

DYNAMICS OF EJECTA DURING THE FORMATION OF AN IMPACT CRATER: DISCRETE NUMERICAL SIMULATIONS. V. J. Langlois¹ and C. Quantin-Nataf¹, ¹Laboratoire de Géologie de Lyon, Université de Lyon, France (vincent.langlois@univ-lyon1.fr).

Introduction: The ability of crater chronometry techniques to assess ages and evolution of planetary surfaces has been recently challenged, especially in the case of using small impact craters because of the expected secondaries [1]. Many studies have detailed the secondaries formed by a well-recognized primary impact in terms of shape and repartition, based on the high resolution imagery available on the surfaces of the Moon [2] or Mars [3]. However, well-used numerical models of impact crater formation which use continuous approaches (hydrocodes) [4] are not always well suited to reproduce the fragmentation processes at small scales that are required to explain the secondary cratering. Because they rely on a mesh, these models, though very efficient in predicting the deformations within the target and the properties of the subsequent crater, cannot take into account explicitly the fragmentation of material, which leads to the ejection of particles of variable sizes. Therefore, we propose here to develop a Discrete Element Method (DEM) to simulate impact cratering in order to better understand the fragmentation of ejected material and consequently the secondary craters formed after a primary impact.

Methods: Contrary to hydrocodes or other continuous approaches, DEMs do not require any mesh and allow to compute explicitly the dynamics of individual particles [5,6]. Therefore we do not impose directly a macroscopic rheology but the material's deformation results from the collective dynamics of all particles and bonds. In this study we compute the behaviour of a target made of a two-dimensional assembly of 800,000 particles of diameter $d=0.4$ m, after the impact of a projectile (Fig. 1).

Both within the target and the projectile, neighbour particles are initially linked by cohesive beams. Under elongation and bending, these bonds exert restoring elastic forces and torques on the adjacent particles, which gives the material its initial cohesion. To account for its brittleness, a yield strain is assigned to each bond: when a bond is extended and/or bent beyond a given threshold, it breaks irreversibly.

When in direct contact, particles behave as a frictional granular material: two individual particles that are in direct contact experience two forces. The normal repulsive force follows a spring-dashpot model and the tangential friction force follows Amontons-Coulomb law, with ageing contacts.

With all forces known, Newton's equations of motion (for translation and rotation) are solved simultaneously for all particles by classical Molecular Dynamics techniques.

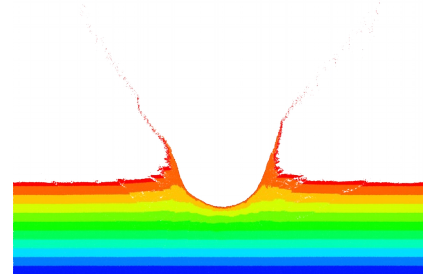


Fig. 1 : Example of a transient crater obtained with the DEM simulation. Colour bands only indicate the initial vertical position of particles.

Characteristics of the crater: The present investigation focuses on the influence of 3 control parameters: size (a) and velocity (V) of the projectile, and dimensionless strength (S) of the target material. The latter parameter is defined as the ratio between the tensile force exerted by a bond at yield and the weight of a particle.

We first validate our approach by analyzing the properties of the final crater obtained after relaxation of motion.

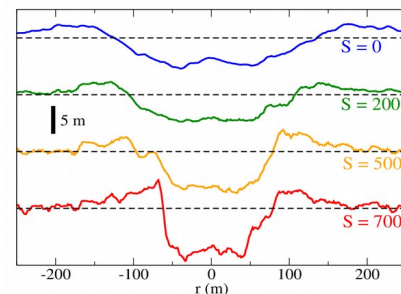


Fig. 2 : Final crater obtained after the impact of a projectile of size $a=2$ m at $V=2$ km/s.

As can be observed in Fig. 2, the diameter of the crater decreases and its maximal depth increases when the mechanical strength of the target increases. Let us note that in some cases a central peak is observed, though no melting process is involved in our simulation.

For a projectile of given size and a target of given strength, the diameter of the crater (defined between the two highest points of the rim) as well as its total

height (defined between the lowest and highest points) both increase as power laws of the impact velocity (Fig. 3), whose indices are consistent with common estimates [7].

