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RPPR Final Report
as of 05-Feb-2019

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Submitted By: Douglas Jerolmack Email: sediment@sas.upenn.edu
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STEM Degrees: 0 **STEM Participants:** 0

Major Goals: 1. Primary goal was to construct a novel experimental apparatus for examining the failure and flow of Earth materials under exquisitely controlled initial conditions. This goal was accomplished.

2. Secondary goal was to train a graduate student on the operation of this experimental flume, and to carry out first experiments to demonstrate viability of the apparatus. This was also accomplished.

Accomplishments: 1. A unique experimental apparatus was built. It has the ability to create a controlled "dam break" style experiment. Particles in a reservoir may be fluidized to varying degrees, allowing us to prepare densely packed to fully liquefied grain-fluid mixtures. A knife gate opens to allow this mixture to flow out into a channel. A granular front retreats backward, and creates a flow; we track both. A laser and camera instrumented cart moves with the retreating granular front, tracking how particles move into the front and mix with fluid. Another stationary setup downstream examines the flow developed from the failing front.

2. We have demonstrated the capability to create distinct modes of failure: (i) initially compacted sand in water produces "breaching", in which the front slowly fails to create a dilute particulate "turbidity current" but does not collapse rapidly due to pore pressure suction at the face; and (ii) slumping, where an initially dilated bed rapidly collapses to create a dense-granular "debris flow". We have also shown capability to measure the necessary fluid and particle behaviors to understand these dynamics. In short, we have shown the experiment can do what we hoped it would.

3. Graduate student Andrew Gunn helped to construct the flume with the hired contractor. He is fully trained in its operation, and is leading independent experiments.

Training Opportunities: PhD student Andrew Gunn helped to assemble and trouble shoot this complex apparatus. He has led development of the instrumentation suite, and conducted experiments that are part of his PhD thesis.

Masters student Jad Daif helped to develop code for controlling the experiment and analyzing results.

Results Dissemination: Four conference proceedings from graduate student Andrew Gunn have been presented.

In addition, PI Jerolmack has communicated some new results of this work in departmental seminars delivered at various universities across the USA.

Honors and Awards: 1. 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.

2. Keynote Speaker at 2016 Binghamton Symposium in Connectivity in Geomorphology.

Protocol Activity Status:

Technology Transfer: Nothing 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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Participant: Jad Daif
Person Months Worked: 6.00 **Funding Support:**
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Authors: Jad Daif, Andrew Gunn, Douglas Jerolmack
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Authors: Andrew Gunn, Douglas Jerolmack
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RPPR Final Report
as of 05-Feb-2019

DURIP: "W911NF1610196 Novel experiment to examine failure and flow of Earth materials": **Final Report**

Dr. Douglas Jerolmack, University of Pennsylvania

1 Introduction

Much of the Earth's surface is composed of granular material; soil, sand, pebbles and boulders. Most of the time, the landscapes made from these materials appear to be static. Indeed, the infrastructure we build — such as bridges, roads, homes and fortifications — relies on the assumption of stability. When under the action of a flood, storm, earthquake or eruption the granular landscape begins to flow, the results are often catastrophic. Witness landslides and debris flows, which occur when apparently stable soil suddenly loses its rigidity and fluidizes (Fig. 1). Although more difficult to observe, undersea observations reveal that similar mass failures occur at the bottom of the ocean. Another spectacular example is the collapse of lava domes on volcanoes, which produce gas-fluidized granular currents known as pyroclastic flows. *All of these Earth-material flows result from the loss of rigidity of a marginally-stable granular solid*, and their fluidity depends on inter-particle friction and the degree of mixing with the fluid medium. Soil on hillsides is also known to "creep" at slopes well below the angle of repose (Fig. 1), and our recent experiments have shown that river sediment may also creep for fluid stresses below the apparent onset of motion (Houssais et al., 2015a). Thus, *even granular solids are not solid*.

Typically, the onset of failure is treated using a simple yield stress criterion, below which the granular bed is immobile; this is, however, incompatible with the existence of sub-threshold creep. Above that threshold, the various types of geophysical flows discussed above are often modeled with some kind of shear-dependent effective viscosity (Iverson and Denlinger, 2001). While much progress has been made, Earth-material flows are often studied in isolation from each other by specialized communities with specific models — e.g., landslides, pyroclastic flows and submarine gravity currents are distinct entities. More critically, models and experiments focus on *one state of flow*, rather than transitions between states. For example, there is a mature literature examining the controls on the velocity and concentration profiles of steady-state turbidity currents (Felix and Peakall, 2006; Sequeiros et al., 2009; 2010; Talling et al., 2012) — submarine density currents made of suspended sediment — however there are remarkably few studies documenting *how* these currents are formed from a collapsing granular pile (You et al., 2012).

