

Particle angularity controls granular flow under vibration

Yuna Isobe , Hideaki Miyamoto *, and Yuta Shimizu 

Department of Systems Innovation, Graduate School of Engineering, *The University of Tokyo*,
7-3-1 Hongo, Bunkyo-ku, Tokyo 113–8656, Japan



(Received 14 April 2025; accepted 9 September 2025; published 10 November 2025)

Granular materials exhibit complex transitions between solid-like and fluid-like states. Although natural granular particles typically have irregular shapes, the impact of particle angularity on granular flow remains poorly understood. Here, we demonstrate, through laboratory experiments and numerical simulations, that particle angularity controls vibrated granular flow. Highly angular particles sustain long-lived convective motion, whereas smoother (more rounded) particles rapidly form dense, solid-like structures that suppress fluidization. We further show that rolling resistance models commonly used in simulations fail to fully capture these angularity-driven effects. Our findings challenge standard simulation approaches and indicate that natural granular flows (e.g., landslides and planetary regolith) could be far more dynamic than predicted by spherical-particle approximations. This underscores the crucial but often underappreciated role of particle shape in granular physics.

DOI: [10.1103/w5dw-55qr](https://doi.org/10.1103/w5dw-55qr)

I. INTRODUCTION

Granular materials are assemblies of discrete solid particles that exhibit complex transitions between fluid-like and solid-like states. They play important roles across diverse fields, including agriculture, medicine, geophysics, and planetary science. Understanding granular dynamics is essential for optimizing industrial processes [1], mitigating geological hazards [2], and interpreting planetary surface evolution [3]. Under external force (e.g., vibration), granular materials display rich collective phenomena such as convection [4], segregation [5], surface waves [6], and arching [7]. However, most fundamental studies simplify granular materials to idealized spherical particles, even though natural granular systems are rarely spherical.

Our direct experience with planetary exploration has illustrated the broader context of this problem. High-resolution images from the Hayabusa mission revealed that seismic vibrations triggered global-scale migration and sorting of very angular regolith particles on the small asteroid Itokawa, effectively resurfacing the asteroid despite its extremely low gravity [3]. We have repeatedly observed that minor perturbations can mobilize loose and angular gravels on small asteroids, indicating their surprisingly high particle mobility [8,9]. Such planetary examples underscore the broader significance of granular dynamics of wide ranges of particle shapes and sizes, and motivate our study of how fundamental particle

properties, particularly particle angularity, govern granular flow.

Real granular particles have irregular shapes (characterized by angularity, surface roughness, and elongation) that significantly influence bulk properties like settling velocity, shear strength, and energy dissipation [10–14]. Among these characteristics, particle angularity (the presence of sharp edges and flat facets) is particularly important because angularity directly affects contact mechanics, influencing phenomena such as suffusion in soil [15] and the accretion processes in asteroid formation [16]. Although previous studies have investigated shape effects such as aspect ratio [17,18], the impact of angularity, especially under dynamic conditions such as vibration, remains poorly understood. Clarifying the role of angularity is essential for accurately interpreting sediment transport on Earth and planetary surfaces, optimizing industrial mixing processes, and improving the fidelity of numerical simulations.

Numerical studies of granular flow commonly employ the discrete element method (DEM), frequently using spherical particles to reduce computational cost. A typical approach to incorporate particle shape effects is the rolling resistance model, which introduces rotational friction to spherical particles to approximate behaviors induced by irregular shapes [19]. However, this model does not explicitly include many geometric effects of angular grains, such as anisotropic contact networks or localized stress concentrations at sharp edges. Consequently, it remains unclear whether the rolling resistance model can adequately capture the complex flow dynamics of angular particles.

