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Reproducibility of debris-flow fan physical modeling experiments

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Abstract

Debris-flow fans are common in steep mountainous terrain. The complexity of these environments makes it difficult to be onsite at the time of the debris flow, which has led many researchers to turn to physical models. While physical models have played an integral role in unraveling how alluvial fans have been developed, little work has been done to test and validate the approaches and results reported in physical models. Here, we replicated a debris-flow physical model developed at Utrecht University in a laboratory at East Carolina University (ECU). The ECU physical modeling experiment was done in an independent laboratory from the original study and was conducted with different equipment and different operators. Sediment size and water volume varied slightly from the original experiments. Fifty-six debris flows were released to form the ECU fan. Each debris flow was recorded with video. Terrestrial laser scanning recorded the topographic changes on the ECU fan throughout the experiment. Despite sediment size and water volume differences, ECU's physical model replicated the autogenic processes promoting flow avulsion patterns in a debris-flow fan with simulated unlimited accommodation space (the trap door in feeder channel and table edge did confine the maximum extent the fan could grow). These results corroborate previous findings from the Utrecht fan and support the repeatability of processes from the different models despite differences in the materials used as the debris-flow medium. Reproducibility also permits future collaborative efforts to run multiple concurrent physical modeling experiments to increase the sample size of the study populations on debris-flow processes and resulting forms.

Keywords: debris flow; runout; alluvial fan; digital elevation model; autogenic processes

1. Introduction

Physical modeling is by no means a novel approach in alluvial fan research and can be traced back to the seminal works of Hooke (1967; 1968; Hooke and Rohrer, 1979) and Schumm (1977; Schumm et al., 1987). Early small-scale physical experiments demonstrated many of the fundamental features and processes (i.e., avulsions, lateral migration, channel entrenchment, channelization, and sheetflow) present in natural alluvial fans. Findings from the early experiments were often compared to field evidence, but the experiments themselves were not directly scalable to any specific natural alluvial fans. Paola et al. (2009) later showed that the morphodynamics active on experimental and real-world surfaces are often scale independent, which in turn has allowed many studies to invoke a similarity of processes and form approach to physical modeling. These findings provide a subsequent means to validate some of the earlier assertions made about the relations of natural alluvial fans and fans generated from physical model experiments.

A recent proliferation of studies using physical models has led to the observation of a wide array of processes and features on alluvial fans (Kim and Paola, 2007; Kim and Jerolmack, 2008; van Dijk et al., 2008, 2009, 2012; Hoyal and Sheets, 2009; Clarke et al., 2010; Reitz et al., 2010; Reitz and Jerolmack, 2012; Hamilton et al., 2013; Clarke, 2015; Eaton et al., 2017). While many studies have focused on fluvial processes, recent work has started to emphasize debris flow fan development (de Haas et al., 2015, 2016; 2018a). Significant advances have been made within this body of literature, but to date, little effort has been made to independently test the repeatability of results from physical models. This is a critical step in the progression of the field because not only are scientists verifying results and

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methods, but validation of methods and findings permit researchers to address more in-depth questions. If physical models produce similar outcomes, then multiple concurrent simulations can be performed to expand the ability of scientists to provide deeper understandings of fan development. Multiple simulations run concurrently in various labs means more samples can be used to either refute or advance our current understanding of how processes and forms are changing, which has both scientific and applied implications. Here, we replicate the specification and procedures of a debris-flow fan physical modeling experiment described in de Haas et al. (2016) and qualitatively and quantitatively determine if the experimental details of the fans that develop and the findings are reproducible.

1.1. Prior physical modeling results from Utrecht experiments

De Haas et al. (2015; 2016; 2018a) designed and built an experimental debris-flow flume in which they examined runout, depositional mechanisms, deposit morphology and the impact of debris-flow magnitude-frequency distributions and autogenic processes on avulsion and debris-flow fan development in a setting with unlimited accommodation space. Details of the flume dimensions, operations, and data recording for the original simulations are thoroughly described in de Haas et al. (2015, 2016) and are described below, as our own experiment is designed to reproduce the original physical model and the debris-flow fan experiment of de Haas et al (2016). Therefore, our review touches on the key methodological and scientific findings from the experiments as they are critical from a comparative standpoint.