2 Proposal Goals

We aimed to build a unique laboratory research flume, that will facilitate a new approach to examining the failure and flow of Earth materials that spans disciplinary boundaries. Disparate Earth-material flow experiments are conducted in different facilities by different researchers, so we cannot directly compare and isolate the influence of variables such as the ambient fluid. The constructed research flume allows examination of the failure and flow of granular materials in air and underwater by using: (1) a pressurized chamber able to fluidize granular material, and then release this material in a "dam break" type experiment to examine runout and mixing; and (2) a coupled-camera laser system mounted on an automated, precision cart that is capable of moving with the retreating front of a failing granular pile and measuring fluid and particle motion simultaneously. The channel also recirculates water and sediment, to examine more conventional river transport scenarios. Thus, the experiment allows us to study a range of Earth-material flows that are usually treated separately: landslides and debris flows, turbidity currents, pyroclastic flows, and river transport.

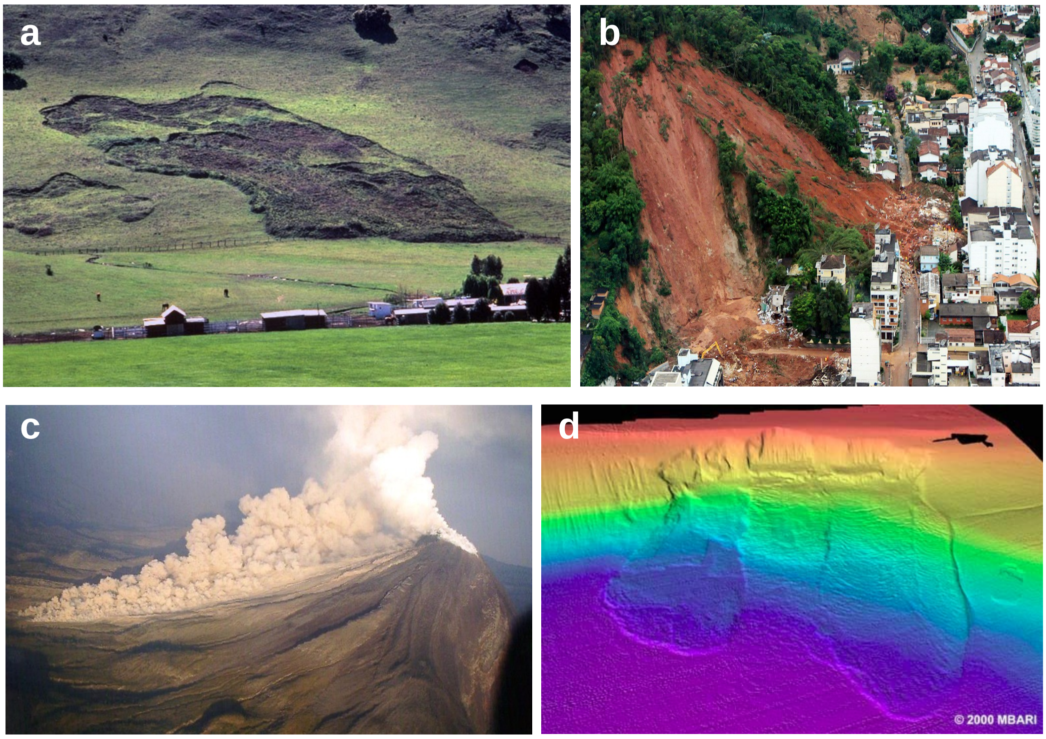

Figure 1: Examples of Earth-material flows involving granular material. a) A slumping, slow-moving landslide that is below the threshold for fluidization. b) A fast-moving fluidized landslide, showing long runout with catastrophic consequences. c) A pyroclastic flow, in which particles ranging from ash to boulder size are ejected from a volcano and mixed with hot gas, causing a fluidized granular flow to move downslope. d) A submarine landslide, in which sediment on the continental slope was fluidized to create a debris flow. Image credits for (a)-(d), respectively: wallpaper222.com/explore/earthflow, www.weatherwizkids.com, Abel Cortes of the Colima Volcano Observatory, and the Monterey Bay Aquarium Research Institute.