In this study, we systematically investigate the effect of particle angularity on granular flow under vertical vibration using both laboratory experiments and DEM simulations. We demonstrate that the angularity of real granular particles profoundly affects granular flows, challenging conventional

*Contact author: hm@sys.t.u-tokyo.ac.jp

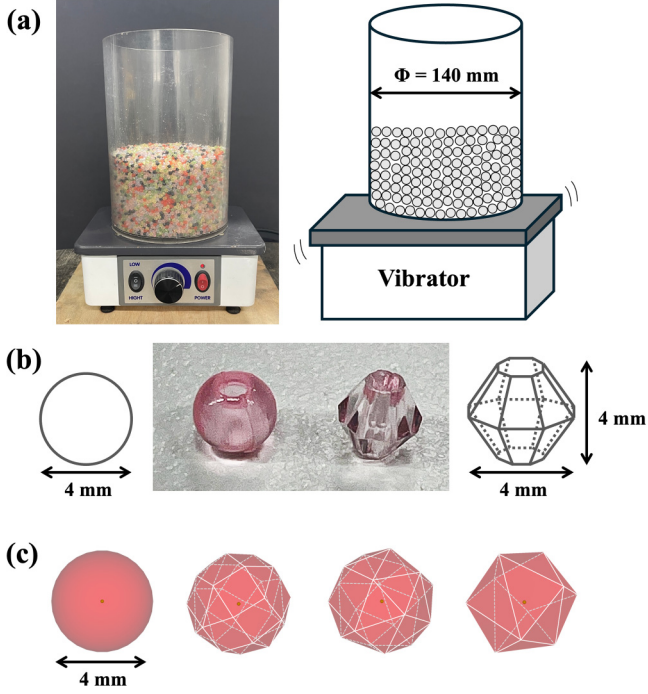


FIG. 1. (a) Experimental setup (photograph and schematic). (b) Acrylic particles used in the experiment: left, a 4 mm spherical bead; right, a polyhedral bead. (c) Particles used in the simulation: from left to right, a sphere ($\alpha = 0$), a 30-vertex polyhedron ($\alpha = 0.0323$); a 20-vertex polyhedron ($\alpha = 0.0479$); and a 10-vertex polyhedron ($\alpha = 0.0902$).

modeling approaches and revealing that natural granular flows may be significantly more dynamic (fluidized) than predicted by traditional spherical-particle approximations.

II. METHODS

Figure 1(a) shows an image and schematic of the experimental apparatus. To minimize directional wall effects, a cylindrical container (140 mm inner diameter) is used. Approximately 24 000 particles of identical size and shape are poured uniformly from above into the container, forming a granular bed about 100 mm deep, with no tapping or other precompaction. The container is rigidly mounted on a device that provides vertical vibrations. We apply a continuous sinusoidal vertical vibration for 90 s with amplitude $A = 0.5$ mm and frequency $f = 50$ Hz, corresponding to a dimensionless acceleration $\Gamma \sim 5.0$ (where $\Gamma = A(2\pi f)^2/g$).

The experiments use spherical and polyhedral acrylic particles [Fig. 1(b)], both with a characteristic size of 4 mm (diameter for the sphere). While each particle has a small central hole (a byproduct of manufacturing), we verified that it does not significantly affect its behavior. The polyhedral particles have eight vertices, making them more angular in shape than the spherical particles. Particle motions at the free surface and near the container wall are recorded on video for analysis.

Precise control of particle density, size, and surface conditions is challenging in experiments, making it difficult to isolate the effect of particle angularity alone. Therefore, we

also conduct numerical simulations using the DEM (Rocky DEM software). The simulation setup matches the experimental conditions: Approximately 24 000 particles of identical size and shape are poured uniformly into a cylindrical container (inner diameter 140 mm) without compaction. The same vibration conditions as the experiment ($f = 50$ Hz and $A = 0.5$ mm) are applied. The interparticle friction coefficient is $\mu = 0.5$, and other parameters are chosen to match the properties of the experimental acrylic particles.

In the simulations, we examine both spherical and polyhedral particles. To investigate the effect of particle angularity on natural granular materials, we use asymmetrical polyhedra. The polyhedral particle shapes are defined by the number of vertices, the aspect ratios, and the degree parameters of the superquadric function. The shape is expressed by the superquadric equation [20]

$$\left(\left|\frac{x}{a}\right|^{n_2} + \left|\frac{y}{b}\right|^{n_2}\right)^{\frac{n_1}{n_2}} + \left|\frac{z}{c}\right|^{n_1} - 1 = 0, \quad (1)$$