De Haas et al. (2016) found that debris-flow fans developing under constant formative processes evolve through phases of autogenic channelization, backfilling, and avulsion (Fig. 1). Fan development is limited by maximum possible debris-flow length, which depends on debris-flow volume and composition. Individual debris flows alternate between channelized within coarse-grained levees, resulting in distal deposition, and unchannelized forming short and wide deposits with limited runout. As flows become progressively short and wide they backfill the active channel by upstream migration of depositional lobes, until the channel is completely filled, and the flows avulse to a topographically favorable pathway. The characteristic fan shape is developed over multiple avulsion cycles that are driven by topographic compensation as the fan avulses toward the steepest flow path. The findings provide valuable insights into the processes governing the autogenic formation of debris-flow fans.

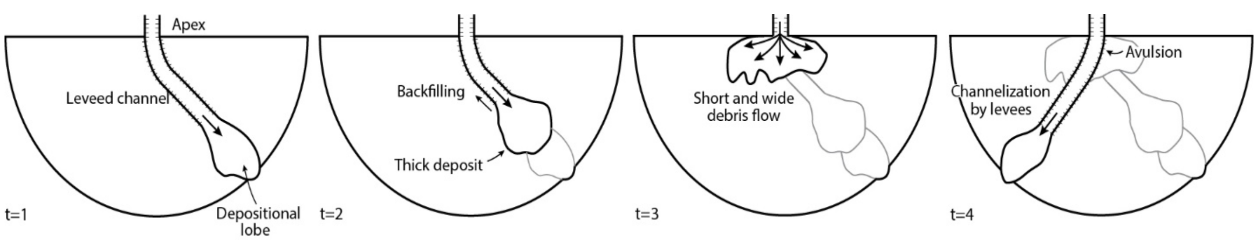

Fig. 1. Schematic of the autogenic cycle on a debris-flow fan (after De Haas et al., 2016). The presence of a channel results in distal deposition. Distal deposition reduces the distal channel gradient and flows start to retrograde over multiple debris flows. Flows become progressively short and wide, backfilling the channel. The next debris flows avulse and form a new channel along a topographically more favorable pathway.

2. Methods

2.1. Physical model

In the ECU experiment, a mixing tank agitates and releases a debris flow into a 2 m long flume, replicating a feeder channel positioned at a 30° angle and then onto the outflow plain (1.8 m by 1.8 m) (Fig. 2). Each debris flow mixture consisted of 1,650 g water, 288 g kaolinite clay, 1,010 g fine sand, 2,837 g coarse sand, and 865 g gravel. The sediment-water mixture varies slightly from de Haas et al. (2016) in that our debris-flow mixture contains 150 g more water. Additional water leads to longer runout and larger fans to enhance the potential for measuring multiple avulsions. The addition of 150 g of water was also validated by testing other sediment ratios and water volumes to determine which combination yielded morphologically and morphometrically similar results to de Haas et al. (2016).

Experimental fans were formed over many individual flows, which is consistent with alluvial fan development in natural settings. Each debris flow was created using the following process: (1) each portion of the debris mixture was weighed; sediment was roughly mixed by hand to ensure that clay did not stick to sides of the mixing bucket; (2) the sediment mixture was poured into the opening of the mixing tank, followed by the water; (3) the total debris mixture was manually agitated for approximately 20 seconds; (4) the mixing tank gate was opened pneumatically via a manually operated switch; (5) debris was released into the flume and transported onto the outflow plain; (6) 1.5 seconds after the gate was opened, a hatch located in the bottom of the flume 0.75 m from the apex of the fan opened, preventing debris flow tailwater from entering the outflow plain and obscuring fan morphometry; and (7) the debris-flow deposits were allowed to dry for 2-3 hours with one portable fan directed at the fan apex and another directed at the active fan section.