I hypothesize that the rheology of Earth-material flows, and the transitions between flow regimes, are controlled by two parameters; the dimensionless shear rate (I) and the particle concentration (C). Further, I propose that the sudden fluidization of Earth materials represents an unjamming transition, that is essentially controlled by granular friction. Our previous work on fluid-granular flows presents a starting point for designing a specialized experimental setup capable of examining a broad suite of Earth-material flows and their initiation. To succeed, one should be able to control the factors that govern granular friction and pore pressure; namely, initial granular packing fraction, fluid viscosity and density, particle diameter, confining pressure and gravity force. In addition, the research apparatus should be flexible enough to support more general research and teaching goals, including examining the fluid and sediment motions associated with more conventional (but still not understood) river-type flows. This will also allow side-by side comparison of the latter with Earth-material flows, to scrutinize the proposition that all of these systems exhibit the same granular phase transitions. Accordingly, the experiment must be capable of:

- accommodating a wide range of flow thickness and velocity, while minimizing material usage;
- examining flows in air, and underwater;
- tuning the initial packing fraction and height of a granular pile;
- quickly releasing the granular pile to simulate a "dam break" scenario;
- imaging granular and fluid motions in the vicinity of a moving granular front;
- tracking grain and fluid motions of the flow produced by the collapsing granular pile;
- varying the channel slope; and
- having a recirculating mode for water and sediment.

More broadly, the goals and expected outcomes of this equipment proposal may be stated as follows:

- construct a state-of-the-art and unique research facility, that will build capacity for DoD-relevant research in the area of Earth-material flows and associated hazards;
- launch a new research direction in unjamming of granular materials under a wide range of conditions, with cross-disciplinary collaborations;
- provide the first detailed observations of granular motion in a failing Earth flow;
- examine in particular the granular dynamics of breaching and turbidity current generation, to test for similarity with steady-state fluid-sheared river flows;
- use the research flume as a vehicle for training students and postdocs in how to conduct research at the interface of materials and disciplines;
- create a flexible apparatus, with a long life, to be used for general teaching in Earth Surface Processes; and
- generate new research proposals — within and outside DoD — facilitated by the novel apparatus developed here.

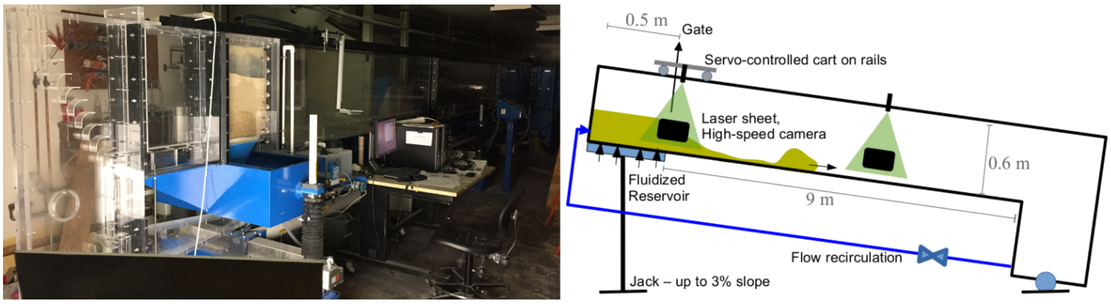

Figure 2: The turbidity current apparatus. On the right, a schematic of the entire flume shows an upstream fluidized reservoir of 0.5 m and a 9 m run-out channel for the turbidity current, separated by a pneumatic door. The flume has a trolley along its top surface with a hanging camera that can track a moving front. On the left is the actual flume in our lab, built in May 2017. The upstream reservoir sits on the blue jack, and the arm for the hanging camera can be seen downstream.

3 Accomplishments

We have completed construction, calibration and testing of the new experimental Earth-material failure and flow facility. We have demonstrated its ability to generate a range of relevant failure and flow behaviors. I report some relevant progress below.

The purpose-built subaqueous flume allows us to prepare a pack of grains that fails as a gate is opened, allowing flow down a long channel (Figure 2). To understand the role of granular friction and pore pressure for the breaching front supply of the generated particulate "turbidity current", we have the following free parameters; many aspects of the granular media (including its size distribution, mass and packing fraction) and the flume slope. The resultant flow dynamics are measured with images taken during the experiment.