where a , b , and c are half the lengths of the particle along the x -, y -, and z -axes, respectively, and a/b and c/b define the aspect ratio. In our simulations, to isolate the effect of angularity, we set $a = b = c$ (equal dimension) and choose exponents $n_1 = n_2 = 2$. To quantify particle angularity, we introduce a metric α , defined as the ratio of the particle's sphericity to its number of vertices (a simple and commonly used definition [10]). Here, sphericity is the ratio of the surface area of a volume-equivalent sphere to the surface area of the particle. By varying the number of vertices of the polyhedron, we obtain particles with the different angularities. Figure 1(c) shows the spherical particle and three polyhedral particles used in the simulation with $\alpha = 0$ (sphere), 0.0323 (30 vertices), 0.0479 (20 vertices), and 0.0902 (10 vertices). All particle shapes are generated to have the same volume as a 4 mm sphere.

III. RESULTS

A. Granular convection driven by angularity

Figures 2(a)–2(d) show the particle trajectories at the free surface and the container sidewall for spherical and polyhedral particles. These results indicate that spherical particles exhibit minimal fluidization under vibration, whereas polyhedral particles exhibit noticeable flow. Furthermore, the flow pattern suggests the presence of particle convection. Notably, the convective motion of polyhedral particles persists for the entire 90-s duration of vibration, while spheres never develop significant motion (a slight overall rotation was observed, which we attribute to a minor asymmetry in the apparatus). The difference in behavior due to particle shape is also observed when we increase the vibration amplitude. Although spherical particles exhibit some degree of flow at higher amplitudes, polyhedral particles move significantly faster (see Fig. S1 in Supplemental Material [21]).

To confirm that the differences observed in the experiments are indeed due to particle shape, we turn to DEM simulations where all other properties can be kept identical. Figure 3(a) shows the particle displacement over 30 s for the most angular particles (10 vertices, $\alpha = 0.0902$) and for spherical particles ($\alpha = 0$). Initially, both spherical and angular particles develop two symmetric convection rolls near the surface. However,

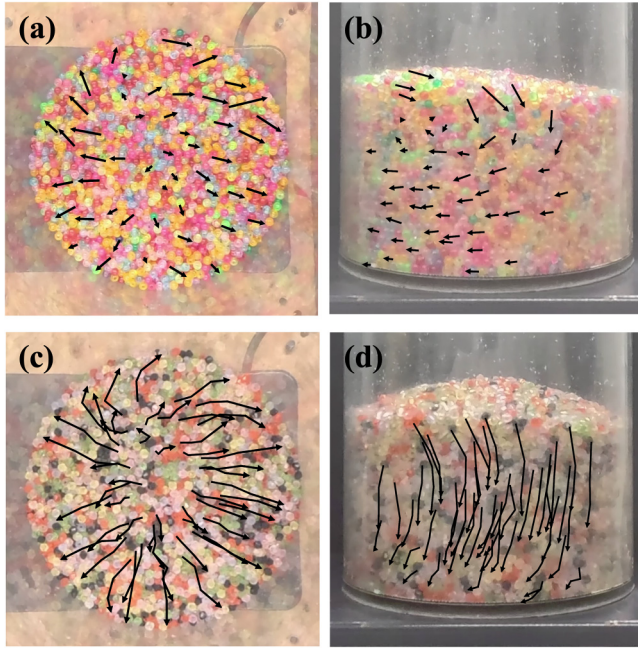


FIG. 2. Trajectories of spherical particles at (a) the free surface and (b) the container sidewall, and of polyhedral particles at (c) the free surface and (d) the sidewall. Trajectories are obtained by tracking 50 randomly selected particles and plotting their positions over a 30-s interval (from 20 s to 50 s after vibration start, once the flow had stabilized). Because spherical particles move only slightly, their positions are shown at 20 s and 50 s; for more mobile polyhedral particles, positions are plotted at 10-s intervals.

these convection cells are transient for spheres (disappearing after some time), whereas they persist throughout the simulation for highly angular particles.

