Granular segregation on the rubble-pile asteroid Itokawa

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Abstract. We investigate the dynamics of regolith on rubble-pile asteroids to explain granular processes observed in reality. In particular, we explain how the appearance of boulders on the surface of asteroid Itokawa could have resulted from a size sorting process in granular media called the Brazil Nut Effect (BNE). The Discrete Element Method (DEM) is implemented to perform numerical simulations of the BNE in a micro-gravity environment caused by inter-particle collisions during seismic vibrations. Firstly, we present the results of how the BNE depends on the magnitude of surface gravity. It is estimated that segregation processes on Itokawa occur over much longer time-scales (in the order of a few hundred years) than the same processes would require in the presence of a strong gravitational field, like on Earth. Secondly, we also find that the size sorting could also result from kinetic sieving encountered during granular avalanches. Finally, we discuss how the void-filling mechanism becomes more efficient when there is a higher relative size difference between the boulders and the surrounding grains. Our model has important implications in understanding the resurfacing of Itokawa by trying to explain one of the many complex geophysical processes that occur in such unique conditions.

1 Introduction

Surface images of near-Earth asteroid (NEA) Itokawa by Hayabusa spacecraft reveal a non-uniform regolith distribution over the surface in terms of grain sizes [1]. A wide range of distinct geological features suggests a dynamically active regolith cover, even in a micro-gravity environment. The surface of Itokawa has two distinct types of terrain with a sharp boundary. The rough terrain, which covers around 80% of the surface area, has numerous boulders (meter-sized), whereas the smooth terrain is generally featureless with fine particles (centimeter or millimeter-sized). Regions, where the smaller particles are found to accumulate are also low total potential areas where total potential comprises gravitational and rotational components. This suggests that the migration must have been gravity-driven after initial deposition [1]. Seismic shaking due to micrometeorite bombardments on airless bodies provides sufficient energy to excite (fluidize) the regolith bed [1]. This may destabilize local features and initiate granular avalanches in which, by the mechanism of kinetic sieving, finer particles percolate in the voids, and the force imbalance pushes the larger particles towards the surface [2]. Another mechanism that may cause size-segregation is the BNE, where local rearrangements among particles occur due to vibrations. Understanding the dynamics of granular materials on asteroids is paramount to interpret their surface geophysics and evolutionary history.

Figure 1 shows the regolith cover of Itokawa with large boulders sitting on the surface without being buried by fine

grains. In this work, we explore BNE on Itokawa using DE simulations [3] of grains subjected to vertical vibrations, one of the causes for which might have been impact-induced seismic shaking [1]. Tancredi et al. [4] showed the occurrence of BNE in surface gravity of 10^{-4} g; where g is the acceleration due to the gravity of the Earth. However, the simulations were performed with walled boundary conditions, far from reality on the surface of asteroids. Maurel et al. [5] tried to overcome this constraint using a periodic boundary condition (PBC) and show that the void filling mechanism can be responsible for the size segregation. We improve upon their work by considering the actual surface gravity of a patch on Itokawa (Patch X), the centrifugal effects, and the local slope, which affects the flow. This work is a first attempt to understand the magnitude of seismic shaking due to impacts on Itokawa, which may cause BNE by using impact modeling theory [6].

Figure 1. Itokawa close-up image taken by the Hayabusa spacecraft (Source: JAXA Digital Archives)

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2 Methodology

We simulate a 3D granular flow with PBC along the x and y directions of the flow, as shown in Fig. 2. The flow consists of spherical, cohesionless, inelastic (coefficient of restitution $e = 0.5$), rigid (with soft contact) and rough (friction angle $\Phi = 35^\circ$) grains. The choice of Φ and density $\rho = 3600 \text{ kgm}^{-3}$ corresponds to individual grains of ordinary chondrites [7]. Introduction of polydispersity and non-spherical grains will be better able to predict the dynamic behavior of the regolith but has not been incorporated in the current model due to computational time constraints. The base is made to oscillate sinusoidally, characterized by the amplitude and shaking frequency of seismic shaking, as will be discussed in Sec. 2.2. The energy dissipation among particles is only due to their mutual collisions, rolling and rubbing friction. The timesteps for the simulation have been kept sufficiently small so that the collisions can be resolved accurately.

