Bed load dynamics at the onset of motion

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Introduction

**Bed load:** transport of heavy sediment material by a fluid along an erodible bed.

→ **Complexity**
- Granular media
- Turbulent Flow
- Naturally instable

→ At the onset of motion, the complexity is increased
→ Large dispersion on the value of the stress « threshold» of particle motion
**Introduction**

Laminar flow (Re<3); Small plastic beads $St = Re_p \rho_p / \rho_f \sim 10^{-2}$

Houssais et al., *Onset of sediment transport is a continuous transition driven by fluid shear and granular creep*. Nature communications, *2015*
Introduction

Clark et al., *Onset and cessation of motion in hydrodynamically sheared granular beds*. Physical review E, 2015

Simulation DEM
+ model drag, $St \sim 10^{-1} - 10^{3}$

Contrainte

$Nb. \text{ de Stokes}$
Introduction


Turbulent flow \((Re>10^4)\)

Large grains, \(St = \frac{Re_p \rho_p}{\rho_f} \sim 10^3\)

Clustering of particles
Motivations

What are the dominant transport dynamics close to the motion threshold?

→ in the case of high Stokes number

Methods

• Measurements at the grain scales (spatially and temporally)
• Large data-sets (since transport is intermittent)
Experimental setup

Acquisition system:
- 2 cameras
- 200 frames/s
- 16 pixels/d_{50}

\[ d = 6.4 \text{ mm} \]
\[ w_s = 0.55 \text{ m/s} \]
\[ \text{St,Re}_p \sim 10^3 \]
\[ -0.3 < \tan \theta < 0.1 \]
Méthodes expérimentales

Automated Particle Tracking Algorithm

(Available at https://goo.gl/p4GbsR)

~ 40 sequences of 150 s at 200 fps (~1.2 million images)

Particle trajectories in space-time plane
Variables

Position \( \vec{x}_p(t) \)

Speed \( \vec{v}_p(t) = \frac{\vec{x}_p(t + 1) - \vec{x}_p(t - 1)}{2\Delta t} \),

Acceleration \( \vec{a}_p(t) = \frac{\vec{x}_p(t + 1) + \vec{x}_p(t - 1) - 2\vec{x}_p(t)}{\Delta t^2} \),

...and other variables: - water depth-average velocity and shear velocity
- water depth
- bed elevation and slope...
On-board camera following a bedload particle

\[ ||\vec{u}|| = 0.83 \text{ m.s}^{-1} \quad ||\vec{a}|| = 4.69 \text{ m.s}^{-2} \quad ||\omega|| = 2.01 \text{ tr.s}^{-1} \]
Results

1) Kinematics

2) Deposition
Results / Particle velocity
Results / Particle velocity

Shear velocity $u_*/w_s$

$\langle u_p \rangle$ : Average particle velocity
$\sigma_{u_p}$ : Standard deviation
$w_s$ : Settling velocity
$\bar{u}$ : Average flow velocity
$u_*$ : Shear velocity

\begin{align*}
\langle u_p \rangle & = 3.63u_* - 0.06w_s \\
& = 0.57\bar{u} - 0.16w_s \\
\end{align*}
Results / Particle velocity

Gaussian-distributed particle velocities

\[ P(u_p) \]
\[ P(u_p | z_p \leq 0) \]
\[ P(u_p | z_p > 2d_{50}) \]

\[ \mathcal{N}(3.3, 2.2) \]
\[ \mathcal{N}(6.9, 1.5) \]
\[ \mathcal{E}(3.1) \]

\[ \langle u_p \rangle : \text{Average particle velocity} \]
\[ \sigma_{u_p} : \text{Standard deviation} \]
\[ w_s : \text{Settling velocity} \]
\[ \bar{u} : \text{Average flow velocity} \]
\[ u_* : \text{Shear velocity} \]
Results / Particle acceleration
Résultats / Accélérations

\[ \phi_s = 36^\circ \]

\[ v_{\text{trap}} \propto \sqrt{2gd(1 - \cos[\phi_s - \theta])} \]
\[ \approx 0.14 \, \text{m/s} \]
\[ \approx u_* \]
Dynamics of a grain on a sandpile model

