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RPPR Final Report

as of 05-Feb-2019

Agency Code:

Proposal Number: 64455EV

Agreement Number: W911NF-13-1-0458

INVESTIGATOR(S):

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Final Report for Period Beginning 23-Sep-2013 and Ending 22-Sep-2017

Title: Granularity and Jamming: A New Approach to Understanding and Predicting Near-Threshold Sediment Transport

Begin Performance Period: 23-Sep-2013

End Performance Period: 22-Sep-2017

Report Term: 0-Other

Submitted By: Douglas Jerolmack

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STEM Degrees: 1

STEM Participants: 1

Major Goals: Landscape evolution, such as the formation and erosion of rivers, results from fluid-driven sediment transport. Predicting sediment transport rates is essential for modeling landscape change and protecting infrastructure. Current approaches, which typically focus on fluid dynamics while neglecting granular dynamics, predict transport rates that are often off by more than an order of magnitude. In this proposal we seek a new approach, that describes a river bed as the interface between a jammed disordered solid and a shearing fluid. We study bed load particles, particles frequently in contact with the river bed, because they probe the near-yield phase space along this jammed-flowing interface. However, the very concept of yielding on this interface is slippery, and historical approaches to understand this phenomenon emphasize momentum-based hydrodynamic transport laws, which break down for intermittent bed load transport. The effects of collective particle modes and mechanical constraints have a contribution of growing importance on the interfacial dynamics near-yield, which could be understood as a type of jamming transition, but data exploring these effects are lacking. We seek to experimentally acquire data on the most fundamental variables characterizing the dynamics of grains driven by a fluid, the positions and velocities of particles in the bed, using unobtrusive but direct methods. To do so, we have pursued two strategies. In the lab we have constructed a unique apparatus, in order to extract the positions of every particle in a region of space using the method of refractive-index matching and laser scanning. We are also working to compare findings from this small, viscous experiment with a larger 2D flume in which inertial effects (particle collisions and fluid turbulence) are significant, to isolate the origins of observed dynamics.

Accomplishments: 1. The onset of erosion of a granular bed by a fluid is a continuous phase transition. Contrary to our hypothesis, it is not a "jamming" transition, but is rather consistent with a "glass transition" from creeping to flowing. This transition occurs at a critical dimensionless shear rate that is identical for dry granular flows and viscous granular suspensions.

2. Unification of bed load and suspension river transport with a common granular rheology. We showed that a recently developed granular-suspension rheology can also successfully describe the rheology of river-sediment transport across the dense to dilute regime.

3. Grain size segregation in a river is a granular phenomenon and occurs in two phases: (i) rapid segregation due to shear-rate dependent advection in the bed-load layer; and (ii) slow diffusion-limited segregation due to shear-rate independent creep.

4. Collision-driven river sediment transport exhibits collective entrainment, in which a particle colliding with the bed

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induces clusters of particles to move. These dynamics follow generic avalanching behavior seen in, e.g., sandpiles.

5. The creep to landslide transition on hillsides is identical to fluid-driven river sediment transport, and follows a recently proposed glass transition associated with percolation of plastic rearrangements.

Training Opportunities: Postdocs trained:

1. Morgane Houssais, POSTDOC: currently a postdoc at the Levich Institute at City College in New York.
2. Carlos Ortiz, POSTDOC: now a consultant at Deloitte in Philadelphia.
3. Behrooz Ferdowsi, POSTDOC: currently a Hess fellow at Princeton University.
4. Dylan Lee, GRADUATE STUDENT: completed his thesis with partial support from this program.

These trainees collaborated with myself and Doug Durian in Physics and Astronomy to design and develop original experiments, perform challenging processing and analysis of experimental data, and interpret these data using concepts from modern soft-matter physics and geophysics.

Results Dissemination: 1. Six peer reviewed publications resulted from this work.

2. New code developed for particle tracking in very challenging conditions has been posted freely available online as part of these papers and in online repositories.
3. PI has given a large number of talks at national and international conferences in Earth science, physics and engineering, and also departmental seminars. PI has also delivered popular science talks to the public in Philadelphia, and recorded lectures as part of the Kavli Institute for Theoretical Physics visitors program.