The flume was designed by Engineering Laboratory Design Inc. (ELD) to the specifications of PI Douglas Jerolmack and postdoc Carlos Ortiz, and its construction was completed in Spring 2017. Matt Thomforde, an ELD engineer, and graduate student Andrew Gunn constructed the flume at the University of Pennsylvania. Experiments for multiple different geophysical flows can be performed using the flume, however we limit discussion here to the first tests conducted to generate turbidity currents. The turbidity current is created in the body of the flume, which consists of an upstream margin, a channel body (both made of clear 0.025 m thick acrylic) and a downstream catch tank (made of opaque fiberglass). The upstream margin and the channel body are 0.5 m and 9 m long, respectively. They are both 0.6 m tall and 0.05 m wide. The narrow width of the flume (O(10^2) grain diameters) may interfere with the front dynamics (i.e. the Janssen effect), however there are rigorous models accounting for this. The downstream catch tank is large to maintain a sub-critical Froude number ($Fr = U/Lg$) of flow for as long as possible during an experiment (flows inevitably impinge upon the geometry of the tank, reflect back into the channel, and disturb the dynamics of the turbidity current).

The upstream margin and channel body are separated by a steel pneumatically operated door, forced with a pressure drop of 100 Pa. In an experiment this door is opened starting failure. Ideally this would happen instantaneously and not displace any material, however the confining pressure on the door when the flume is filled with fluid (and maintaining a water-tight seal) require a 0.025 m thickness and slow the opening time to O(10^{-1}) s. Still, the reproducibility of this mechanism is novel with respect to other turbidity current laboratory experiments.

An important parameter that regulates breaching dynamics is the volume packing fraction ϕ of the granular material. Our experiment allows me to tune this parameter in the upstream margin (done before the pneumatic door is opened) by recirculating water flow through the granular material. Hydrostatic pressure on the grains is counteracted by this pressure-driven flow of water upward through them, the resultant Darcian flow decreases ϕ by increasing the Capillary number ($Ca = \mu U/\sigma$). This allows the packing fraction of the failing material to be a free independent parameter, within an approximate range of 0.1, limited by the highest achieved under hydrostatic load and the lowest when fluidized channels form within the material. The recirculating flow must diverge from a pipe of cross-sectional area O(10^{-4}) m^2 (required for the pump) into a uniform flow under the upstream margin (surface area 0.025 m^2), which I have achieved by filling a cone that joins the two surfaces with dense foam, creating an intermediate Darcian flow. Finally, for any imposed force field, the non-equilibrium packing fraction can be modeled as $\partial_t \phi = -\phi/\tau_r$, where τ_r is a relaxation timescale. To ensure near-equilibrium between the recirculating flow and the packing fraction, flow is maintained for at least $O(10) \cdot \tau_r$ (around 20 minutes) before breaching.

Experiments on the breaching front are measured with 3 different imaging systems from the side of the flume (preliminary results shown in Figure 3). Firstly, a far-field Nikon 5100 DSLR with frame rate of 24 Hz takes stationary images of flow in the channel body. These images are back-lit with an array of 72 W LED panels that provide a homogeneous light source, allowing us to measure the bulk shape and strain rate of the current as it blocks the light between the LED panels and the DSLR. Secondly, another far-field stationary 24 Hz DSLR takes images from the side of the upstream margin as the breaching front recedes upstream from its initial position. These images allow us to measure the bulk strain of the initial pack (notably the front profile and speed). Thirdly, a non-stationary Ximea xiQ MQ013MG-ON camera takes near-field images of the breaching front at 100 Hz. The Ximea is combined with an Opteka telescopic lens, allowing a useful grain to pixel size ratio whilst mounted far away from the focal plane. A Coherent Stingray 520 nm laser sends a sheet of light close and parallel to the channel wall, illuminating both seed-particles in the water and granular material sent into suspension near the breaching front. Secondly, another LED panel front-lights the upstream margin, allowing Ximea observation of grain movement within the granular media before it is lost to the current through the breaching front.

The resultant phase velocities from near-field and bulk deformation from far-field are determined from the images using tracking algorithms that are based principally on auto-correlation and edge-detection. All the image data is stored in hard-drives with the experiment workstations, and written to the laboratory Synology server.