2.1 Selection of Patch on Itokawa

Figure 2. Schematic diagram of our simulation box

From the shape model of Itokawa, we selected Patch X on the western face showing a transition zone with dimensions of $10 \text{ m} \times 10 \text{ m}$ with the regolith bed depth to be 5 m [6]. Using the polyhedral approach, as implemented by Werner and Scheeres (1996), we get the local gravitational acceleration to be $8.5 \times 10^{-5} \text{ ms}^{-2}$. The angle between the surface normal and the effective gravity vector (which accounts for rotational and gravitational forces) gives the local slope at Patch X to be around 12° , which is close to the values calculated in Scheeres et al. [8]. Locating the rotation pole of Itokawa and subsequently calculating the effect of centrifugal forces on the grains due to its spin, we find that the magnitude of the centrifugal acceleration is much smaller as compared to gravitational acceleration. Therefore we assume that the rotational effects on Patch X contribute very little to grain motion.

2.2 Boulder Distribution

The grain size distribution has been done according to the actual boulder distribution observed at Patch X on Itokawa. We consider three particle sizes, which relate to pebble, cobble, and boulders, as per the terminology of Miyamoto et al. [1]. The total number of particles has been constrained to 30000 particles to achieve the desired regolith depth and reasonable computational balance requirements. Based on the values of the cumulative number of a given diameter boulder as provided by Tancredi et al.

Table 1. Grain size distribution at Patch X

Type	Diameter (m)	Volume %
Small	0.25	83.63
Medium	0.75	15.16
Large	1.5	1.22

[4], we estimate in Patch X the number of grains for each size, and this is given in Table 1. The particles used have the same density $\rho = 3600 \text{ kgm}^{-3}$ so that only the effect of size on particle segregation can be studied. We randomly generate the particles inside the simulation box, which are allowed to settle above the base under Earth's gravity for faster deposition. The fine grains occupied the top layers of the regolith bed at the end of the filling phase. The settling time was kept high enough for the particles to attain an equilibrium.

Figure 3. Grain size distribution in the simulation box

2.3 Impact Modelling

Impacts on airless bodies are a ubiquitous phenomenon. Due to Itokawa's small size, even centimeter's sized impactors can cause global seismic shaking [1] and subsequent granular motion. We are interested in the typical values of non-dimensional acceleration $\Gamma = A\omega^2/a_g$ where A and ω are, respectively, the amplitude and frequency of the globally averaged vibration caused by an impact.[4-5] use arbitrary values of Γ . Figure 4 shows the typical values of Γ for impacts specifically on Itokawa. The equation below provides a simplistic model to compute Γ assuming the impactor to be spherical.

$$\Gamma = \frac{a_{\max}(D_i, D_a)}{g(D_a)} = \frac{3fv_i}{G} \sqrt{\eta \frac{\rho_i}{\rho_a^3} \frac{D_i^3}{D_a^5}} \exp\left(\frac{-fD_a^2}{K\pi Q}\right) \quad (1)$$

Here D represents the mean diameter and subscript i and a represent impactor and asteroid properties, respectively. The exponential term in Eqn. 1 accounts for the attenuation of the energy due to the rubble pile nature of Itokawa. The impactor density ρ_i , seismic efficiency η , seismic diffusivity K , seismic quality factor Q are, respectively, 2500 kgm^{-3} , 10^{-4} , $0.25 \text{ km}^2\text{s}^{-1}$, 2000 in accordance with the values given by Miyamoto et al [1]. The velocity of impact v_i is assumed to be 15 kms^{-1} , which is typical of the collisional velocities of impactors in the NEA belt, and the shaking frequency f is chosen to be 30 Hz [5].

