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Dynamics of regolith dunes on small planetary bodies

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Abstract. The surfaces of small planetary bodies are covered with regolith which keeps evolving with time. Studying the dynamics of these regolith can explain various surface features observed in recent space explorations. We use a computationally efficient depth-averaged theory for dense granular flows to study the dynamics of regolith dunes on small planetary bodies. Extending the approach of [1, 2], we derive the governing equations in spherical coordinates. This framework is then used to simulate the evolution of regolith dunes on a spherical and (101995) Bennu shaped asteroid. We discuss the significant effects of Coriolis force and surface topography.

1 Introduction

Recent space explorations to near-Earth asteroids (NEAs) find an abundance of regolith-loose granular materials-on their surfaces [3]. This regolith can evolve over time due to factors, such as changes in the asteroid's rotation rate or impacts from micrometeorites [4]. The evolution of regolith results in various surface phenomena, *e.g.* a lack of small craters on the surface [4], segregation of big and small size grains [5] and the formation of an equatorial ridge [6].

Recently, [7] implemented a computationally intensive discrete element method (DEM) simulation to follow regolith flow on the asteroid Bennu. The alternate continuum model proposed by [1, 2] uses the depth-averaged method of [8]. The method is computationally fast and can easily incorporate additional physics, such as spin evolution and impact induced regolith motion [2].

To understand the complex motion of grains on small planetary bodies, we explore the dynamics of an initially Gaussian-shaped regolith dune on a fast rotating and self-gravitating asteroid. Using the depth-averaged model of [1, 2], we conduct simulations on both spherical and Bennu-shaped asteroid.

2 Methodology

To describe dune evolution, we employ spherical coordinates (r, θ, ϕ); the coordinate $\theta \in (0, \pi)$ represents the co-latitude while $\phi \in (0, 2\pi)$ is the azimuthal angle in anti-clockwise direction. The mean radius of the asteroid is R.

Initially, a dune is created on the surface of the asteroid using a Gaussian function

$$h(\theta, \phi) = Ae^{-\dfrac{(\theta-\theta_0)^2 + (\phi-\phi_0)^2}{2\sigma^2}}, \tag{1}$$

where A determines the height of the dune, (θ_0, ϕ_0) is the peak of the dune and σ controls spread of the dune. This dune is then allowed to evolve under the influence of rotation, gravity and basal topography. The evolution equation is derived using the depth-averaged approach of [2, 8]. The main assumptions of the model are as follows:

- the change in moment of inertia due to regolith motion are small and are, hence, neglected;
- the thickness of the flow is much smaller than the length scale of the flow, which allows us to depth average the governing equations;
- the grains are cohesionless and the flow is incompressible;
- there is no erosion or deposition during the flow;
- the mass lifts off from the surface when the basal pressure goes to zero and is lost with no further interaction with the remaining system; and
- the shape of the asteroid may be approximated as a sphere with a shallow topography overlying.

Using these assumptions we depth-average the linear momentum balance and mass conservation equations in spherical coordinates; details in [9].

The depth-averaged governing equations for grains in spherical coordinates are

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$$\frac{\partial}{\partial t}\left\{h\lambda^2 \sin\theta\right\} + \frac{\partial}{\partial\theta}\left\{u_\theta h\lambda \sin\theta\right\} + \frac{\partial}{\partial\phi}\left\{u_\phi h\lambda\right\} = 0 \tag{2}$$

$$\frac{\partial}{\partial t}\left\{u_\theta h\lambda^3 \sin\theta\right\} + \frac{\partial}{\partial\theta}\left\{\left(u_\theta^2 + \psi\frac{h}{2}\right)h\lambda^2 \sin\theta\right\} + \frac{\partial}{\partial\phi}\left\{u_\theta u_\phi h\lambda^2\right\} = \ldots$$
$$\ldots\left\{-\left(\mu\hat{u}_\theta^b + \frac{\partial h^b}{\partial\theta}\right)\psi + \frac{u_\phi^2}{\lambda}\cot\theta + \left(g_\theta + 2u_\phi\omega_0\cos\theta + \omega_0^2\lambda\sin\theta\cos\theta\right)\right\}\lambda^3 h\sin\theta \tag{3}$$