To quantitatively assess the presence and intensity of convection, we calculate the vorticity of the particle motion as seen in Fig. 3(a). In a two-dimensional plane, vorticity ω is defined as $\omega = \partial v_z / \partial x - \partial v_x / \partial z$. The particle displacement vectors of particles are gridded and treated as a flow field to compute vorticity. When convection is present, the magnitude of ω is large in the regions where convection cells form. Figure 3(b) shows the temporal evolution of the mean $|\omega|$ for all four particle shapes. We find that the convection intensity (mean $|\omega|$) decays fastest for spheres ($\alpha = 0$) and slowest for the most angular case ($\alpha = 0.0902$) with intermediate angularities in between, indicating that convection is suppressed more quickly for particles with smoother shapes.

B. Structural transition

As the void space between particles decreases, the granular bed transitions toward a solid-like state, effectively suppressing granular flow. To quantify the transition from fluidization to solidification, we analyze the radial distribution function (RDF), $g(r)$, of the particles [22], which reflects the packing structure. In a loose, fluid-like state, the RDF shows primary peaks at interparticle distances $\sim 1d$ and $\sim 2d$ (d = particle diameter). As the packing becomes denser and more ordered, the peak at $2d$ is split and a new peak appears at $\sqrt{3}d$. The $\sqrt{3}d$ peak corresponds to equilateral triangular arrangements

of contacting particles, indicating local crystalline order. The growth of a sharp $\sqrt{3}d$ peak (and subsequent higher-order peaks of a tightly packed lattice) indicates a transition to a solid-like crystallized state with fewer voids. Conversely, the absence or weakness of the $\sqrt{3}d$ peak indicates that the packing remains disordered (liquid-like).

Figure 4 shows the evolution of the RDF over time for each particle shape. Examining the $\sqrt{3}d$ peak in particular reveals clear differences among particle shapes. Spherical particles develop a $\sqrt{3}d$ peak as early as 30 s after vibration begins, and this peak becomes very sharp by 90 s. In contrast, the highly angular polyhedral particles (10 vertices, $\alpha = 0.0902$) do not develop a $\sqrt{3}d$ peak even at 90 s. Polyhedral particles with intermediate angularity (20 or 30 vertices) do develop a $\sqrt{3}d$ peak, but it remains less pronounced than in the spherical cases.

These differences in the RDF correspond to the changes in vorticity observed in the previous section. Particles that retain an open structure under vibration preserve fluidity and sustain convection. In contrast, particles that pack into denser, more compact structures exhibit solid-like behavior that suppresses convection. In other words, the flowability of the particles depends on how easily they form ordered structures. This tendency to form ordered structures can be attributed to two key factors.

These results suggest that particles with higher angularity tend to maintain a disordered structure even under vibration, which sustains convection. In fact, for irregular polyhedral particles, it has been shown that higher angularity leads to lower packing fractions under external forcing [11].

However, it is important to note exceptions to this trend. Highly symmetric particles are prone to crystallize [23]. For instance, even with high angularity, cubic particles can easily form dense packings under vibration due to their high symmetry, thereby suppressing convection (see Fig. S2 in Supplemental Material [21]).

Thus, we conclude that in the case of irregular, asymmetrical polyhedral particles, such as those commonly found in natural environments, higher angularity tends to promote sustained flow under vibration.

C. Limitations of the rolling resistance model

A common way to model particle shape effects in simulations is by introducing a rolling resistance torque [24], which opposes particle rotation. In DEM simulations, spherical particles with rolling resistance are often used to approximate the behavior of angular particles while keeping computations tractable. We perform additional simulations using a type C rolling resistance model [25] under the same conditions as the polyhedral particle simulations. To observe the behavior of particles for a longer duration, the total vibration time is extended to 180 s in these simulations. The rolling resistance coefficient is set to $\beta = 0.08$, chosen such that the mean angular velocity of vibrating spherical particles match that of the 10-vertices polyhedral particles [Fig. 5(a)].