A novel aspect of this project is that grain motions can be resolved at the breaching front during an entire experiment. Usually this is not possible because the focal width of a camera capable of resolving grain-scale motion is narrower than the total breach. The Ximea and Stingray are both mounted to a trolley driven by an Oriental Motors stepper motor, allowing it to move along rails on top of the flume at tunable speeds (maximally faster than the front breaches). We are currently working to create a system in which during an experiment the trolley moves with the breaching front; the displacement of the breaching front between recently captured sequential images from the Ximea will be calculated on-the-fly with the Dell workstation, which then passes a signal to the stepper motor updating the trolley speed to match the front's. This task is computationally demanding, however achievable with assistance from the robotics contingent at the University of Pennsylvania and a purpose built Dell computer.

We are currently running a suite of experiments that provides information at points in a space spanned by 2 independent parameters; median grain size d_{50} and initial packing fraction ϕ_i. The d_{50} provides a characteristic measure of the distribution of grains in the solid-phase of the turbidity current. Full particle size distributions of common experimental sand samples are determined using our laboratory's Beckman Coulter Laser Diffraction Particle Size Analyzer LS 13 320.

3.1 Expected Outcomes

This project is expected to produce novel experimental data on turbidity current breaching. Significant progress has already been made; a challenging build of the flume has been completed, and preliminary experiments have resulted in alterations of the set up and grains required for turbidity current formation. Most importantly, we have shown that we can produce two distinct modes of failure: "breaching" from highly compacted initial grains, and debris flow failure from more dilated samples.