and

$$\frac{\partial}{\partial t}\left\{u_\phi h\lambda^3 \sin^2\theta\right\} + \frac{\partial}{\partial\theta}\left\{u_\phi u_\theta h\lambda^2 \sin^2\theta\right\} + \frac{\partial}{\partial\phi}\left\{\left(u_\phi^2 + \psi\frac{h}{2}\right)h\lambda^2 \sin\theta\right\} = \ldots$$
$$\ldots\left\{-\left(\mu\hat{u}_\phi^b + \frac{1}{\sin\theta}\frac{\partial h^b}{\partial\phi}\right)\psi + \left\{g_\phi - 2\omega_0 u_\theta\cos\theta\right\}\right\}\lambda^3 h\sin\theta, \tag{4}$$

where u_i $(i = \theta, \phi)$ are depth-averaged components of velocity, h is the height of the flowing layer, μ is the basal friction coefficient, h^b is the height of the basal surface measured from the best fit sphere, $\lambda = h^b + R$, ω_0 is the rotation rate , g_i $(i = r, \theta, \phi)$ are components of gravitational acceleration on the surface and

$$\psi = -\frac{\partial p}{\partial r} = -\left(\frac{u_\theta^2 + u_\phi^2}{\lambda} + g_r + \omega_0^2\sin^2\theta + 2u_\phi\omega_0\sin\theta\right),$$

where p is the pressure [9]. In the absence of rotation and curvature, $\psi = -g_r$, which recovers the lithostatic pressure typically used in modeling terrestrial landslides [10]. The basal pressure p^b is given by

$$p^b = \psi h. \tag{5}$$

The mass shedding (lift off of mass from the surface) criterion is given by $P^b < 0$.

The governing equations (2)-(4) are hyperbolic in nature and are solved using the non-oscillatory central scheme of [11].

3 Results & Discussions

To observe the effects of rotation on slumping of dunes, we first analyse the ideal case of zero basal friction $\mu = 0$ on a fast rotating spherical body. Figure 1 shows the evolution of such a dune located at $\theta_0 = 30°$ and $\phi_0 = 180°$ on a sphere having rotation period of 4 hrs. In the absence of rotation the dune should slump gradually and its peak remains at the same spot, as gravity is normal to the surface. However, due to rotation of the body the peak also starts to move towards the equator. Once the dune gains motion, the Coriolis force comes into play and move the dune westward. As the dune reaches the equator, it slows down and begins spreading in the azimuthal direction. We also notice that the single dune breaks into two. This occurs because the influence of rotational forces is weaker near the poles, causing some grains to move more slowly and lag behind.

We now turn to a second example. The asteroid Bennu can be estimated as a spherical body with a maximum topographic deviation of around 15% near the equator. Hence, (2)-(4) may be used to simulate regolith flow on Bennu. Figure 2 shows the slumping of a dune on a Bennu-shaped asteroid with rotation period equal to Bennu, $T = 4.3$ hrs. The basal friction angle is assumed to be 20° and the gravity of the asteroid is replaced by the gravity of a sphere with mean radius equal to Bennu, R= 245 m. We observe that the dune slumping and peak movement are now less pronounced. This reduced motion is primarily due to frictional resistance from the base and the underlying topography's deviation from a sphere. Near the equator, the basal elevation h^b exceeds 40 meters, which acts as a barrier, limiting regolith movement toward the equator. As a result, the regolith tends to flow into nearby lower-lying regions instead.

Figure 3 shows the dune evolution on the same Bennu-like body but at a smaller rotation period of $T = 3.4$ hrs. Due to high rotation rate, the dune is able to travel to longer distances. However, due to equatorial ridge, we find that the motion is driven westward. Also, mass shedding starts as the grains move towards the equator; this was also observed by [7].

Mass shedding at a given location begins when basal pressure becomes negative, i.e.$P^b < 0$. As seen from (5), Coriolis force on grains moving eastward ($u_\phi > 0$) tends to reduce the basal pressure, whereas it causes P^b to increase on grains moving westward. Consequently, westward-moving grains remain in contact with the surface, while eastward moving lift off into the orbit. This is observed in Fig. 3, where only westward moving grains remain on the surface, causing the dune to appear to drift westward.

4 Conclusions and future improvements

Using the depth-averaged model, we simulated the evolution of an initially Gaussian-shaped regolith dune on small, rotating asteroids. Our results show that at high rotation rates, the dune migrates toward the equator and drifts westward due to the Coriolis force. In the presence of topography, we observe mass shedding of eastward moving grains, particularly near the equatorial region.