3 Results and Discussion : DE Simulations

In this section, we report upon simulations performed with molecular dynamics package LAMMPS using the parameters discussed in Sec. 2. We first examine whether the

Figure 4. Variation of non-dimensional acceleration Γ with impactor diameter for Itokawa

BNE remains relevant in a micro-gravity environment as found on asteroids. The BNE has been studied extensively using both simulations and experiments where a bounding wall is present. However, in this case, we compare cases when a wall is present and absent and investigate the segregation mechanisms. Furthermore, we explore the parameter Γ and see how it affects the dynamics of the system. The discussions about the results are presented in Sec. 4. For all our simulations, we employ normal spring stiffness k_n and simulation time-step δt as follows:

$$k_n = 5.81 \times 10^{10} \text{ kgs}^{-2}, \delta t = 5.00 \times 10^{-5} \text{ s} \quad (2)$$

3.1 Effect of magnitude of gravity

To determine the efficacy of the BNE across different gravity regimes, we have performed simulations with the averaged surface gravity of the Earth, the Moon, Eros, and the computed gravity at Patch X on Itokawa. To understand only the effect of surface gravity, we keep the regolith bed on a flat surface, such that the gravity is acting in the downward direction normally. We compare different dynamic conditions by maintaining the non-dimensional acceleration Γ to be constant [4]. We have seen in Sec. 2.3 that the magnitude of Γ depends on the size, density, and velocity of the impactor. Since Γ is implemented in our shaking model through the amplitude and frequency, we select these parameters to imitate realistic seismic shaking due to impacts on these bodies. For the chosen amplitude, in the case of Itokawa, the grains are lifted to a much higher height from the surface, giving more time for the grains to re-arrange themselves (more fluidized behavior).

Table 2. Oscillation amplitude and period adopted in simulations

$a_g \text{ (ms}^{-2}\text{)}$	Amplitude (m)	Time period (s)	Γ
9.81	0.5	0.6	5.6
1.62	0.1	0.66	5.6
0.0059	0.05	7.7	5.6
0.000085	0.01	28.8	5.6

We consider the BNE to occur when the large boulders rise to the regolith bed's surface at the end of the shaking sequence. From our simulations, we find BNE to occur in all the cases but on different timescales. A linear fit in the log-log space in the data points, as seen in Fig. 5, suggests that a large number of vibrations are required for the full rise of the larger boulders up the surface on Itokawa. A high value of Γ , e.g., $\Gamma > 10$, represents violent shaking, which may not be feasible on an asteroid because an impact of such magnitude will disrupt it entirely or cause significant mass loss. Therefore, impacts from interplanetary

Figure 5. Comparison of the number of shakes required for BNE to occur for different surface gravity

dust or other asteroids that cause Γ in the lower ranges are sufficient to resurface the asteroids which suggests that, the appearance of large boulders on the surface of Itokawa may be due to recurring seismic events of small magnitude over its lifetime.

3.2 Effect of slope

Figure 6. The rise of one of the large boulders during seismic shaking on a surface with inclination ϕ

With the introduction of a slope, there is a tendency for the grains to flow when there is an input of energy. Seismic shaking may also induce avalanches, which results in the dilation of the flow. Smaller particles fall under gravity into the voids created by the larger particles, and the force imbalance squeezes the larger particles towards the surface [2]. From our simulations, we find that when particles are subjected to vertical vibrations on an inclined surface, local rearrangements occur both due to vibrations and *kinetic sieving*, thus aiding in the process of size segregation. Gray and Chogunov [9] give the following equation to model the segregation and remixing in avalanche flows mathematically:

$$\frac{\partial \phi}{\partial t} + \frac{\partial \phi u}{\partial x} + \frac{\partial \phi v}{\partial y} + \frac{\partial \phi w}{\partial z} - \frac{\partial (S_r \phi (1 - \phi))}{\partial z} = \frac{\partial}{\partial z} \left(D_r \frac{\partial \phi}{\partial z} \right) \quad (3)$$

