radius and in height, filled with a controlled atmosphere and target material. Tests were monitored with high velocity cameras and 15 accelerometers buried within the target material at different depths and at different positions radially. Here, we focus on one experiment where the target material is a pumice sand with grain size of 0.1 to 0.2 mm with a porosity of 62%. This pumice sand was chosen to be similar in composition, grain size, and density to the Johnson Space Center (JSC) Mars-1 Regolith Simulant [17]. The impactor is a Pyrex bead with a diameter of 6.3mm, weighting 0.29g and with an impact velocity of 0.98m/s.

**Results and discussion:** We perform a parametric study of the EOS to infer the appropriate parameters to fit the experimental data. These parameters are fit with two experiments: $K_0$ is set at 10MPa, $P_e$ at 1kPa, $K_{\text{man}}$ at 6MPa, in order to match timing of first arrival, peak pressure, and evidence of elastic precursor at the receiver 21 cm down. The SE yield point was set at 1MPa. The comparison between modeling and experiment is shown on Fig 2. Two simulations were performed, one without gravity, and one with gravity where the elements are “relaxed” to reach a hydrostatic equilibrium prior to the impact. Velocity amplitude, timing and duration modeled with gravity fit well with the experiment, when the amplitude of the modeled acceleration is 33% lower, respectively higher, for modeling with and without gravity respectively.

This indicates a strengthening of the system of sand particles relaxed in the gravity field, strong enough such that material in depth shows upward motion.

Our model assumes a single phase medium which is valid for a fully desiccated sand as the Mars regolith is expected to be close to the equator [5].

**Conclusion:** We present a novel numerical modeling of impacts in Mars regolith based on a discrete-finite element method which comes to agreement with experimental data performed in pumice sand. More work is needed in order to model the signal on shallow accelerometers of this experiment that are the most relevant to the InSight mission as SEIS is a surface receptor.

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**References:**


![Figure 2. Comparison of numerical and experimental vertical acceleration (left) and velocity (right) signals for the 0.98 m/s impact velocity shot, recorded at the first sensor 21 cm down the impact point. Dashed light-blue lines correspond to a simulation conducted without gravity while plain blue lines correspond to simulations considering Earth gravity.](image)