Honors and Awards: 1. Promotion to Full Professor, 1 July 2018.

2. Kavli Institute for Theoretical Physics (KITP) Visiting Scholar, Spring 2018.
3. 2016 Gordon Warwick Medal: Made for excellence in geomorphological research by someone within 15 years of being awarded their doctorate, by the British Society for Geomorphology.
3. Keynote Speaker at 2016 Binghamton Symposium in Connectivity in Geomorphology.

Protocol Activity Status:

Technology Transfer: 1. Dr. Paramsothy Jayakumar from TARDEC visited our lab to discuss potential research coordination on 24 October 2016. We are examining possibilities for a TARDEC postdoc.

2. Met with Christopher Hocut from ARL-CISD on 11 December 2018 to coordinate research connecting atmospheric boundary layer flows to sand and dust transport at White Sands New Mexico. We are now in the process of scheduling a follow up visit to their lab to share data and methods, and to seek research collaboration.

Nothing else to report.

PARTICIPANTS:

Participant Type: Graduate Student (research assistant)

Participant: Andrew Gunn

Person Months Worked: 12.00

Funding Support:

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

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First Page #: 4827

Date Submitted: 2/4/19 12:00AM

Date Published: 5/1/18 4:00AM

Publication Location:

Article Title: Glassy dynamics of landscape evolution

Authors: Behrooz Ferdowsi, Carlos P. Ortiz, Douglas J. Jerolmack

Keywords: granular flow | creep | landscape evolution | dynamical phase transition

Abstract: Soil creeps imperceptibly downhill, but also fails catastrophically to create landslides. Despite the importance of these processes as hazards and in sculpting landscapes, there is no agreed-upon model that captures the full range of behavior. Here we examine the granular origins of hillslope soil transport by discrete element method simulations and reanalysis of measurements in natural landscapes. We find creep for slopes below a critical gradient, where average particle velocity (sediment flux) increases exponentially with friction coefficient (gradient). At critical gradient there is a continuous transition to a dense-granular flow rheology. Slow earthflows and landslides thus exhibit glassy dynamics characteristic of a wide range of disordered materials; they are described by a two-phase flux equation that emerges from grain-scale friction alone. This glassy model reproduces topographic profiles of natural hillslopes, showing its promise for predicting hillslope evolution over geol

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Article Title: Determining the scales of collective entrainment in collision-driven bed load

Authors: Dylan B. Lee, Douglas Jerolmack

Keywords: bed load, avalanche, collective motion, river

Abstract: Fluvial bed-load transport is notoriously unpredictable, especially near the threshold of motion where stochastic fluctuations in sediment flux are large. Laboratory and field observations suggest that particles are entrained collectively, but this behavior is not well resolved. Collective entrainment introduces new length scales and timescales of correlation into probabilistic formulations of bed-load flux. We perform a series of experiments to directly quantify spatially clustered movement of particles (i.e., collective motion), using a steep-slope 2-D flume in which centimeter-scale marbles are fed at varying rates into a shallow and turbulent water flow. We observe that entrainment results exclusively from particle collisions and is generally collective, while particles deposit independently of each other. The size distribution of collective motion events is roughly exponential and constant across sediment feed rates. The primary effect of changing feed rate is simply to change the

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CONFERENCE PAPERS:

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Date Received:

Conference Date: 25-Jul-2016

Date Published: 25-Jul-2016

Conference Location: Stonehill College, Easton (MA), USA

Paper Title: Granular segregation in an experimental river

Authors: B. Ferdowsi, C. P. Ortiz, M. Houssais, D. J. Jerolmack

Acknowledged Federal Support: Y

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Conference Name: American Geophysical Union Fall Meeting 2016
Date Received: Conference Date: 14-Dec-2015 Date Published: 14-Dec-2015
Conference Location: San Francisco (CA), USA
Paper Title: Granular controls on hillslope deformation and creep
Authors: B. Ferdowsi, C. P. Ortiz, D. J. Jerolmack
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Gordon Research Conference and Seminar: Particulate Systems in Science and Technology
Date Received: Conference Date: 27-Jul-2015 Date Published: 07-Jul-2015
Conference Location: Stoneham College, Easton (MA), USA
Paper Title: Understanding the coexistence of granular flow and creep regimes: a new paradigm for predicting landscape morphodynamics
Authors: Morgane Houssais, Carlos Ortiz, Douglas Jerolmack
Acknowledged Federal Support: **Y**

Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: American Physical Society March Meeting
Date Received: Conference Date: 14-Mar-2016 Date Published: 14-Mar-2016
Conference Location: Baltimore (MD), USA
Paper Title: Slow Relaxations in Fluid-Driven Granular Flows
Authors: Carlos Ortiz, Douglas Durian, Douglas Jerolmack
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Publication Type: Conference Paper or Presentation **Publication Status:** 1-Published
Conference Name: Conference on Mathematical Geophysics
Date Received: Conference Date: 20-Jun-2016 Date Published: 20-Jun-2016
Conference Location: Paris, France
Paper Title: CREEPY LANDSCAPES: THE ORIGINS AND CONSEQUENCES OF SUB-THRESHOLD TRANSPORT
Authors: C. Ortiz, B. Ferdowsi, M. Houssais, D.J. Durian, D.J. Jerolmack
Acknowledged Federal Support: **Y**

Final report for “Granularity and Jamming: A new approach to understanding and predicting near-threshold sediment transport”

Doug Jerolmack

February 4, 2019

Abstract

We report our conclusions toward developing a new granular physics approach to understanding fluid-driven sediment transport. We have completed our analysis of the rheology of laminar sediment transport, finding that bed-load and suspension follow a local granular flow model but that sub-threshold creep violates this model. A new set of experiments examined the contribution of granular segregation to river-bed armoring, i.e., the development of a coarse surficial layer of grains. Our work shows that bed-load transport in the near-surface layer drives rapid segregation while creeping grains beneath the bed-load layer give rise to slow but persistent segregation; this leads to a two-stage armoring process with distinctly different mechanisms. Numerical simulations examining the dynamics of creeping grains reveal that creep in river beds is identical to the more familiar hillslope creep — the slow downhill movement of soil. Finally, we probe entrainment of bed sediment by collisions in high-reynolds number flows, and find that it is collective and behaves similar to avalanches.

1 Statement of the problem studied

(Note: this section is similar to last year’s report, with some modifications.) Landscape evolution, such as the formation and erosion of rivers, results from fluid-driven sediment transport. Predicting sediment transport rates is essential for modeling landscape change and protecting infrastructure. Current approaches, which typically focus on fluid dynamics while neglecting granular dynamics, predict transport rates that are often off by more than an order of magnitude. In this proposal we seek a new approach, that describes a river bed as the interface between a jammed disordered solid and a shearing fluid. We study bed load particles, particles frequently in contact with the river bed, because they probe the near-yield phase space along this jammed-flowing interface. However, the very concept of yielding on this interface is slippery, and historical approaches to understand this phenomenon emphasize momentum-based hydrodynamic transport laws, which break down for intermittent bed load transport. The effects of collective particle modes and mechanical constraints have a contribution of growing importance on the interfacial dynamics near-yield, which could be understood as a type of jamming transition, but data exploring these effects are lacking. We seek to experimentally acquire data on

the most fundamental variables characterizing the dynamics of grains driven by a fluid, the positions and velocities of particles in the bed, using unobtrusive but direct methods. To do so, we have pursued two strategies. In the lab we have constructed a unique apparatus, in order to extract the positions of every particle in a region of space using the method of refractive-index matching and laser scanning. We are also working to compare findings from this small, viscous experiment with a larger 2D flume in which inertial effects (particle collisions and fluid turbulence) are significant, to isolate the origins of observed dynamics.

2 Summary of the most important results

2.1 Experimental description

This grant has supported the development of a unique laboratory experimental setup. The experiment has been described in detail in previous reports and also in our two related research papers. We summarize the setup here for completeness, and refer the reader to our recent publication (*Houssais et al., Nature Comm., 2015*) for full details. We study an experimental model river, composed of acrylic spheres immersed in silicon oil, driven by a layer of fluid under steady shear. We choose to drive fluid flow in the laminar regime ($Re < 1$) to suppress fluid turbulence and isolate granular and bed structure controls. We use a refractive-index-matched laser scanning technique to observe the motion of particles at the surface of the bed as well as the particle dynamics below the surface. The apparatus is an annular couette cell, which ensures mass continuity and allows us to approximate the conditions of an infinitely long river.