The current model needs further improvement to track shed mass, which subsequently returns back to the surface [7]. Additionally, assuming a spherical gravity field limits

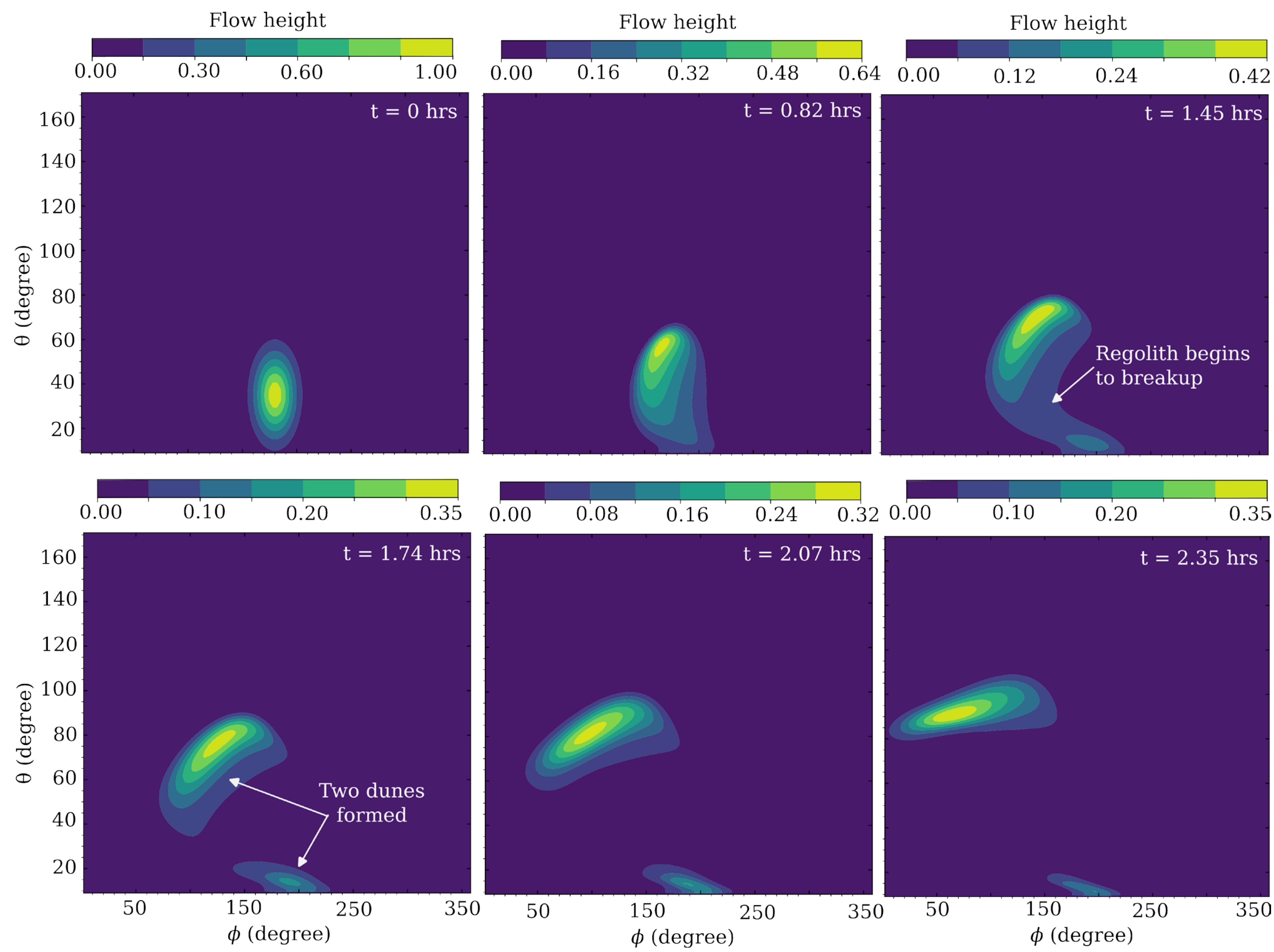

Figure 1. The slumping over time of a frictionless dune on a rotating sphere of radius $R = 250$ m and rotation period $T = 4$ hrs . The dune was created using the parameters $A = 2.5$ m, $\theta_0 = 30°$, $\phi_0 = 180°$ and $\sigma = 9°$ in (1). The flow height is non-dimensionalized with A.

the accuracy of the solution. Finally, we need to generalize the model to include the topography of arbitrarily shaped asteroids.

