Planetary saltation: Should we care about cohesion?

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Highlights

- Hypothesis: In natural environments, saltation occurrence is determined by transport cessation rather than its initiation
- General model of sediment transport cessation and saturated mass flux based on momentum and energy balances of transported particles
- Model simultaneously reproduces cessation threshold and saturated flux measurements for aeolian saltation and noncohesive fluvial bedload
- Model explains recent finding that the cessation threshold and saturated flux of aeolian saltation are not much affected by cohesion
- Model is consistent with eastward dune propagation of Titan's sand dunes in spite of the predominance of westward winds

Outline

Motivation: Titan's dune propagation

1. Titan's sand dunes propagate eastward in spite of the predominance of westward winds[1].
2. The leading explanation for this observation is that the saltation threshold on Titan is too high for westward storms to move sand but lower than the strength of eastward storms[2].
3. This explanation is based on saltation initiation threshold models that assume that the cohesiveness of Titan's soils is comparable to that of Earth's soils[3].
4. However, soils on Titan are probably much more cohesive than on Earth, challenging this explanation[4].
5. We find that Titan's dune propagation is consistent with the hypothesis that the cessation (cohesion-independent[5]) rather than the initiation of saltation determines its threshold.

References (click to open):

(1) Lorenz et al. (Science, 2006); Radebaugh et al. (Geomorphology, 2010)
(2) Tokano (Aeolian Research, 2010); Charnay et al. (Nature Geoscience, 2015)
(3) Lorenz (Icarus, 2014); Burr et al. (Nature, 2015)
(4) Méndez Harper et al. (Nature Geoscience, 2017); Yu et al. (JGR: Planets, 2017)
(5) Comola et al. (GRL, 2019)

Saltation threshold hypothesis

1. In natural environments (long fetch), a single airborne grain can trigger a collision chain resulting in saturated saltation[1].
2. Since bed grains can relatively easily become airborne in natural environments (see below), saltation cessation rather than its initiation determines the saltation threshold.

Airborne grains are readily generated in nature because of

- topography inhomogeneities, which can expose bed grains and dramatically enhance turbulence (and thus entrainment[2]).
- rare strong wind gusts associated with thick natural atmospheric boundary layers[3].
- the sublimation of subsurface ice (carbon dioxide, methane, and nitrogen ice) in cold environments[4].

References (click to open):

(1) Sullivan & Kok, (JGR: ES, 2017)
(2) Diplas et al., (Science, 2008)
(3) Pähtz et al. (Geoscience, 2018)
(4) Sagan & Chyba (Nature, 1990); Jia et al. (PNAS, 2017); Telfer et al. (Science, 2018)

Saltation threshold hypothesis

Cessation- rather than initiation-limited saltation is consistent with

- field observations suggesting widespread and persistent saltation on Mars, which would be very difficult to explain if saltation initiation was an issue[1].
- field observations of widespread and persistent snow drift in Antarctica[2] in spite of a large saltation initiation threshold due to the high cohesiveness of old snow and ice grains[3].

References (click to open):

(1) Sullivan & Kok, (JGR: ES, 2017)
(2) Leonard et al. (CRST, 2011)
(3) Schmidt (JoG, 1980)

General sediment transport model (definitions)

Environmental parameters:

- Particle density ρ_p [kg/m^3]
- Particle diameter d [m]
- Fluid density ρ_f [kg/m^3]
- Kinematic fluid viscosity ν_f [m^2/s]
- Fluid shear stress τ [N/m^2]
- Sediment transport rate Q [kg/(m.s)]
- Gravitational constant g [m/s^2]

Dimensionless numbers:

Density ratio: $s \equiv \rho_p/\rho_f$

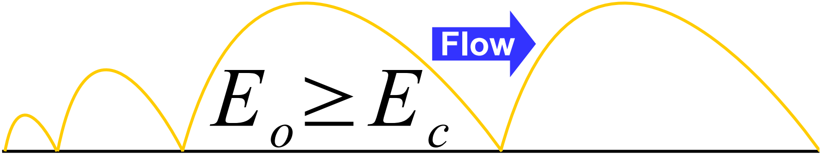
Galileo number: $\mathrm{Ga} \equiv d\sqrt{(s-1)gd}/\nu_f$