Figure 5(b) shows the evolution of the mean $|\omega|$ for the 10-vertex polyhedral particles, for spherical particles without rolling resistance, and for spherical particles with $\beta = 0.08$. For approximately the first 50 s, the spherical particles with

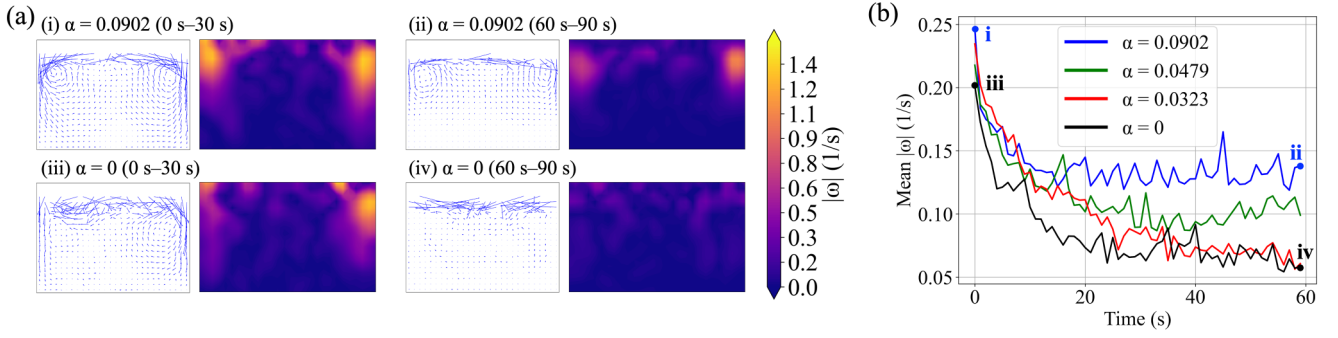


FIG. 3. (a) Particle displacements and vorticity fields in cross sectional plane for different particle types over 30-s intervals: (i) polyhedral (10-vertex) particles from 0–30 s; (ii) polyhedral (10-vertex) particles from 60–90 s; (iii) spherical particles from 0–30 s; and (iv) spherical particles from 60–90 s. The left panels show particle displacements, computed on a $5 \text{ mm} \times 5 \text{ mm}$ grid using all particles in a central quasi-2D slice ($|y| < 10 \text{ mm}$). The right panels show the absolute vorticity ($|\omega|$) fields, calculated from the particle displacements. (b) Time evolution of the mean absolute vorticity of the entire granular bed, plotted against the starting time of the 30-s window (for example, the point at 60 s represents the mean vorticity from 60–90 s). Labels (i)–(iv) in (b) correspond to the cases in (a).

$\beta = 0.08$ sustain a high vorticity similar to that of the polyhedral particles. However, after 50 s, the vorticity decreases rapidly, and by 110 s it becomes comparable to that of the spherical particles without rolling resistance. This outcome is consistent with the RDF analysis [Figs. 5(c) and 5(d)], which showed that the loss of void space over time leads to a more ordered structure and suppressed convection.

Our results show that although adding rolling resistance to spherical particles can initially mimic some effects of particle angularity, it cannot reproduce the sustained convection observed with truly angular particles. This is because, even with rolling resistance, spherical particles eventually form ordered structures under vibration due to their inherent geometry. Therefore, as long as spherical particles are used, we cannot accurately reproduce the packing structure formed by irregular angular particles, making it difficult to capture the long-term behavior of such particles. Furthermore, capturing the effects of varying degrees of angularity becomes even more challenging.

IV. CONCLUSIONS

Our laboratory experiments and simulations demonstrate that particle angularity plays a critical role in granular flow under vibration. In the case of irregular angular particles, low-angularity particles (smooth spheres) tend to form dense, ordered packings under vibration, eventually halting any convective motion. In contrast, highly angular particles maintain more disordered packings and thus sustain continuous convection throughout the vibration. Furthermore, simple rolling resistance models in DEM cannot adequately reproduce this effect. This is because spherical particles, even with rolling resistance, tend to form ordered structures under vibration due to the nature of their shape. Consequently, rolling resistance models cannot accurately capture the long-term behavior of irregular angular particles.