2.2. Data recording techniques

A Leica P40 laser scanner in a nadir-looking position was placed above the outflow table (Fig. 2) and recorded high-resolution topography (3 mm horizontal point spacing) after every debris flow. Four black and white targets were affixed at each corner of the outflow table and four additional targets were dispersed evenly on the walls of the laboratory (Fig. 2). The nadir-looking positioning of the scanner allowed a single scan position per debris flow. Targets located on the corners of the outflow plain and laboratory walls were used in the registration process. All registration was conducted within Leica's Cyclone software in order to resolve any differences in the non-fixed scanner location and provide a consistent coordinate system relative to the first scan position.

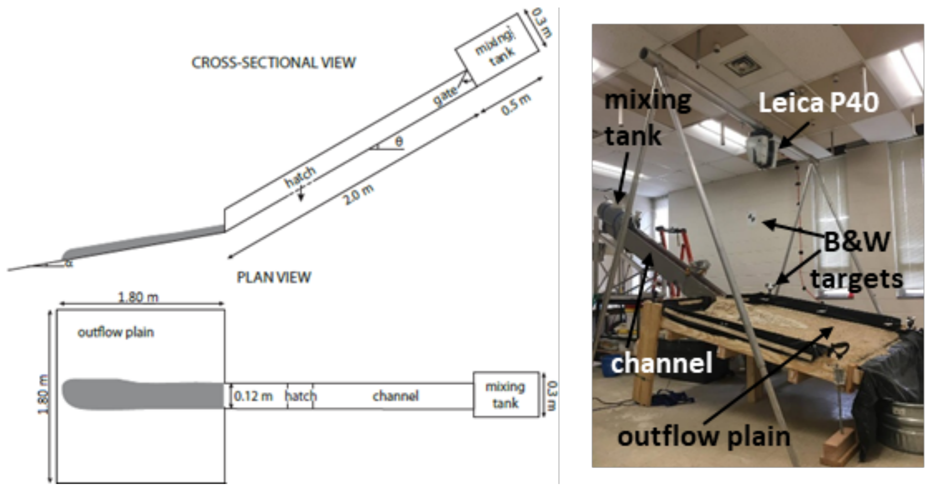

Fig. 2. Sketch of experimental laboratory setup [left, adapted from de Haas et al. (2016)] and picture of ECU laboratory setup (right).

2.3. Data processing and analysis

All analyses were conducted in ArcGIS. Registered point clouds were processed into 3 mm digital elevation models (DEMs) using LAStools (cf. Staley et al., 2014). DEMs were used to measure debris flow slope, thickness, and length. Fan slope was measured from the fan apex to the maximum active debris flow extent. Debris flow length was measured from the apex to the maximum flow runout position. Average debris-flow thickness was derived from elevation differences between pre- and post-topographic surfaces following the methodology of Wheaton et al. (2010). Outlines of individual debris flows were digitized from the topographic change detection (TCD) and subsequently used to extract elevations from the TCDs. This step was necessary to ensure that only elevation changes resulting from debris flows were included in calculations. Extracted elevations were then averaged to calculate average debris-flow thickness.

3. Results

3.1. Morphometric characterization of flows and fan

The experimental debris-flow fan was developed from 56 individual debris flows and the fan shape evolved as a result of two avulsion cycles. The experiment was terminated after flow 56 as debris backfilled the feeder channel and debris flows could no longer reach the outflow plain. Debris-flow fan evolution occurred as a result of channelization, backfilling, and avulsion. These phases of development result directly from autogenic cycles as no external forcing mechanism was introduced over the duration of this experiment.

During channelization, flows were characterized by progressively longer deposits constrained by coarse-grained levees and punctuated by thick depositional lobes (Fig. 3A, Fig. 4A). Conversely, flows became increasingly short and wide during the backfilling phase (Fig. 3B, Fig. 4B). Average flow thickness ranged between approximately four and ten millimeters with no discernable correlation between flow thickness and autogenic phases.