Shields number: $\Theta \equiv \tau/[(\rho_p - \rho_f)gd]$

Dimensionless transport rate: $Q_* \equiv Q/\left[\rho_p d\sqrt{(s-1)gd}\right]$

Cessation threshold conceptualization:

- Particle hop in nonfluctuating wall-bounded flow
- $E_{\uparrow(\downarrow)}$ = kinetic energy immediately after (before) a rebound
- $\theta_{\uparrow(\downarrow)}$ = rebound (impact) angle; $E_o \equiv E_\uparrow(t = 0)$
- Mean rebound laws from experiments: $(E_\uparrow/E_\downarrow, \theta_\uparrow) = f(\theta_\downarrow)$
- Cohesive DEM simulations: rebounds independent of cohesion



- For sustained motion, a critical energy E_c must be exceeded:
- If $E_o \geq E_c(\Theta, \mathrm{Ga}, s)$, a periodic trajectory is approached.
- If $E_o < E_c(\Theta, \mathrm{Ga}, s)$, no motion is approached.
- For $\Theta < \Theta_t(\mathrm{Ga}, s)$, only trivial solutions exist ($E_c = \infty$).

Θ_t is the cessation threshold (independent of cohesion).

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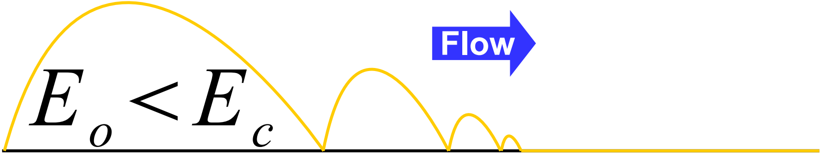

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Outline of mathematical model[1] for cessation threshold Θ_t:

1. For given values of Ga and s, find all periodic trajectory solutions $\Theta(\mathrm{Ga}, s, E_\uparrow)$ (various analytical solutions exist[1,2]).
2. Only consider particle trajectories with a rebound energy that exceeds the potential barrier energy E_b set by the pockets of the bed surface: $E_\uparrow \geq E_b$.
3. Consider that E_b is weakened by the near-surface flow. In particular, E_b vanishes when Θ exceeds the yield stress (important for bedload).
4. Obtain the cessation threshold from the trajectory for which Θ is minimal: $\Theta_t = \min_{E_\uparrow} \Theta[\mathrm{Ga}, s, E_\uparrow \geq E_b(\Theta)]$.
5. Minimization yields also the dimensionless threshold average particle velocity $\overline{v_x}_{*t}$ and rebound friction coefficient $\mu_b \equiv \left.\frac{v_{\downarrow x} - v_{\uparrow x}}{v_{\uparrow z} - v_{\downarrow z}}\right|_t$.

References (click to open):

(1) Pähtz et al. (RoG, 2020); Pähtz et al. (submitted, 2020)
(2) Jenkins & Valance (POF, 2014); Berzi et al. (JFM, 2016); Berzi et al. (JGR: ES, 2017)

General sediment transport model (transport rate)

From Θ_t, $\overline{v_{x*t}}$, and μ_b, we obtain dimensionless transport rate Q_* using the momentum and energy balances of transported particles[1]:

$$Q_* = M_* \overline{v_{x*t}}(1 + c_M M_*), \quad \text{with} \quad M_* = \frac{1}{\mu_b}(\Theta - \Theta_t),$$

where $c_M = 1.7$ (from DEM-based sediment transport simulations).

Notes on combined general model for Θ_t and Q_*:

- Model does not contain parameters fitted to cessation threshold or transport rate measurements.
- Model does not contain elements associated with cohesive interparticle forces.
- $\sqrt{\Theta_t}$ is identical to Bagnold's threshold parameter A.
- Q_* is the (Hans Albert) Einstein-rescaling of the transport rate, typically used in fluvial geomorphology (see slide #7).