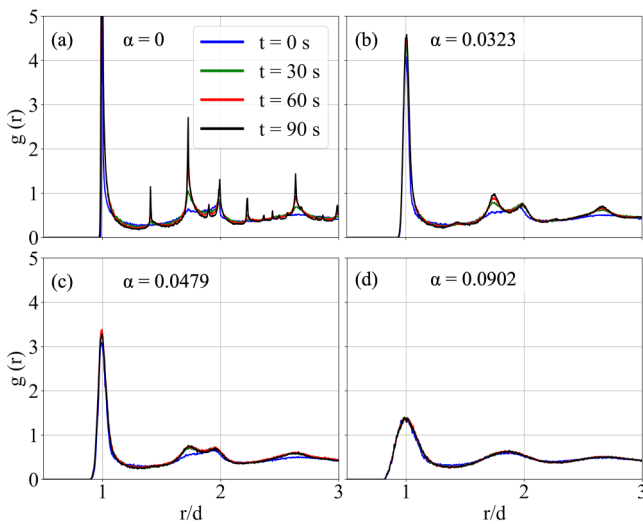


FIG. 4. Time evolution of the radial distribution function for (a) spherical particles ($\alpha = 0$), (b) polyhedral particles with 30 vertices ($\alpha = 0.0323$), (c) polyhedral particles with 20 vertices ($\alpha = 0.0479$), and (d) polyhedral particles with 10 vertices ($\alpha = 0.0902$).

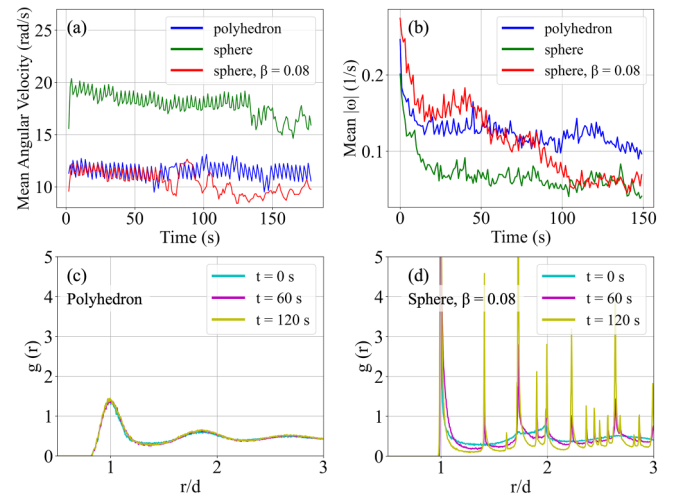


FIG. 5. (a) Time evolution of the mean angular velocity for polyhedral particles (10 vertices), spherical particles, and spherical particles with rolling resistance ($\beta = 0.08$). (b) Time evolution of the mean absolute vorticity for the same cases as in (a). (c) Time evolution of the RDF for the 10-vertex polyhedral particles. (d) Time evolution of the RDF for spherical particles with rolling resistance ($\beta = 0.08$).

These insights emphasize the importance of explicitly considering particle shape in the study and modeling of granular flow. In particular, natural granular materials (e.g., planetary regolith) may be more prone to fluidization under vibration than would be predicted by models assuming spherical particles. Our results challenge current modeling approaches and call for a reevaluation of shape effects in granular dynamics. Finally, we note that different vibration conditions or particle properties (e.g., size, polydispersity) could yield different outcomes; further work is required to fully understand the particle shape influence across a broader range of conditions.

ACKNOWLEDGMENTS

We appreciate the technical suggestions by Prof. Mikio Sakai. We acknowledge support from JSPS KAKENHI (Grants No. JP21J21798, No. JP23H00279, and No. JP24K22896).

DATA AVAILABILITY

The data that support the findings of this article are openly available [26].