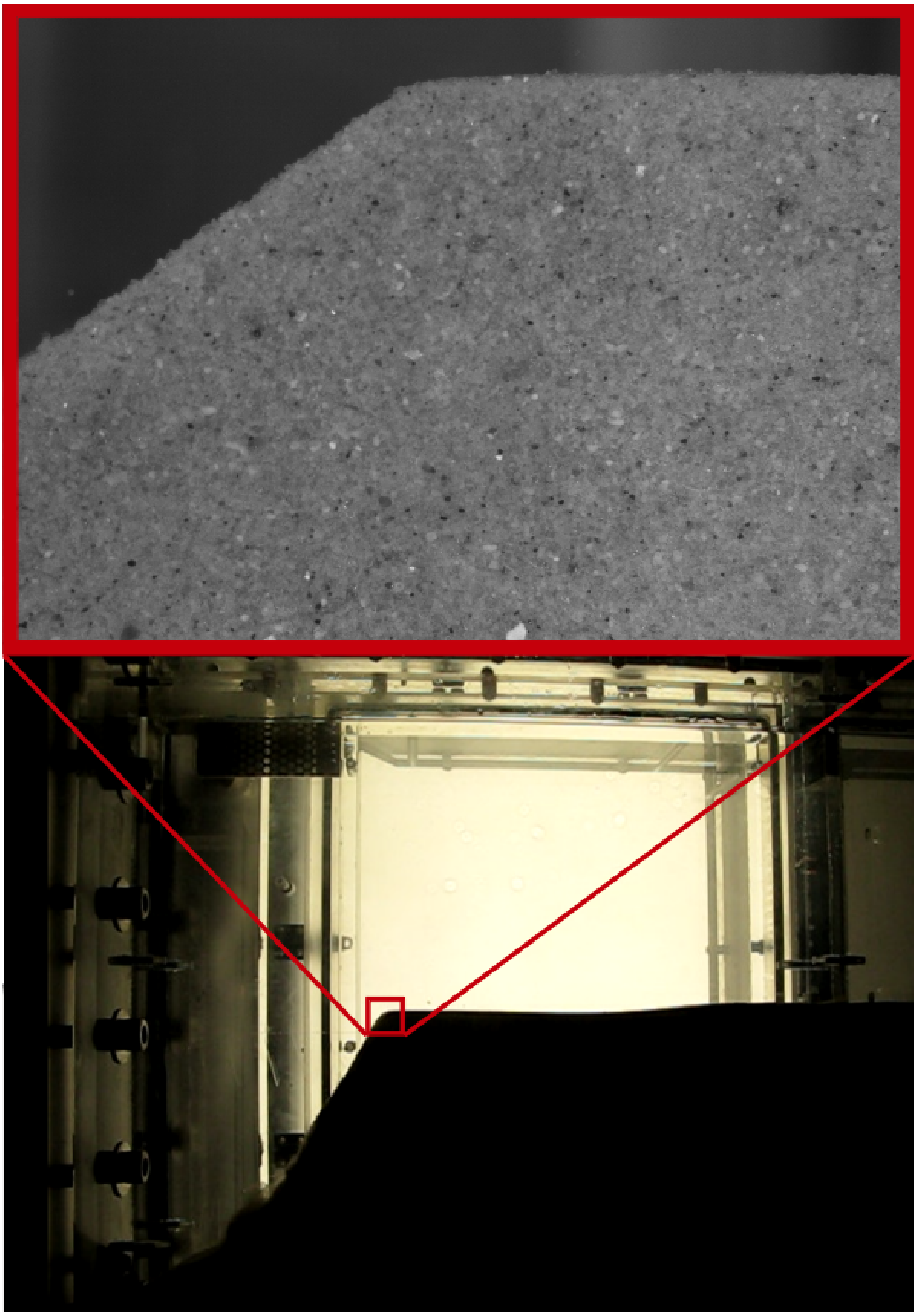

Figure 3: Preliminary experiments of a breaching front in the flume (see Figure 2). (below) A far-field view from a stationary DSLR camera of the upstream reservoir of a collapsing pack (opaque region, back-lit), creating a flow to the right of the image. The red inset (above) shows a near-field view from the Ximea camera mounted to the trolley, able to capture individual grains in the pack (front-lit).

4 Relevance to DoD

Landscape instability affects nearly every human on the planet in one way or another, and often limits the lifetime of major infrastructure. From slow soil creep causing settling and breaking of pipes, to collapsing river banks chewing away roads, to landslides burying entire communities, to turbidity currents snapping undersea cables, Earth-material flows are ubiquitous agents of destruction. The research facilitated by this equipment is relevant to many areas of DoD. As stated above, however, this work most directly supports the mission of the Material Science Division of the Army Research Office, in particular related to Earth Materials and Processes. These efforts have satisfied the following objectives of the division:

- "...to discover the fundamental relationships that link...microstucture...with the resultant material properties and behavior." Our work on connecting grain-scale motion to rheology and resultant flow relates to this.
- "...to advance the understanding of geological materials and processes, to establish opportunities from which to optimize the performance of future Army systems functioning within them." Understanding failure of Earth materials can be used to predict or manipulate landscape stability.
- "Foundational research that integrates novel experimental work with the development of new predictive materials theory...Furthermore, there is lasting interest in new ideas and cross-disciplinary concepts in Material Science that may have future applications for the Army." The entire proposal is in this spirit.

4.1 Enhancements of current DoD-funded research and education

This flume created new research opportunities that built on a previous ARO-funded project, and also led in part to the development of a new ARO-MURI proposal on Topic 14 - Control of particulate flows.

4.2 New capabilities for DoD-related research and education

The developed experiment is developing into a nexus for collaborating researchers from EES, Physics and Engineering. Nothing like it exists on campus, or indeed in the Philadelphia area. Moreover, the facility includes several truly unique elements that make it stand out anywhere. The thrust of research conducted with this facility will be the application of emerging frameworks from soft-matter physics and materials science to understanding geologic materials and their flow. Also, discoveries of Earth-material behaviors under new boundary conditions will likely challenge existing theory, leading to new breakthroughs in materials science. The new facility is already featured prominently in Jerolmack's GEOL305 class, "Earth Surface Processes", which is taught each spring. Students are able to perform experiments and collect real data, in laboratory exercises that confront theoretical concepts learned in class with messy reality.

5 Bibliography

1. Arai, Kazuno, Hajime Naruse, Ryo Miura, Kiichiro Kawamura, Ryota Hino, Yoshihiro Ito, Daisuke Inazu, et al. "Tsunami-Generated Turbidity Current of the 2011 Tohoku-Oki Earthquake." Geology 41, no. 11 (November 2013): 1195-98. doi:10.1130/G34777.1.
2. Balmforth, N. J., and R. R. Kerswell. "Granular Collapse in Two Dimensions." Journal of Fluid Mechanics 538 (September 2005): 399-428. doi:10.1017/S0022112005005537.
3. Banigan, Edward J., Matthew K. Illich, Derick J. Stace-Naughton, and David A. Egolf. "The Chaotic Dynamics of Jamming." Nature Physics 9, no. 5 (May 2013): 288-92. doi:10.1038/nphys2593.

