Particle Entrainment under Turbulent Flow Conditions

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Backyard Erosion
Coastal Erosion
Gully Erosion
River with Heavy Sediment Load
2. Boulder deposited on the Hwy 35 roadbed. More of these bad boys went into Mineral Creek where they were dug out just today (1/23/07)
3. Hwy 35 bridge over White River completely plugged underneath by 25 ft of rock, and the bridge itself buried. This is the downstream side.
4. 200 yards north of the bridge, the river found a new route where iron Creek used to flow thru the 5 ft culvert. The river was later placed into two 8 ft culverts here to carry the water during the re-opening of the main channel and they will remain for future emergencies.
Pier foundation exposure due to river bed degradation, Cache River, CA
Soil Erosion/Contaminant Transport

- Overall erosion of the continental surface via water and wind amounts to 80 bn metric tones annually; 20 bn of the eroded sediment is delivered by rivers to the oceans.

- The redistribution of material over the surface of the earth affects most of its physical, chemical and biological processes in ways that are not understood and which are exceedingly difficult to comprehend.

- Dynamic interplay between fluctuating turbulent fluid forces and particle dislodgement for flows over an erodible boundary constitutes the central problem in earth surface dynamics and many industrial processes.
Early Laboratory Studies:

Bed Material Transport
Outline

• Background – Need for a new threshold of motion criterion
• New hypothesis
• Particle dislodgement due to an instantaneous *drag force* – Electromagnet simulation experiments (fully exposed particle - rolling motion)
• Analytical solution to particle dislodgement
  – Due to instantaneous *lift force* (hidden particle - saltation)
  – Due to instantaneous *lift and drag forces* (exposed particle-rolling)
• Results from laboratory flume experiments
• Conclusion
Background

• Traditional approach for identifying threshold of motion conditions
  – Time-averaged characterization of boundary shear stress (Shields, 1936)

• Wide recognition of the role of instantaneous forces in turbulent flows on particle entrainment (Varenious 1650)

• Quantitative determination of the influence of turbulent fluctuations on threshold condition is rare
Present Initiation of Motion Criterion

Shields (1936)
Fluctuating turbulent fluid forces applied on a sediment particle located at the bottom of a channel flow

Are velocity spikes responsible for particle dislodgement?
Earlier VT study

Question

• Do all peak instantaneous turbulent events (higher than a critical value) result in particle entrainment?
Experimental Set Up

Side view of test test section
Mobile particle: 8 mm Viton ball
Retaining pin to inhibit complete particle dislodgement
Detecting Particle Dislodgement: Experimental Set-up

- He-Ne Laser Tube
- Flow
- Opaque Wall
- Plexiglass Flume Walls
- PMT View
- Focal lens
- LDV Beams
- Beam expander
- PC
- 2D LDV Signal
- DLINK

Plan View

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Virginia Tech Experiments

Some of the velocity spikes correspond to particle entrainment, but not all
Early Laboratory Studies:

Bed Material Transport
Result

- High instantaneous velocity values (which lead to large instantaneous drag forces) are necessary but not sufficient to dislodge a sediment particle
Hypothesis

• Force duration, besides force magnitude, is important in identifying threshold of motion conditions. A simple way to account for both aspects is to consider \textit{impulse} as the appropriate parameter.
Simulation of Instantaneous Drag Force with an Electromagnet
Electromagnet Experimental Setup

Laptop with LabView 7.1 generating pulses for output and reading back analog input voltages

LabView

Data Acquisition system for analog to digital conversion for both output and input

NI DAQPad 6015

SC-2345

Signal conditioner with feed through modules

Amplification Circuit

Amplifies voltages sent to electromagnet and de-amplifies voltages to appropriate range for DAQ system read in

Power supply for amplification circuit

Electromagnet
Experimental Setup

- Spherical particles
- Controllable magnetic forces
- Easiest path of motion
- “Drag” force only, no “lift”
Experiment Objectives

- Determine *steady state threshold* voltage value necessary to remove the ball from its pocket
- Determine minimum pulse duration to remove the ball from its pocket at various voltages
- Relate voltages and pulse durations to impulse required to remove particle from pocket
Experiment Objectives

- Determine minimum voltage pulse duration and amplitude combinations necessary for dislodging the ball from its pocket
Pulse Duration: 15 ms; Increase amplitude until ball dislodgement occurs
Experiments

Same Geometry

Equal Distance

Side view

Top view

- 7 Setups
- 3 repeatable pulses
- 1709 experiments
Experiment Objectives

• Relate voltages and pulse durations to impulse required to remove particle from pocket