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(Received 5 June 2000)

The dynamics of a macroscopic grain rolling on an inclined plane composed of fixed identical investigated both experimentally and theoretically. As real sand, the system exhibits an hysteretic between static and dynamical states for angles smaller than $\varphi$. The rolling dynamics start for angles $\varphi < 4^\circ$. The force acting on the roller is plotted as a function of the velocity for different angles: $\varphi = 4^\circ$ (long-dashed line), $\varphi = \varphi_d$ (solid line), $\varphi = 14^\circ$ (dashed line), $\varphi = 19^\circ$ (dotted line), $\varphi = 24^\circ$ (dotted-dashed line), and $\varphi = \varphi_s$ (solid line).

FIG. 12. Continuous model of the force globally acting on the roller. The force is plotted as a function of velocity for different angles.
Results

1) Kinematics

2) Deposition
Résultats / Déposition
Definitions:

Particle deposition rate: \( r_\downarrow p \text{ [s}^{-1}] \)

Dimensionless Particle deposition rate: \( r^*_p = r_\downarrow p \frac{d_{50}}{w_s} \)
Dependence of deposition rate to shear velocity:

Mean deposition rate pdf of shear velocities at deposition sites

\[ r^{*} \downarrow_{p} (u_{*}) = \langle r^{*} \downarrow_{p} \rangle \frac{f_{u_{*}} D}{f_{u_{*}}} \]

pdf of shear velocities anywhere*

*: on particle trajectories

Deposition sites

\[ \text{Distance (m)} \]

\[ \text{Time (s)} \]

\[ u_{*} \]

\[ 0 \]

\[ 1 \]

\[ 0 \]

\[ 0.2 \]

\[ 0.4 \]

\[ 0.6 \]

\[ 0.8 \]

\[ 1 \]

\[ 0 \]

\[ 50 \]

\[ 100 \]

\[ 150 \]
Various spatial averages of the shear velocity.
Results / Deposition

Remember Trapping!

\[ u_p < v_{\text{trap}} \]

\[ u_p > v_{\text{trap}} \]

Probability of being trapped

\[ P(u_p) \]

\[ P(u_p < v_{\text{trap}}) \]

\[ r_{\downarrow p}^* \approx 0.08 P(u_p < v_{\text{trap}}) \]

DEPOSITION ↔ TRAPPING?
Resuming:

\[
\langle u_p \rangle \approx 3.65u_* - 0.06w_s \\
\sigma_{u_p} \approx 1.38u_* + 0.15w_s \\
u_p \sim \text{Gaussian} \\
v_{\text{trap}} \approx 0.11 \text{ m/s} \\
r^*_p \propto P(u_p < v_{\text{trap}})
\]

\[
P(u_p < v_{\text{trap}}) = \text{erfc} \left[ \frac{\langle u_p \rangle - v_{\text{trap}}}{\sqrt{2} \sigma_{u_p}} \right]
\]

\[
r^*_p \propto \text{erfc} \left[ \frac{3.65u_* - 0.06w_s - v_{\text{trap}}}{\sqrt{2}(1.38u_* + 0.15w_s)} \right]
\]
Conclusions

A large experimental dataset of particle trajectories
(available online at https://goo.gl/p4GbsR )

\[ \text{Re}_p, \text{St} \approx 10^3, \quad \frac{\rho_p}{\rho_f} = 2.5, \quad \tan \theta \approx 0 - 30\% \]

Close to the onset of motion

- 2 equilibrium particle velocities: 0 and the depth-average flow velocity
- Deposition rates increase dramatically while decreasing flow strength
- Trapping mainly govern particle deposition
Outlook

→ Particle entrainment is triggered by particles in motion

→ ~ Splash ?!