References

[1] K. Gaurav, D. Banik, I. Sharma, P. Dutt, Granular flow on a rotating and gravitating elliptical body, J. Fluid Mech. **916** (2021).

[2] D. Banik, K. Gaurav, I. Sharma, Regolith flow on top-shaped asteroids, Proc. R. Soc. A **478**, 20210972 (2022). 10.1098/rspa.2021.0972

[3] D. Lauretta, 28 others, and The OSIRIS-REx Team, The unexpected surface of asteroid (101955) Bennu, Nature **568**, 55 (2019).

[4] K.J. Walsh, and 37 others, and The OSIRIS-REx Team, Craters, boulders and regolith of (101955) Bennu indicative of an old and dynamic surface, Nat. Geosci. **12**, 242 (2019).

[5] S. Ghosh, I. Sharma, D. Dhingra, Segregation on small rubble bodies due to impact-induced seismic shaking, Proc. R. Soc. A **480**, 20230715 (2024).

[6] O.S. Barnouin, 29 others, The formation of terraces on asteroid (101955) bennu, Journal of Geophysical Research: Planets **127** (2022).

[7] Z. Song, Y. Yu, S. Soldini, B. Cheng, P. Michel, An integrated dem code for tracing the entire regolith mass movement on asteroids, Mon. Not. R. Astron. Soc. **532**, 1307 (2024).

[8] S.B. Savage, K. Hutter, The motion of a finite mass of granular material down a rough incline, J. Fluid Mech. **199**, 177 (1989).

[9] K. Gaurav, D. Banik, I. Sharma, Coupled shape and spin evolution of small near spherical asteroids due to global regolith motion, arXiv preprint arXiv:2505.18960 (2025).

[10] Gray, JMNT, M. Wieland, K. Hutter, Gravity-driven free surface flow of granular avalanches over complex basal topography, Proc. R. Soc. Lond. A. **455**, 1841 (1999).

[11] A. Kurganov, E. Tadmor, New high-resolution central schemes for nonlinear conservation laws and convection–diffusion equations, J. Comput. Phys. **160**, 241 (2000).