4. Boyer, Francois, Elisabeth Guazzelli, and Olivier Pouliquen. “Unifying Suspension and Granular Rheology.” Physical Review Letters 107, no. 18 (October 24, 2011): 188301. doi:10.1103/PhysRevLett.107.188301.

5. Eke, Esther, Enrica Viparelli, and Gary Parker. “Field-Scale Numerical Modeling of Breaching as a Mechanism for Generating Continuous Turbidity Currents.” Geosphere 7, no. 5 (October 2011): 1063-76.

6. Felix, M., and J. Peakall. “Transformation of Debris Flows into Turbidity Currents: Mechanisms Inferred from Laboratory Experiments.” Sedimentology 53, no. 1 (February 1, 2006): 107-23. doi:10.1111/j.1365-3091.2005.00757.x.

7. Foreman, Brady Z., Steven Y. J. Lai, Yuhei Komatsu, and Chris Paola. “Braiding of Submarine Channels Controlled by Aspect Ratio Similar to Rivers.” Nature Geoscience 8, no. 9 (September 2015): 700-703. doi:10.1038/ngeo2505.

8. Houssais, Morgane, Carlos P. Ortiz, Douglas J. Durian, and Douglas J. Jerolmack. “Onset of Sediment Transport Is a Continuous Transition Driven by Fluid Shear and Granular Creep.” Nature Communications 6 (March 9, 2015): 6527. doi:10.1038/ncomms7527.

9. Houssais, Morgane, Carlos P. Ortiz, Douglas J. Durian, and Douglas J. Jerolmack. “Rheology of sediment transported by a laminar flow.” Submitted to Physics of Fluids (2015).

10. Iverson, Richard M., and Roger P. Denlinger. “Flow of variably fluidized granular masses across three-dimensional terrain: 1. Coulomb mixture theory.“ J. Geophys. Res 106, no. B1 (2001): 537-552.

11. Lacaze, Laurent, and Rich R. Kerswell. “Axisymmetric Granular Collapse: A Transient 3D Flow Test of Viscoplasticity.” Physical Review Letters 102, no. 10 (March 13, 2009): 108305.

12. Lajeunesse, E., A. Mangeney-Castelnau, and J. P. Vilotte. “Spreading of a Granular Mass on a Horizontal Plane.” Physics of Fluids 16, no. 7 (July 1, 2004): 2371-81. doi:10.1063/1.1736611.

13. Liu, Andrea J., and Sidney R. Nagel. “The Jamming Transition and the Marginally Jammed Solid.” Annual Review of Condensed Matter Physics 1, no. 1 (2010): 347-69. doi:10.1146/annurev-conmatphys-070909-104045.

14. Lube, Gert, Herbert E. Huppert, R. Stephen J. Sparks, and Mark A. Hallworth. “Axisymmetric Collapses of Granular Columns.” Journal of Fluid Mechanics 508 (June 2004): 175-99. doi:10.1017/S0022112004009036.

15. Masson, D. G., C. B. Harbitz, R. B. Wynn, G. Pedersen, and F. Lovholt. “Submarine Landslides: Processes, Triggers and Hazard Prediction.” Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences 364, no. 1845 (August 15, 2006): 2009-39. doi:10.1098/rsta.2006.1810.

16. Mastbergen, Dick R., and Jan H. Van Den Berg. “Breaching in Fine Sands and the Generation of Sustained Turbidity Currents in Submarine Canyons.” Sedimentology 50, no. 4 (August 1, 2003): 625-37. doi:10.1046/j.1365-3091.2003.00554.x.

17. Mitchell, Neil C. “Bedrock Erosion by Sedimentary Flows in Submarine Canyons.” Geosphere 10, no. 5 (October 2014): 892-904.

18. Mohrig, David, Anders Elverhoi, and Gary Parker. “Experiments on the Relative Mobility of Muddy Subaqueous and Subaerial Debris Flows, and Their Capacity to Remobilize Antecedent Deposits.” Marine Geology 154, no. 1-4 (February 2, 1999): 117-29. doi:10.1016/S0025-3227(98)00107-8.

19. Ovarlez, G., C. Fond, and E. Clement. “Overshoot effect in the janssen granular column: A crucial test for granular mechanics.“ Physical Review E 67, 060302 (2003).

20. Pailha, M., M. Nicolas, and O. Pouliquen. “Initiation of Underwater Granular Avalanches: Influence of the Initial Volume Fraction.” Physics of Fluids 20, no. 11 (November 1, 2008): 111701. doi:10.1063/1.3013896.