Reference (click to open):

(1) Pähtz & Durán (PRL, 2020)

Experimental and numerical validation

DEM-based sediment transport simulations:

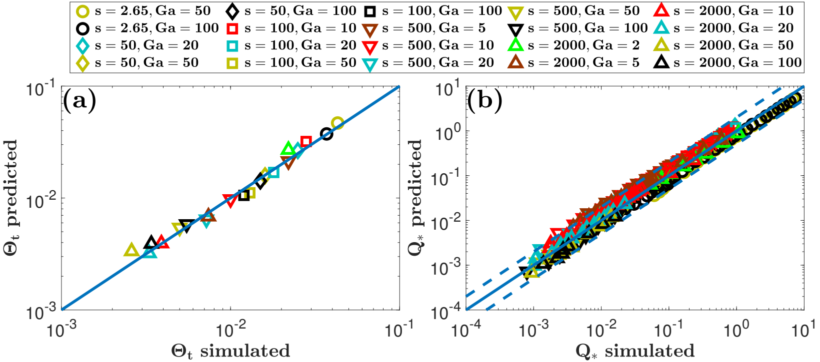

Figure: Test of general model against data from DEM-based sediment transport simulations. Both Θ_t and Q_* are predicted using only the simulation control parameters s (density ratio), Ga (Galileo number), and Θ (Shields number) as input. Solid lines indicate perfect agreement, dashed lines in (b) a deviation by a factor of 2.

Experimental and numerical validation

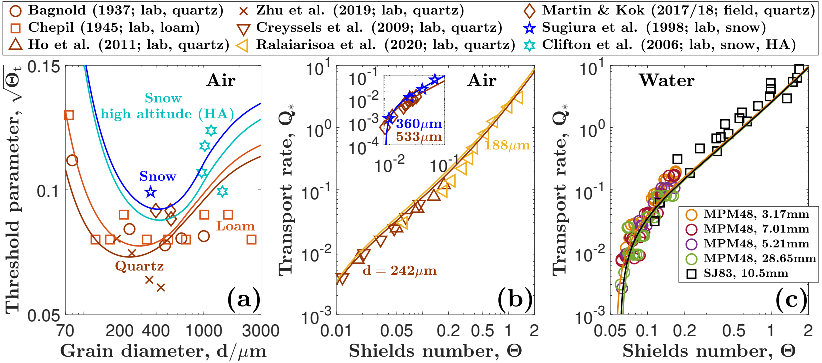

Figure: Test of general model against experimental data in air[1−3] and water[4]. Note that the increase of $\sqrt{\Theta_t}$ for small $d \lesssim 200\ \mu$m is captured.

References (click to open):

(1) Bagnold (TGJ, 1937); Chepil (Soil Science, 1945); Martin & Kok (JGR: ES, 2018); Zhu et al. (JGR: ES, 2019)
(2) Creyssels et al. (JFM, 2009); Ho et al. (PRL, 2011); Martin & Kok (Science Advances, 2017)
(3) Sugiura et al. (CRST, 1998); Clifton et al. (JoG, 2006); Ralaiarisoa et al. (PRL, 2020)
(4) Meyer-Peter & Müller (TU Delft, 1948) after Wong & Parker (JHE, 2006); Smart & Jaeggi (ETH Zürich, 1983)

Implications for extraterrestrial saltation

Findings (most plots not shown to avoid copyright issues):

- Significant saltation with active dust cycles on Earth, Mars, and Titan (bedload on Venus)
- Potential marginal transport on Triton and Pluto
- Westward storms on Titan too weak to move sand, therefore eastward dune propagation

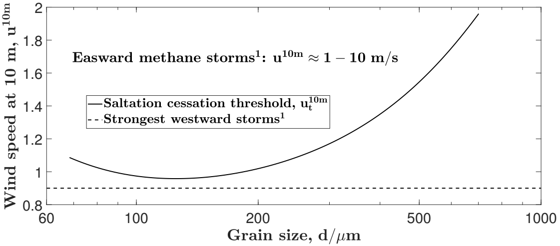

Figure: Strongest westward winds on Titan below cessation threshold.

Reference (click to open):

(1) Charnay et al. (Nature Geoscience, 2015)

Conclusions

Question:

Planetary saltation: Should we care about cohesion?

Our answer:

Cohesion has a negligible influence on the occurrence of aeolian saltation.

References regarding results (click to open):

Comola et al. (Geophysical Research Letters **46**, 5566–5574, 2019)
Pähtz et al. (Reviews of Geophysics **58**, e2019RG000679, 2020)
Pähtz & Durán (Physical Review Letters **124**, 168001, 2020)
Pähtz et al. (submitted, 2020)