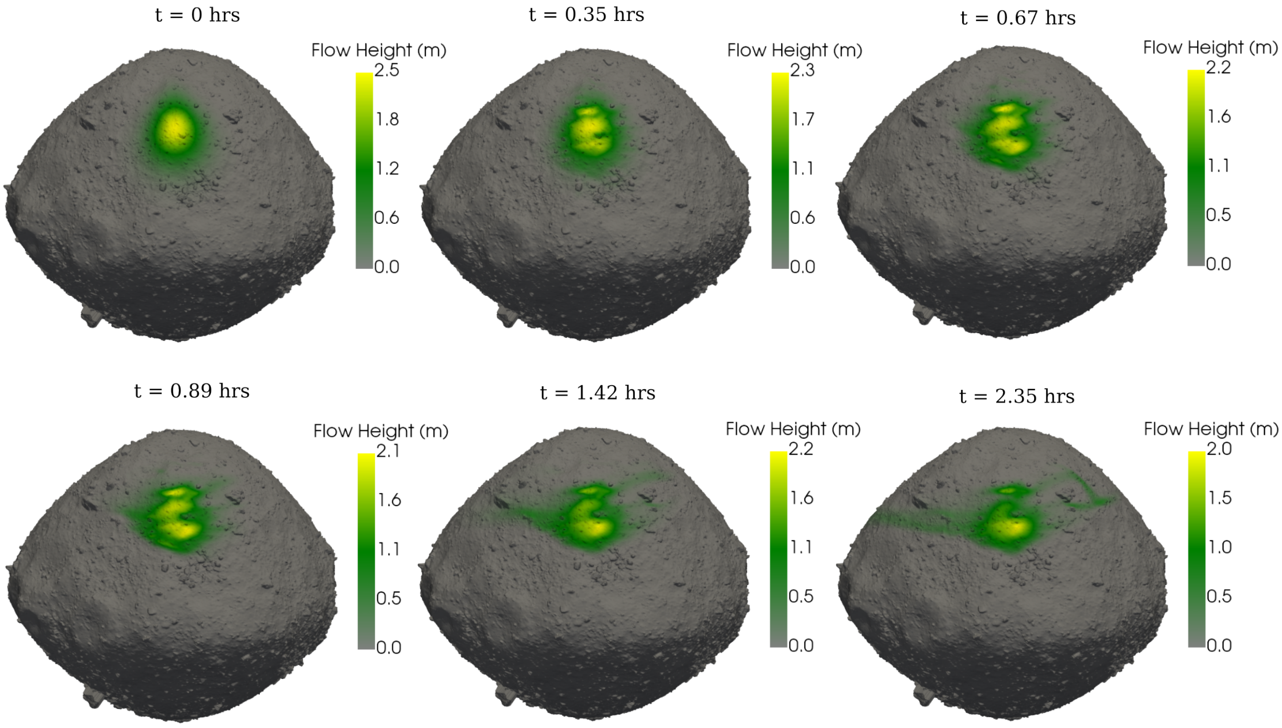

Figure 2. Slumping with time of a dune on a Bennu-shaped asteroid. The dune was created using the parameters $A = 2.45$ m, $\theta_0 = 45°$, $\phi_0 = 180°$ and $\sigma = 9°$. The rotation period is same as Bennu, $T = 4.3$ hrs, and friction angle of grains is 20°, which equals the basal friction angle.

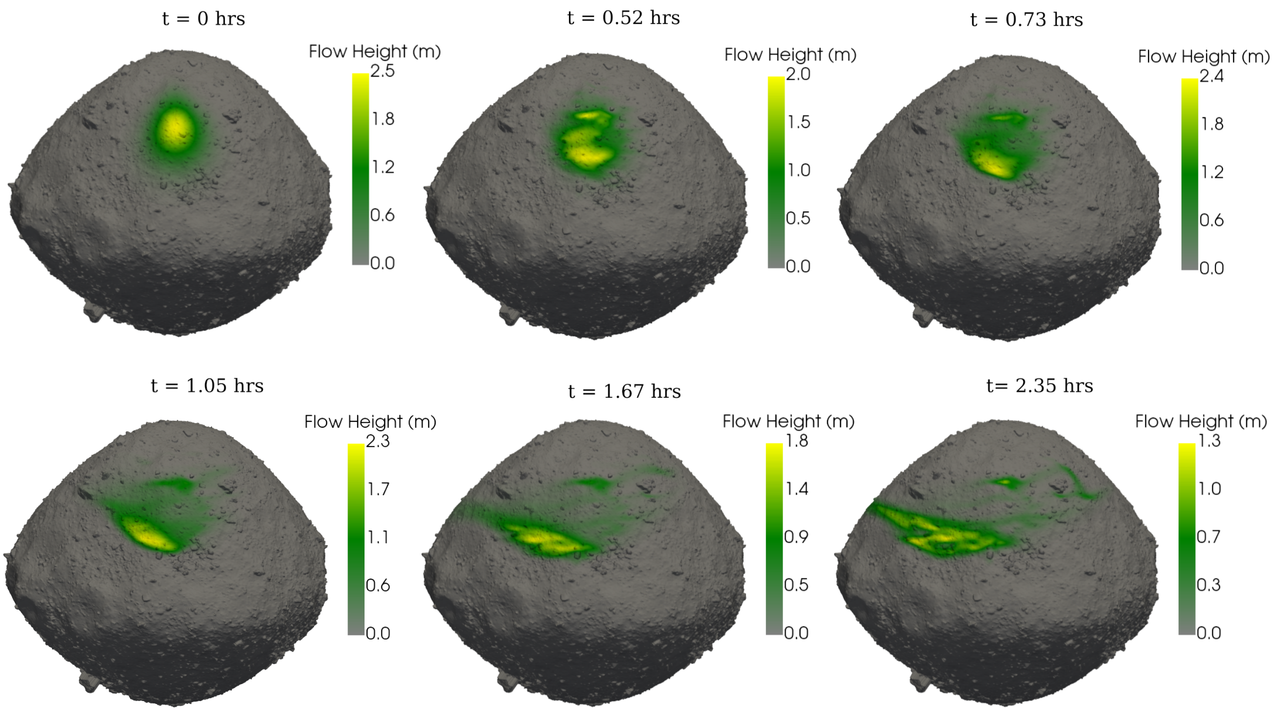

Figure 3. Slumping with time of a dune on a fast rotating Bennu-shaped body. The rotation period is $T = 3.4$ hrs. All other parameters are same as Fig. 2

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