PENETRATION RESISTANCE IN POROUS GRANULAR BODIES: RESULTS FROM NUMERICAL SIMULATIONS.

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Introduction: Recent exploration missions to asteroids have revealed that small asteroids possess many features related to impact processes on their surfaces. Even on the surface of very small (<500m) asteroid Itokawa, we see regolith layers composed of fine pebbles or dust, crater-like circular depressions, large boulders, and dimple structures around rocks [e.g, 1,2]. In order to understand forming mechanisms of these features and to clarify the evolution of asteroids, we need to reveal the impact cratering process on the asteroidal surfaces. We have not yet, however, obtained a set of complete scaling relations applicable to the asteroidal surfaces because of the properties particular to asteroids: asteroidal surfaces are covered with regolith layers that are expected to have a large porosity due to micro gravity of asteroids. Impact process on porous granular targets under micro gravity and its scaling relations should be elucidated for understanding evolution of asteroids.

In this study, we carry out numerical simulations of impacts into porous granular targets under micro gravity with using a kind of *N*-body code, Distinct Element Method (DEM) [e.g., 4, 5]. The impact velocities in our simulations are less than several 100 m/s, which are relatively low but enough to form various impact features on the asteroidal surfaces. Here, in particular, we focus on the penetration process of projectiles and penetration resistance acting on them. Penetration process and its resistance law are also critical when missions have plans of active impact experiments or interior explorations with penetrators. Previous laboratory studies revealed resistance laws for penetration into sand under 1G [5], aerogel [6], or highly porous sintered glass beads [7]. However, the resistance law for penetration into porous granular targets under micro gravity is not well understood so far, although some laboratory experiments are ongoing. We will obtain the penetration resistance law from our numerical simulations.

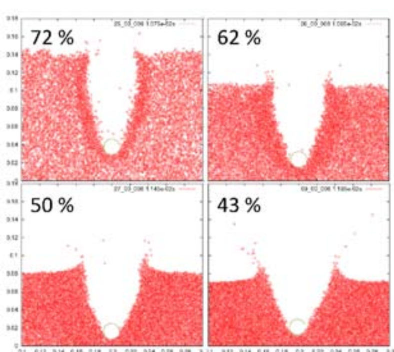

Figure 1: Snapshots of impacts into targets with different porosities (72, 62, 50, and 43 %) at ~0.01 sec after impact (r_p=9 mm, U=30 m/s, g=10^{-4} G, and F_a= 10^{-5} N).

Numerical Settings: A target consists of 384,000 spherical particles with a radius of 1 mm (density 2.7 g/cm^3, Young's modulus 94 GPa, Poisson's ratio 0.17). These particles are randomly fallen into a rectangular container with a base of 20 cm x 20 cm. We succeed in preparing 4 types of targets with a porosity of 43, 50, 62, and 72 % (Fig. 1), by changing adhesive force and rolling resistance of particles.

A projectile particle (density 2.7g/cm^3, Young's modulus 70GPa, Poisson's ratio 0.35) impacts vertically into the target at velocities of U=30, 100, or 300 m/s. Gravity g is set to 1 or 10^{-4} G (*cf.* g~10^{-3} G on Eros and 10^{-5} G on Itokawa). Corresponding to the two gravitational environments, we take F_a=10^{-1} N for 1 G and 10^{-5} N for 10^{-4} G (F_a=10^{-5} N for a 2 mm particle in general). We also change projectile radius r_p =3 or 9 mm.

Results: Figure 1 shows examples of snapshots of our simulations for cases with the same parameters of r_p=9 mm, U=30 m/s, g=10^{-4} G, and F_a= 10^{-5} N. Observing all cases, as a whole, we see a general trend that penetration of (large) projectiles into highly porous targets makes long cavities with compressed walls.

As a result, we find that penetration resistance consists of two terms, independent of parameters, represented by

$$F_{resist} = -(1/2)C_D \rho_t S v^2 - \beta \rho_t S v,$$

where C_D ~1-3 is the drag coefficient, ρ_t is the target bulk density, S is the cross-section of projectile, v is the penetration speed, β ~5-10 m/s is the coefficient for the second term. These values are consistent with the previous impact experiments [5-7] and ongoing experimental study. Further investigation in a wider range of parameters is necessary in the future to affirm this resistance force.

References: [1] Fujiwara A. et al. (2006) *Science*, 312, 1330-1334. [2] Saito J. et al. (2006) *Science*, 312, 1341-1344. [3] Wada K. et al. (2005) *LPS XXXVI*, Abstract #1596. [4] Cundall P. A. and Strack O. D. L. (1979) *G´eotechnique*, 29-1, 47-65. [5] Katsuragi H. and Durian D. J. (2007) *Nature Physics*, 3, 420-423. [6] Niimi R. et al. (2011) *Icarus*, 211, 986-992. [7] Okamoto T. et al. (2012) *LPS XLIII*, Abstract #1782.