We have performed an exhaustive set of experiments with a bimodal mixture of spherical grains in order to examine granular segregation. We have also continued to improve instrument control and to suppress vibration, leading to enhanced data resolution and an ability to probe slower dynamics than before.

Our experiments have generated observations of particle velocities that span seven orders of magnitude. In short, our vertical profiles of particle dynamics are the highest resolved of any granular system that we know of. A major difference between typical sheared granular systems, and fluid-driven sediment transport, is that the latter: (1) has a free-surface condition; and (2) allows slip between the driving stress (the fluid) and the surface grains. As a result, all phases of granular transport — gas, liquid and solid — occur simultaneously and are vertically stratified for a given flow. Typical experiments on sheared granular systems focus on one just one of these phases, and rarely document the nature of the transitions among them. Our experiment is the first that we know of to examine all three phases, and to quantify the dynamical transitions associated with crossing phase boundaries. Moreover, our experiments have produced the first observations of granular segregation by creep, and novel data on creeping motion of grains.

2.2 Rheology and Creeping

One of the most novel findings of this project is that particle motion does not stop at very low fluid stresses. Instead, particles slowly creep by localized, intermittent rearrangements of grains, in a manner characteristic of fragile and

disordered solids. This creep motion is likely ubiquitous, but it has never been reported in sediment transport experiments — probably because it is very slow and difficult to resolve. Last year we reported progress on the rheology of our fluid-granular system, finding that the full range of transport from the onset of bed-load through to dilute suspension could be described by the local granular friction model of *Boyer et al., Phys. Rev. Lett. 2011*. At vanishingly small fluid stress we expected to see a transition to no motion, but instead we observed creep; remarkably, this creep was associated with a (locally-derived) friction coefficient that was *below the static friction value*. That finding indicates the break down of a local model, and our results might be explained by nonlocal models such as that proposed by *Kamrin and Koval, Phys. Rev. Lett. 2012*. This work has been published as *Houssais et al., Physical Review E, 2016*.

To further understand creeping, in the past year we have adopted the glass dynamics framework of “dynamical heterogeneities” which probes the length and timescales associated with collective particle motion. In systems approaching a glass transition, it is known that particle motion slows down and also becomes more coordinated. Applying the dynamical heterogeneities framework to our sediment transport system is challenging because (1) the strong vertical anisotropy that comes from how our particles are sheared and (2) the huge range of particle velocities in our experiments. An immense amount of work has gone into further improving particle tracking in order to generate the necessary data. Accordingly, progress on this aspect of research has been delayed as we worked through technical challenges, from software to hardware to data storage. This work is finally beginning to bear fruit. Analysis indicates that the length and time scales of dynamical heterogeneities grow with depth in our system as grains go from continuous bed-load transport to suspension — as expected for a glass transition — but that this growth unexpectedly saturates in the creeping regime, a finding that has not been reported in any system. The data make clear that bed load and creep are qualitatively different from one another; the former may be described as a fluid when sufficiently coarse-grained, while the latter shows spatially heterogeneous dynamics even at the largest scales. These results reveal another aspect of the strange nature of creep. This work is currently in preparation for a manuscript.

2.3 Grain size segregation

Gravel-river beds typically have an “armored” layer of coarse grains on the surface, which acts to protect finer particles underneath from erosion. Our work has shown that river bed-load transport is a kind of dense granular flow, and such flows are known to vertically segregate grains. The contribution of granular physics to river-bed armoring, however, has not been investigated. Current models in the geophysical literature are all predicated on the idea that grain-size sorting occurs on the surficial layer of grains, as fine particles are preferentially removed leaving behind a coarse lag. To examine whether sub-surface granular motion by bed load and creep contributes to armoring, we have conducted a set of experiments using bimodal sediment sizes subject to a range of fluid stress conditions. Importantly, the annular flume conserves mass so that no grains are removed from the system; any segregation that results cannot therefore be a consequence of removal of fine grains.