where ϕ is the small particle volume fraction in a binary mixture, u, v, w are the non-dimensionalised velocities, S_r and D_r are the non-dimensional segregation and diffusive-remixing numbers respectively. S_r is directly proportional to gravity. This suggests that the efficiency of segregation reduces in low-gravity conditions. Therefore particle segregation processes in the regolith bed on Itokawa requires much longer time-scales than the same

processes would require in the presence of a strong gravitational field like on the Earth. As evident in Fig. 6, in which the height denotes the amount of rising for a large boulder, under Earth's gravity, the large boulders rise to the top of the regolith bed at a slightly lower number of shakes when the surface is inclined. This suggests that kinetic sieving due to the flow of grains aids in the process of size sorting. However, the majority of the dilation spikes in the grains are created due to vertical vibrations. The large particles which occupy the surface are likely to be transported during an avalanche, as observed in segregated landslide deposits on Itokawa (see Fig. 1).

3.3 Effect of relative size ratios

Figure 7. The number of shakes required for BNE to occur for various diameter ratios between the large and small particles

We investigate the effect of relative size ratios between the fine and the coarse grain upon the time taken for BNE to occur. To quantify this, we calculate the vertical rise speeds for different sized particles. The plot above in Fig. 7 shows that the vertical rise occurs at a relatively lesser number of shakes for the greatest diameter ratio between the large boulders and the surrounding particles. This happens because the larger boulders create larger voids when the regolith bed is excited, allowing the finer grains to occupy the space. There is not much variation in the densities in the grains of Itokawa; otherwise, the boulders, when subjected to vibrations, would sink to the bottom of the bed rather than rising, i.e., reverse BNE. In the context of Itokawa, this study provides an estimate of the size resolution and minimum threshold at which BNE could occur.

3.4 Effect of bounding walls

Maurel et al. [4] points out that granular systems subjected to vibrations and bounded by walls exhibit BNE due to a granular convection process. In contrast, for the PBC, the driving mechanism is due to void-filling by fine grains. We have kept the collision parameters for the wall-particle to be equal to particle-particle collisions to make both the boundary conditions as similar as possible. Figure 8 shows that in the case of walls surrounding the grains, the boulders rise to the top in the first few shakes, but it takes greater time for the boulders to rise to the surface for a PBC. Since the walled boundary condition represents a confined environment, the total seismic energy is transferred to the grains entirely, whereas, for the PBC case, the energy transmitted to the grain attenuates significantly.

Although the void-filling mechanism remains prominent in the segregation process under low gravity conditions, as seen in Sec. 3.1, its efficiency is lower than for a walled boundary. However, since a PBC is a more realistic condition on an asteroid surface, we have used it for the analysis.

Figure 8. The rise of one of the large boulders during seismic shaking for (a) periodic BC (b) wall BC

4 Conclusion

We have performed numerical simulations of grains subjected to vibrations in micro-gravity. Our simulations have shown that the void-filling mechanism remains prominent on Itokawa on longer timescales and can explain the appearance of large boulders on its surface. The size sorting process on Itokawa must have occurred through its lifetime via repeated seismic shaking of small magnitudes because a singular non-destructive impact that produces a high Γ is improbable. When there is a certain inclination, more voids are created as the grains flow downslope, making the fine particles fall into them. This leads to the accumulation of large boulders on the surface, similar to what is observed at Patch X. Our study shows that on the surface of asteroids where there are no parallel sidewalls, the BNE can still occur, which suggests that a wall's presence is not a necessity. The relative size distribution among particles is also an essential parameter in the occurrence of BNE. Understanding the segregation process in unconfined environments like the surface of Itokawa can allow us to assess better its surface grain distribution and variation of macro-porosity with depth. A comprehensive study of the parameter space will also allow us to identify the set of realistic initial conditions that led to segregation on Itokawa.

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