Electromagnetic Force

\[ F = \frac{\mu AN^2 I^2}{h^2} \]

Constant for magnet

Constant for experiment

Ohm’s Law

\[ V = IR \rightarrow I = \frac{V}{R} \]

\[ F \propto V^2 \]
Equal Distance Experiments

\[ y = 892.38x^{-1.0685} \]
\[ R^2 = 0.9768 \]

\[ y = 958.09x^{-0.9535} \]
\[ R^2 = 0.9834 \]

\[ y = 1048.3x^{-0.981} \]
\[ R^2 = 0.9816 \]

\[ y = 1109.7x^{-0.887} \]
\[ R^2 = 0.9785 \]
# Best Fit Results

<table>
<thead>
<tr>
<th>Ball Size</th>
<th>Bed Size</th>
<th>Distance from Magnet</th>
<th>Best-fit Equation</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 mm</td>
<td>8 mm</td>
<td>6.31 mm</td>
<td>$V^2 = 958.09 \ T^{-0.9535}$</td>
<td>0.9834</td>
</tr>
<tr>
<td>6 mm</td>
<td>6 mm</td>
<td>4.73 mm</td>
<td>$V^2 = 745.33 \ T^{-1.0018}$</td>
<td>0.9821</td>
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<tr>
<td>4 mm</td>
<td>4 mm</td>
<td>3.15 mm</td>
<td>$V^2 = 449.27 \ T^{-1.0316}$</td>
<td>0.9559</td>
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<tr>
<td>8 mm</td>
<td>6 mm</td>
<td>6.31 mm</td>
<td>$V^2 = 892.38 \ T^{-1.0695}$</td>
<td>0.9768</td>
</tr>
<tr>
<td>6 mm</td>
<td>8 mm</td>
<td>6.31 mm</td>
<td>$V^2 = 1714.5 \ T^{-1.0347}$</td>
<td>0.9829</td>
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<tr>
<td>6 mm</td>
<td>6 mm</td>
<td>6.31 mm</td>
<td>$V^2 = 1048 \ T^{-0.9810}$</td>
<td>0.9816</td>
</tr>
<tr>
<td>4 mm</td>
<td>6 mm</td>
<td>6.31 mm</td>
<td>$V^2 = 1109.7 \ T^{-0.887}$</td>
<td>0.9785</td>
</tr>
</tbody>
</table>
Best Fit Results

6mm on 6mm at a distance of 4.73mm

Equation

\[ V^2 = 745.33 \cdot T^{-1.0018} \]

\[ F \propto V^2 \]

\[ F = 745.33 \cdot T^{-1.0018} \]

\[ F \cdot T^{1.0018} = 745.33 \]

\[ F \cdot T = \text{Impulse} \]

Impulse = Constant
Electromagnet Experiments

\[ F_D = 0.96 T_D^{-0.99} \]

<table>
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<th>d_1 (mm)</th>
<th>d_2 (mm)</th>
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<tr>
<td>8</td>
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<tr>
<td>4</td>
<td>6</td>
</tr>
</tbody>
</table>
Grain Dislodgement via Saltation and Rolling Modes-Analytical Approaches

(a)

(b)
Theoretical Lift Analysis

\[ F_L \]

\[ \nabla (\rho_s - \rho_f)g \]

\[ F \]

\[ F_L \]

\[ T_L \]

\[ t \]
Theoretical Rolling Analysis with both Lift & Drag Forces Present
Theoretical Rolling Analysis with Zero Lift Force
Threshold Surfaces for Saltation & Rolling Motion for an Exposed Particle
Flume Experiments

• Simultaneous measurements of flow velocities with a 2D LDV system and test particle dislodgement (as well as particle trajectory) using non-intrusive laser based techniques.
Flume Experiments

Top view of the pocket geometry

LDV measurement volume

12.7 mm

4th layer

3rd layer

8 mm

Flow
Flume Experiments
Conclusion

• The *critical impulse* concept is more fundamental than that of *critical force* in characterizing threshold of particulate motion.
Credits

• Dr. Clint Dancey
• Dr. Tanju Akar (Postdoc)
• Krista Greer (MS student)
• Manousos Valyrakis (PhD student)
• Ozan Celik (PhD student)
• Brad Dillon (MS student)
• National Science Foundation
How many years can a mountain exist
Before it's washed to the sea?

The answer, my friend, is blowin' in the wind,
The answer is blowin' in the wind.

“Blowin’ in the wind” Bob Dylan (1962)