NUMERICAL SIMULATION OF IMPACT CRATERING ON ADHESIVE GRANULAR MATERIAL.

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Introduction: The impact cratering process on sand targets is generally considered to be controlled mainly by gravity (the so called 'gravity regime'). However, adhesive forces (e.g. van der Waals force) acting between granular particles play an important role when particle size and/or gravity are small. The van der Waals force acting on a particle, F_v, is proportional to its particle size, d, while the gravitational force acting on a particle, F_g, is proportional to $d^3 g$, where g is gravitational acceleration. The ratio between these two forces, F_v/F_g, is thus proportional to $1/(d^2 g)$. Therefore, F_v may become dominant (the so called 'strength regime') for the impact cratering process on granular materials with small particle size and gravity, such as regolith layers on small asteroids. In fact, recent impact experiments show that the crater radius becomes small when the target particle size is small[1]. Under micro-gravity, the crater radius becomes smaller than that predicted by the scaling law for the gravity regime[2].

To investigate the influence of inter-particle adhesion on the impact cratering process, we numerically simulate impacts into granular materials with various values of adhesion. Our code is based on the Distinct Element Method (DEM), in which particle motions are calculated directly by solving the equations of motion for each particle (e.g. [3]). It has been shown that our code is able to simulate the cratering process for granular targets (dry sand) with no adhesion [4,5]. In this study, we introduce a simple adhesion model into our code. We then show how the crater size depends on the force ratio F_v/F_g.

DEM model: In our DEM model, the mechanical interaction forces between contact spherical particles are expressed by elastic force and friction modelled by the Voigt-model, which consists of a spring and dash-pot pair. The spring gives elastic force based on the Hertzian elastic contact theory. The dash-pot expresses energy dissipation during contact to realize inelastic collision with a given coefficient of restitution. For the tangential direction between contact particles, a friction slider is introduced to express Coulomb's friction law with a given coefficient of friction. As an adhesion model, we assume that the constant attractive force given by $F_v = \chi F_g$, where χ is a dimensionless constant, acts on the normal direction between particles during in contact with each other. χ is a parameter used to prescribe the degree of adhesive force.

Initial conditions and parameters: We prepared a granular target that consists of 384,000 equal-sized particles (radius, 1mm; density, 2.7g/cm^3; Young's modulus, 94GPa; Poisson's ratio, 0.17) randomly placed in the rectangular container (20cm×20cm×7cm). The coefficient of restitution of the walls of the container is set to 0 so that the occurrence of reflection waves at the walls can be suppressed as much as possible. A projectile particle (radius, 3mm; density, 2.7g/cm^3; Young's modulus, 70GPa; Poisson's ratio, 0.35) impacts vertically into the target at velocities of 100, 300, and 600 m/s. g is assumed to be 9.8 m/s^2 (or 1G). In this study, we change χ between 1 and 10^4, while the coefficients of restitution and friction between particles are set as 0.4 and 0.5, respectively.

Numerical results: The cross sectional views of the transient craters formed in our simulation for $\chi = 10$ and $\chi = 10^3$ are shown in Fig. 1. The cavity size for $\chi = 10^3$ is clearly smaller than that for $\chi = 10$, indicating that the larger the adhesive force, the smaller the crater cavity.
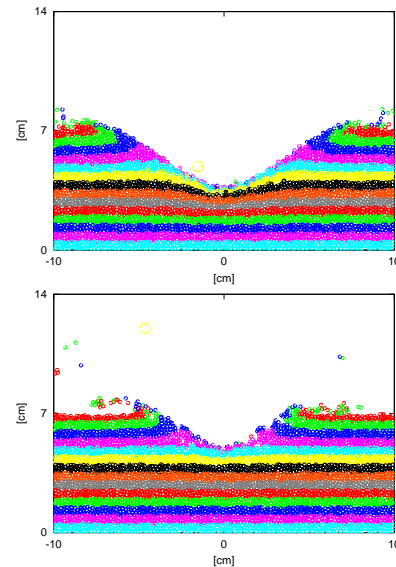

Figure 1: Cross sectional views of the transient crater cavity for $\chi = 10$ (upper) and $\chi = 10^3$ (lower). For visual clarity, only the particles whose centers are located within this cross section (4mm thick) are shown, with colors corresponding to their initial depth.

The crater radii R obtained in our simulations are evaluated in terms of π-scaling dimensionless parameters (e.g. [6]). According to the π-scaling theorem[6], there is a power-law relation between the dimensionless crater radius π_R and the dimensionless gravity-scaled size π_2 for the gravity regime (π_R and π_2 are defined

by $R(\rho_t/m)^{1/3}$ and $3.22ga/U^2$, respectively, where ρ_t is the target bulk density, m is the projectile mass, a is the projectile radius and U is the impact velocity). Our numerical results are plotted on a π_2-π_R diagram (Fig. 2). The data points for $\chi \leq 10^2$ are distributed around the scaling lines obtained by impact experiments for dry sand[6] and also by our previous numerical simulation without adhesion ($\chi = 0$)[4]. However, the data points for $\chi \geq 10^3$ are distributed away from these scaling lines. This suggests that the cratering process for $\chi \leq 10^2$ can be treated within the gravity regime and the influence of adhesive force does not appear clearly until $\chi \geq 10^3$.
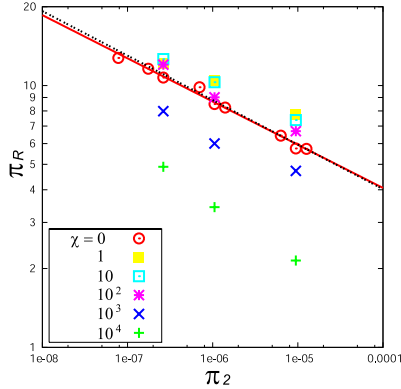