-
- [1] J. Cante, C. Davalos, J. Hernandez, J. Oliver, P. Jonsén, G. Gustafsson, and H.-Å. Häggblad, PFEM-based modeling of industrial granular flows, *Comput. Part. Mech.* **1**, 47 (2014).
 - [2] E. Yang, H. H. Bui, G. D. Nguyen, C. E. Choi, C. W. Ng, H. De Sterck, and A. Bouazza, Numerical investigation of the mechanism of granular flow impact on rigid control structures, *Acta Geotech.* **16**, 2505 (2021).
 - [3] H. Miyamoto *et al.*, Regolith migration and sorting on asteroid itokawa, *Science* **316**, 1011 (2007).
 - [4] M. Faraday, On a peculiar class of acoustical figures; and on certain forms assumed by groups of particles upon vibrating elastic surfaces, *Phil. Trans. Royal Soc. London* **121**, 299 (1831).
 - [5] J. B. Knight, H. M. Jaeger, and S. R. Nagel, Vibration-induced size separation in granular media: The convection connection, *Phys. Rev. Lett.* **70**, 3728 (1993).
 - [6] H. K. Pak and R. P. Behringer, Surface waves in vertically vibrated granular materials, *Phys. Rev. Lett.* **71**, 1832 (1993).
 - [7] S. Hsiau, M. Wu, and C. Chen, Arching phenomena in a vibrated granular bed, *Powder Technol.* **99**, 185 (1998).
 - [8] T. Morota *et al.*, Sample collection from asteroid (162173) Ryugu by Hayabusa2: Implications for surface evolution, *Science* **368**, 654 (2020).
 - [9] K. J. Walsh *et al.*, Near-zero cohesion and loose packing of Bennu's near subsurface revealed by spacecraft contact, *Sci. Adv.* **8**, eabm6229 (2022).
 - [10] S. Zhao, X. Zhou, and W. Liu, Discrete element simulations of direct shear tests with particle angularity effect, *Granular Matter* **17**, 793 (2015).
 - [11] E. Azéma, F. Radjai, and F. Dubois, Packings of irregular polyhedral particles: Strength, structure, and effects of angularity, *Phys. Rev. E* **87**, 062203 (2013).
 - [12] X. Cui, N. Gui, X. Yang, J. Tu, and S. Jiang, Analysis of particle shape effect on the discharging of non-spherical particles in HTR-10 reactor core, *Nucl. Eng. Des.* **371**, 110934 (2021).
 - [13] X. Tang and J. Yang, Wave propagation in granular material: What is the role of particle shape? *J. Mech. Phys. Solids* **157**, 104605 (2021).
 - [14] R. P. Jones, J. M. Ottino, P. B. Umbanhowar, and R. M. Lueptow, Predicting segregation of nonspherical particles, *Phys. Rev. Fluids* **6**, 054301 (2021).
 - [15] J.-G. Qian, C. Zhou, Z.-Y. Yin, and W.-Y. Li, Investigating the effect of particle angularity on suffusion of gap-graded soil using coupled CFD-DEM, *Comput. Geotech.* **139**, 104383 (2021).
 - [16] F. Ferrari and P. Tanga, The role of fragment shapes in the simulations of asteroids as gravitational aggregates, *Icarus* **350**, 113871 (2020).
 - [17] B. Chen, P. Wu, H. Xing, H. Liu, L. Li, and L. Wang, Convection behavior of ellipsoidal particles in a quasi-two-dimensional bed under vertical vibration, *Powder Technol.* **363**, 575 (2020).
 - [18] M. Jiang, P. Wu, H. Liu, L. Li, S. Chen, S. Zhang, and L. Wang, Motion behaviour of ellipsoidal granular system under vertical vibration and airflow, *Soft Matter* **16**, 9559 (2020).
 - [19] H. Sakaguchi, E. Ozaki, and T. Igarashi, Plugging of the flow of granular materials during the discharge from a silo, *Int. J. Mod. Phys. B* **7**, 1949 (1993).
 - [20] A. H. Barr, Superquadrics and angle-preserving transformations, *IEEE Comput. Graphics Appl.* **1**, 11 (1981).
 - [21] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/w5dw-55qr> for the experimental results at higher amplitude and the simulation results using cubic particles.
 - [22] X. An, K. J. Dong, R. Yang, R. Zou, C. Wang, and A. Yu, Quasi-universality in the packing of uniform spheres under gravity, *Granular Matter* **18**, 6 (2016).
 - [23] P. Damasceno, M. Engel, and S. Glotzer, Predictive self-assembly of polyhedra into complex structures, *Science* **337**, 453 (2012).
 - [24] J. Ai, J. F. Chen, J. M. Rotter, and J. Y. Ooi, Assessment of rolling resistance models in discrete element simulations, *Powder Technol.* **206**, 269 (2011).
 - [25] K. Iwashita and M. Oda, Rolling resistance at contacts in simulation of shear band development by DEM, *J. Eng. Mech.* **124**, 285 (1998).
 - [26] Y. Isobe, H. Miyamoto, and Y. Shimizu, figshare dataset (2025), <https://doi.org/10.6084/m9.figshare.29210279>.