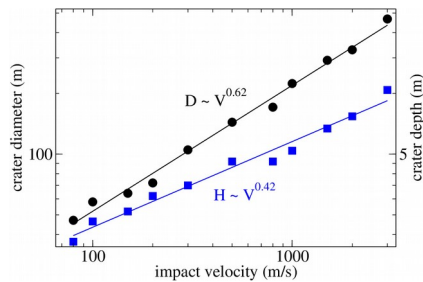


Fig. 3 : Diameter and depth of the final crater as a function of impact velocity, for a projectile of size $a=2\text{m}$ and a granular target. Plain lines are best fits with power laws.

Dynamics of ejecta: In the following we define ejecta as all particles that have been ejected above an altitude $z = 5\text{ m}$ (let us note that, in consequence, some particles classified as ejecta will fall back between the rims of the crater).

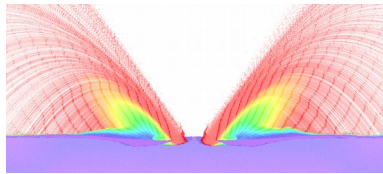


Fig. 4 : Integrated trajectories of all particles after impact. Colour codes for their velocity. Bold lines materialize the ejecta curtain at given times.

The volume of ejected particles is found to vary as a nonlinear power law of the impact velocity (index $1.42 > 1$) and to decrease as an affine function with increasing tensile strength of the target (Fig. 5). As can be seen in Fig. 6, only a relatively small fraction of the impact energy is delivered to ejected material. This fraction increases with impact velocity but appears to tend to a constant value of around 15% at high speeds.

Secondary craters: Since the size of the ejected fragments is comparable to the size of our unit particles, our simulations do not allow us to model properly the formation of the secondary craters. However, since we have access to the size distribution of the ejected fragments, as well as to their position and velocity at impact we are able to infer the thickness of the continuous ejecta blanket near the crater's rims and to predict the size and spatial distribution of secondary craters.

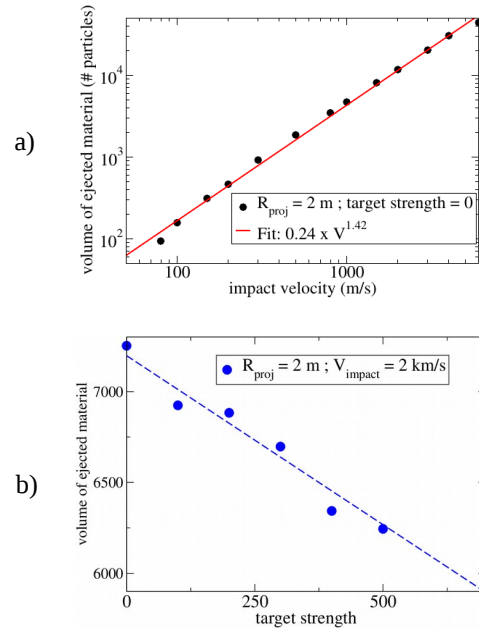


Fig. 5 : Volume of ejecta as a function of (a) impact velocity and (b) target strength. Straight lines are best fits by respectively a power law and an affine function.

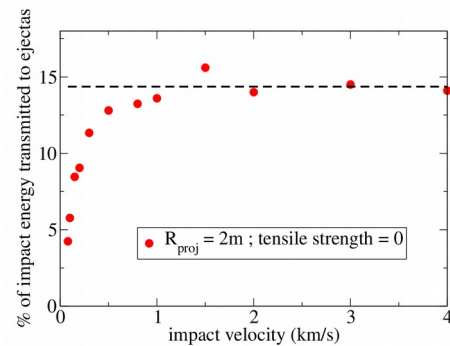


Fig. 6 : Fraction of initial kinetic energy of the impactor converted into kinetic energy of the ejecta.

References: [1] e.g. McEwen, A.S. & Bierhaus, E.B. (2006), *Ann. Rev. Earth Planet. Sci.*; [2] e.g. Basilevsky, A.T. *et al.* (2018), *Planet. Space Sci.*; [3] e.g. Robbins, S.J. & Hynes, B.M. (2014), *Earth Planet. Sci. Lett.*; [4] e.g. iSALE code, <https://isale-code.github.io/>; [5] e.g. Pöschel, T., & Schwager, T. (2005). *Computational granular dynamics: models and algorithms*. Springer; [6] Langlois, V.J., Quiquerez, A., & Allemand, P. (2015), *J. Geophys. Res. Earth Surf.*; [7] Melosh, H.J. (1999), *Impact cratering : a geologic process*, Oxford University Press.