PENETRATION PROCESS IN GRANULAR MEDIA REVEALED BY NUMERICAL SIMULATION. K. Wada[1] and A. M. Nakamura[2], [1]PERC, Chiba Institute of Technology, Tsudanuma 2-17-1, Narashino, Chiba 275-0016, Japan (wada@perc.it-chiba.ac.jp), [2]Department of Earth and Planetary Sciences, Kobe University, Japan.

Introduction: Granular media are widely observed on the surface of asteroids as regolith layers. Even on the 300m-sized small asteroid Itokawa, we see regolith layers composed of fine pebbles or dust. Hayabusa, a Japanese asteroidal exploration mission to Itokawa, has found various features left on the granular media, such as circular depressions, partly-embedded boulders, and dimple structures around rocks [1-6]. These features could be formed by impacts or landing of small bodies on the granular media. To understand the formation mechanism of these features, we should elucidate impact processes on granular media. In the near future, second Japanese asteroidal exploration mission, Hayabusa-2, will be launched toward a C-class asteroid, 1999JU3. In this mission, two types of active impact experiments are planned on the surface of 1999JU3. One is performed with Small Carry-on Impactor (SCI), which will impact a hollow projectile made of 2 kg copper at a velocity of 2km/s. The other is a small impact at 300 m/s to collect ejecta coming from the generated crater as samples of 1999JU3. These impact experiments will provide us a valuable opportunity to directly observe the impact processes on small asteroids covered with granular media and to establish the impact scaling rule applicable to small bodies, e.g., planetesimals. In this study, we carry out numerical simulation of impact penetration into granular media toward understanding the penetration process in regolith layers on small bodies, such as penetration resistance. We use Distinct Element Method (DEM), a kind of *N*-body code [e.g., 7,8]. Since motion of each granular particle and forces acting on it are directly calculated with this code, our numerical simulation will provide us a clear image of impact process on granular media and help us understand the active impact experiments performed during Hayabusa-2 mission.

Recently we also performed a series of experiments of penetration into granular media: a plastic sphere of 6 mm diameter is impacted at 70 m/s into granular media [9]. The granular media consist of glass beads of 50 or 420 μm in diameter and their porosity is ~ 40 %. Our experiments report that penetration resistance consists of the inertia term and the viscous damping term in addition to the velocity-independent term. The numerical simulation in this study aims to reproduce our experiments and to confirm the resistance force. In addition, we discuss what is going on during the projectile penetration in granular media based on our numerical simulation.

DEM Model: In our DEM model, the mechanical interaction forces between spherical particles in contact are expressed by elastic force and friction modeled 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 e. For the tangential direction between contact particles, a friction slider is introduced to express Coulomb's friction law with a given coefficient of friction μ.

Simulation Setting: We prepared a granular target consisting of 384,000 spherical particles of 420 μm in

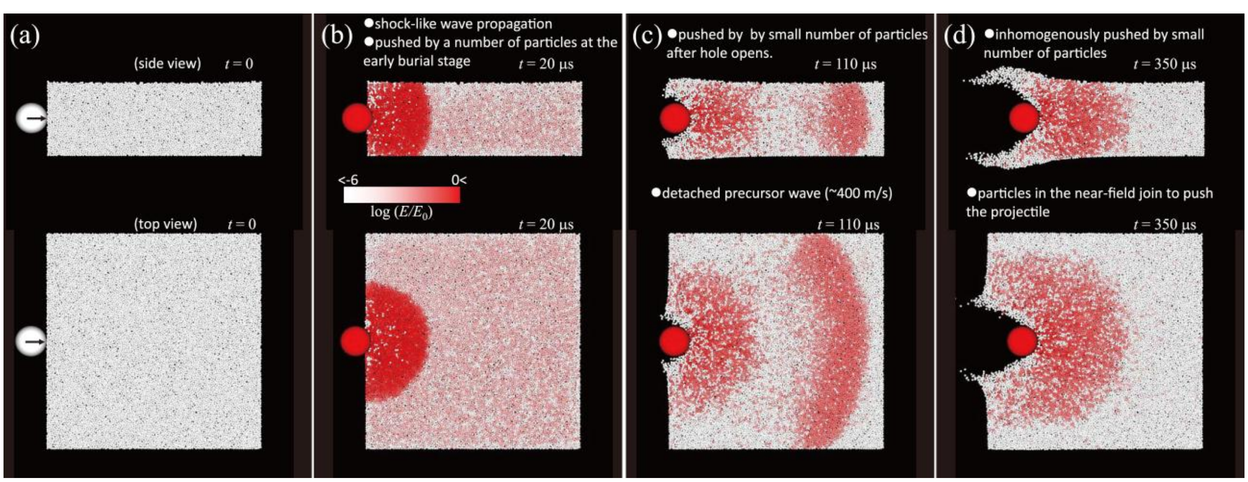

Figure 1: Cross-sectional views of snapshots of our simulation at (a) 0 s, (b) 20 μs, (c) 110 μs, and (d) 350 μs after impact. Each panel has side and top views. Particles are colored depending on the elastic energy stored in each particle, as indicated in the scale bar.