Figure 2: π_2 vs. π_R with various χ values. The red line indicates the scaling line obtained by our simulation for $\chi = 0$[4]:$\pi_R = 0.90\pi_2^{-0.165}$. The black dotted line indicates the scaling lines obtained by impact experiment on dry sand[6]:$\pi_R = 0.84\pi_2^{-0.17}$.
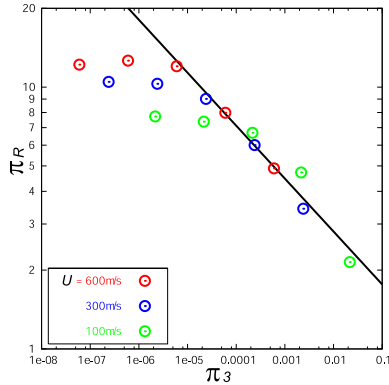

Figure 3: π_3 vs. π_R for numerical results. The black line fits the data for $\chi \geq 10^2$: $\pi_R = 1.1\pi_3^{-0.20}$. The data plotted on the left-hand side of this line are for $\chi \leq 10$.

According to the π-scaling theorem for the strength regime, π_R is given by a power of the dimensionless strength π_3. π_3 is defined by $Y/\rho_t U^2$, where Y is the target strength. In this study, Y is given by the tensile strength and calculated by the Rumpf's equation[7], $Y \simeq ((1-p)/p) \times F_v/d^2$, where p is the target porosity (~ 0.43 in this study). In Fig. 3 we plot π_3 and π_R for our numerical results. The data points with higher

π_3 values ($\chi \geq 10^2$) are distributed linearly on the log-scale plot, independent of impact velocity. This suggests that there exists a scaling law of the strength regime for large χ values. The fitting line for this data is given by $\pi_R = 1.1\pi_3^{-0.20}$. On the contrary, the data points for $\chi = 1$ and $\chi = 10$ for each impact velocity are distributed horizontally independent of π_3, indicating that these are not in the strength regime, but in the gravity regime.

Discussion: Our numerical results show that the cases with $\chi \lesssim 10^2$ are consistent with the scaling relation for the gravity regime, $\pi_R \propto \pi_2^{-\beta}$ (in this study $\beta = 0.165$), whereas the cases with $\chi \gtrsim 10^2$ are for the strength regime, $\pi_R \propto \pi_3^{-\gamma}$ (in this study $\gamma = 0.20$). According to the π-scaling with point source approximation[6], which means introducing the coupling parameter $C \propto aU^\mu$, the power-law exponents of the scaling relations, β and γ, are expressed by $\beta = \mu/(2 + \mu)$ and $\gamma = \mu/2$, respectively. The parameter μ ranges from $1/3$ (momentum scaling limit) to $2/3$ (energy scaling limit). Based on these equations, we can calculate the value of μ from the β and γ obtained in our simulations. The calculated μ becomes 0.40 for both $\beta = 0.165$ and $\gamma = 0.20$. This calculated μ value is close to $1/3$, the momentum scaling limit. Therefore, it is concluded that the cratering process on adhesive granular materials can be scaled by using the momentum scaling in the gravity regime if $\chi \lesssim 10^2$, and in the strength regime if $\chi \gtrsim 10^2$

The critical value of $\chi \simeq 10^2$ corresponds to the van der Waals force acting on a particle with size of $\sim 100\mu$m under gravity of 1G. That is to say, the impact cratering process on granular target with particle size less than $\sim 100\mu$m on the Earth will be affected by the adhesive force. The gravity is much less than 1G on the surface of small asteroids (e.g. $\sim$mG on Eros). Therefore, the adhesive force will be effective for the impact on the regolith layer of asteroids, such as on Eros, even if the particle size of regolith is larger than 1 mm.

References:[1]Yamamoto, S. et al. (2004) *Proc. Lunar Planet. Sci. Conf. 35th*, #1479. [2]Takagi, Y. et al. (2004) *37th ISAS Lunar Planetary Symposium.* [3]Cundall, P. A. and Strack, O.D.L. (1979) *Géotechnique*, 29-1, 47-65. [4]Wada, K. et al. (2003) *Proc. Lunar Planet. Sci. Conf. 34th*, # 1529. [5]Wada, K. et al. (2003) *Proc. Lunar Planet. Sci. Conf. 35th*, # 1520. [6]Schmidt, R. M. and Housen, K. R. (1987) *Int. J. Impact Engng.*, 5, 543-560. [7]Rumpf, H. (1970) *Chemie Ingenieur Technik*, 42, 538-540.