21. Piper, David J. W., and William R. Normark. “Processes That Initiate Turbidity Currents and Their Influence on Turbidites: A Marine Geology Perspective.” Journal of Sedimentary Research 79, no. 6 (2009): 347-62.

22. Puig, P., A. S. Ogston, B. L. Mullenbach, C. A. Nittrouer, J. D. Parsons, and R. W. Sternberg. “Storm-Induced Sediment Gravity Flows at the Head of the Eel Submarine Canyon, Northern California Margin.” Journal of Geophysical Research: Oceans 109, no. C3 (March 1, 2004): C03019. doi:10.1029/2003JC001918.

23. Roche, O., M. A. Gilbertson, J. C. Phillips, and R. S. J. Sparks. “Experimental Study of Gas-Fluidized Granular Flows with Implications for Pyroclastic Flow Emplacement.” Journal of Geophysical Research: Solid Earth 109, no. B10 (October 1, 2004): B10201. doi:10.1029/2003JB002916.

24. Roche, O., S. Montserrat, Y. Nino, and A. Tamburrino. “Experimental Observations of Water-like Behavior of Initially Fluidized, Dam Break Granular Flows and Their Relevance for the Propagation of Ash-Rich Pyroclastic Flows.” Journal of Geophysical Research: Solid Earth 113, no. B12 (December 1, 2008): B12203. doi:10.1029/2008JB005664.

25. Roche, Olivier. “Depositional Processes and Gas Pore Pressure in Pyroclastic Flows: An Experimental Perspective.” Bulletin of Volcanology 74, no. 8 (July 15, 2012): 1807-20. doi:10.1007/s00445-012-0639-4.

26. Rondon, L., O. Pouliquen, and P. Aussillous. “Granular Collapse in a Fluid: Role of the Initial Volume Fraction.” Physics of Fluids 23, no. 7 (July 1, 2011): 073301. doi:10.1063/1.3594200.

27. Savage, S. B., M. H. Babaei, and T. Dabros. “Modeling Gravitational Collapse of Rectangular Granular Piles in Air and Water.” Mechanics Research Communications 56 (March 2014): 1-10.

28. Sequeiros, Octavio E., Hajime Naruse, Noritaka Endo, Marcelo H. Garcia, and Gary Parker. “Experimental Study on Self-Accelerating Turbidity Currents.” Journal of Geophysical Research-Oceans 114 (May 30, 2009): C05025. doi:10.1029/2008JC005149.

29. Sequeiros, Octavio E., Benoit Spinewine, Rick T. Beaubouef, Tao Sun, Marcelo H. Garcia, and Gary Parker. “Bedload Transport and Bed Resistance Associated with Density and Turbidity Currents.” Sedimentology 57, no. 6 (October 2010): 1463-90. doi:10.1111/j.1365-3091.2010.01152.x.

30. Talling, Peter J., Douglas G. Masson, Esther J. Sumner, and Giuseppe Malgesini. “Subaqueous Sediment Density Flows: Depositional Processes and Deposit Types.” Sedimentology 59, no. 7 (December 2012).

31. Wang, Ziwei, and Jie Zhang. “Spatiotemporal Chaotic Unjamming and Jamming in Granular Avalanches.” Scientific Reports 5 (January 30, 2015): 8128. doi:10.1038/srep08128.

32. Xu, J. P., Octavio E. Sequeiros, and Marlene A. Noble. “Sediment Concentrations, Flow Conditions, and Downstream Evolution of Two Turbidity Currents, Monterey Canyon, USA.” Deep-Sea Research Part I-Oceanographic Research Papers 89 (July 2014): 11-34.

33. You, Yao, Peter Flemings, and David Mohrig. “Dynamics of Dilative Slope Failure.” Geology 40, no. 7 (July 1, 2012): 663-66. doi:10.1130/G32855.1.

34. You, Yao, Peter Flemings, David Mohrig, and John Germaine. “How Heterogeneity in the Shear Dilation of a Deposit Controls the Mechanics of Breaching Slope Failure.” Journal of Geophysical Research: Earth Surface, October 1, 2014, 2013JF002983.

35. You, Yao, Peter Flemings, and David Mohrig. “Mechanics of Dual-Mode Dilative Failure in Subaqueous Sediment Deposits.” Earth and Planetary Science Letters 397 (July 1, 2014): 10-18. doi:10.1016/j.epsl.2014.04.024.