diameter (quartz-like material properties: density 2.5 g/cc, Young's modulus 94 GPa, Poisson's ratio 0.17). These particles were randomly dropped into a rectangular container with a base of 42 x 42 mm^2. The resultant height of the granular medium is ~15 mm and its porosity is ~43%, as shown in Figure 1a. In our impact simulation, a projectile particle with a diameter D = 6 mm (polystyrene-like material properties: density 1.7 g/cc, Young's modulus 5 GPa, Poisson's ratio 0.34) is impacted horizontally into the target at a velocity of 70 m/s. To avoid the influence of the target walls, we remove the walls when we simulate the projectile impact and penetration. The coefficients of restitution e and friction μ between particles in contact are fixed as e = 0.4 and μ = 0.5.

Results and Discussion: Figure 1 shows snapshots of cross sections (side and top views) of a penetration simulation. In this Figure, we colored particles depending on the stored elastic energy in each particle. Since elastic energy stored in particles indicates elastic force acting on each particle, the distribution of colored particles enables us to observe the distribution of force chains in the granular target.

Viewing at the very early time of penetration, we find that a hemispherical region in which shock-like wave propagates is formed around the impact point (Fig. 1b) and a detached precursor wave propagates from that region at ~ 400 m/s (Fig. 1c). This detached wave is particular to granular media, and its velocity is close to a sound speed of 1-D elastic beads chains with no restoring forces under traction [10].

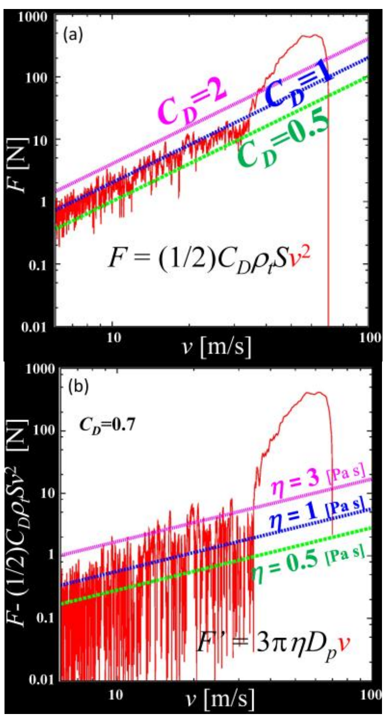

Figure 2: (a) Force F acting on the projectile vs. penetration speed v. (b) The residual force obtained by subtracting the inertia force with C_D = 0.7 with respect to v.

Force acting on the projectile until the half of the projectile is embedded into the target (we call this period the burial stage) has a different trend from the later penetration stage at which crater cavity opens (Fig. 2a). Figure 1b shows that particles pushing the projectile in the burial stage are distributed approximately over the whole hemisphere of the projectile, whereas, as shown in Figures 1c and 1d, only a small number of particles push the projectile in the later stage. This is the reason why the force in the burial stage is large and has the different trend compared to that in the later stage. During the later penetration stage, the distribution of particles pushing the projectile is inhomogeneous (Figs. 1c, d), reflecting the inhomogeneous distribution of force chains in granular media. In fact, this inhomogeneity appears in Figure 2 as the fluctuation of the force. Averaging this fluctuation, however, it is obvious that the resistance force is first-approximately proportional to the square of the penetration velocity v. When we consider this corresponds to the inertia force as

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

where C_D is the drag coefficient, ρ_t is the target bulk density, and S is the cross-section of the projectile, we find C_D = ~ 0.5 – 1.0 at least for the velocity range v < 30 m/s (Fig. 2a). After subtracting the inertia force with C_D = 0.7, the residual force is still dependent on v (Fig. 2b). When we assume this residual force as the viscous drag force proportional to v,

$$F_{vis} = 3\pi\eta D v$$

with η being the viscosity, we find η = ~ 0.5 - 3 Pa s.

In our laboratory experiments, we obtained the resistance force proportional to v^2 and v, in other words, C_D = ~ 0.9 – 1.5 and η = ~ 2 Pa s [9]. Therefore, the numerical results obtained in this study confirm those of experiments. Although we need to further investigate the granular behavior against impact, the resistance force revealed in this study will be useful for the analysis of impact experiments in Hayabusa-2 mission as well as for considering the surface evolution of small bodies including the fate of projectile bodies [9].

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