No experiment to date has examined segregation in a system with creep,

and no river experiment has tracked the motion of particles in order to relate granular dynamics to armor development. Our findings are thus equally novel for geomorphology and granular physics. We find that armor develops by two distinct mechanisms. Bed-load transport in the near-surface layer drives rapid segregation, with a vertical advection rate proportional to the granular shear rate. A relation between vertical segregation and horizontal shear has been proposed by previous researchers, but never directly observed in experiment. Creeping grains beneath the bed-load layer give rise to slow but persistent segregation, which is diffusion dominated and insensitive to shear rate. We adapted a continuum phenomenological model that had been previously developed for dry granular flows. By explicitly accounting for the velocity profiles in bed load and creep, this advection-diffusion model quantitatively reproduces observed segregation rates. To demonstrate unequivocally that the observed armoring in our fluid-grain mixture was the result of granular (and not fluid) segregation alone, we also performed simulations using the discrete element method (DEM) of a granular system with no fluid. By accounting only for the effect of the fluid on the coefficient of restitution (viscous damping), we find that the DEM is in quantitative agreement with our experiments. These results suggest that river beds armor by granular segregation from below — rather than fluid-driven sorting from above — while also providing new insights on the mechanics of segregation that are relevant to a wide range of granular flows. This work was published as *Ferdowsi et al., Nature Comm., 2017*.

2.4 Linking river and hillslope creep

The transition from bed load to creep in our river experiments bears many of the hallmarks of a glass transition — i.e., a diverging viscosity (or friction coefficient) on approach to a critical point, with creeping motion below that critical point. Experiments allow us to track particle motion, but not to measure forces. Also, our experimental technique does not allow examination of dry granular flows, as it relies on refractive-index matched fluid and grains. Accordingly, we have conducted a wide range of DEM simulations — numerical experiments — to examine whether creeping, and the transition from creeping to flowing, is the same in dry and wet granular systems. In geomorphology, creep is typically associated with the exceedingly slow downslope motion of soil in hillsides, although the mechanics of this process have not been studied in detail. Since our experiments were the first to report creep in a 'river' setting, it is unknown whether river and hillslope creep are the same thing.

Our DEM simulations show an identical rheology to the flume experiments, verifying that granular friction is correctly represented in the model. Results also show that other aspects of creep, such as the velocity profile and collective particle motion, are the same in both systems. This work suggests indeed that hillslope and river creep are the same. Perhaps more surprising is that the DEM simulations, which use a collection of dry cohesionless grains with only slight variation in grain size, are able to reproduce the dynamics of creeping and land-sliding soil that are reported from natural hillslopes. In particular, we find that the velocity of creeping grains exhibits an exponential dependence on the local friction, and show that this produces a better fit to field data than all previously proposed transport relations. At the critical friction, creep transitions rapidly to a dense granular flow; this transition also mimics the pattern seen in field data.

These findings demonstrate that the creep to landslide/bed-load transition is a glass transition, and show how consideration of fundamental granular physics can yield qualitative new insight and quantitatively superior predictive power in geomorphology. These findings were published as *Ferdowsi et al., PNAS, 2018*.

2.5 Collective particle entrainment due to collisions

The annular flume results reported above pertain to viscous bed-load transport, where collisions are suppressed by the fluid. Cobbles in rivers are highly inertial, and bed-load transport involves significant transfer of momentum by collisions. To probe this regime we performed experiments in a different flume, where marbles were fed one at a time to a model river, and their motion tracked as they bounced over a marble bed. We found that entrainment of (nearly-)static bed particles invariably resulted from collision and not hydrodynamic stresses, and that this entrainment was collective. Interestingly, the number of particles collectively entrained did not change with increasing overall transport rate, but the frequency of entrainment events did. We offer an explanation for the scales of “bursty” bed-load transport in rivers, which may be introduced into recently developed statistical mechanical descriptions of sediment transport. This work was recently published *Lee and Jerolmack, Earth Surface Dynamics, 2018*.