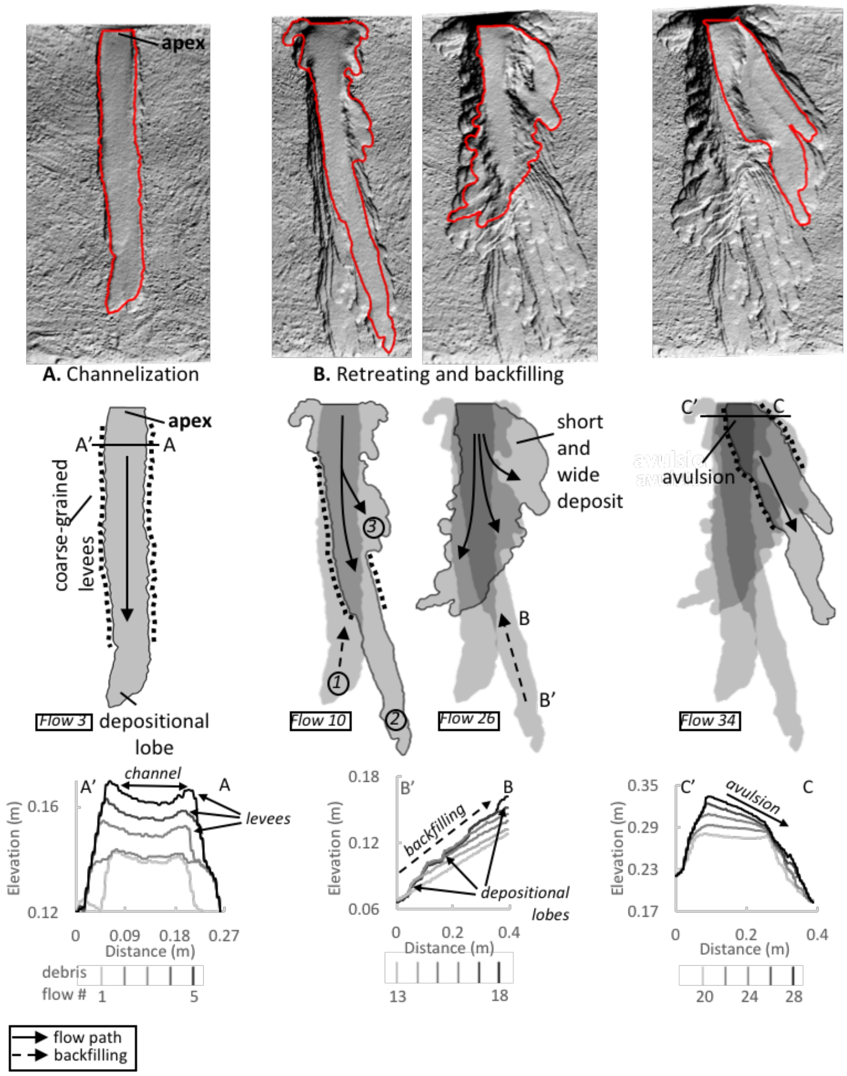

Fig. 3. Diagram showing the avulsion cycle of our experimental debris-flow fan and hillshades of selected debris flows (top panels). Three main processes characterize the avulsion cycles. First (A), flows are channelized between coarse-grained levees, punctuated by thick depositional lobes. Debris-flows retreat and backfill (B), ultimately resulting in short and wide deposits. Channel backfilling can occur multiple times over the course of one avulsion cycle [e.g., (B) channel (1) backfills as flow is diverted to channel (2). Channel (2) backfills as flow is diverted to newly forming channel (3)]. The channel is completely filled, and the fan avulses (C), whereby flow is diverted toward the steepest flow path and the cycle begins again. Cross sections (bottom panel) demonstrate the processes of the avulsion cycle illustrated and labeled in the middle panel.

The final fan surface was primarily covered by stacked depositional lobes and coarse-grained levees. Fan slope ranged between 6° and 20°, averaging approximately 12° (Fig. 4C). Fan slope varied with autogenic phases and between autogenic cycles. During the first cycle, channel slope generally increased as flows were channelized and decreased during backfilling. One exception, however, occurred during the phase of backfilling prior to the first avulsion (flows 21 – 28) when fan slope increased and decreased several times before the fan avulsed. Fan slope during the second autogenic cycle was roughly constant throughout channelization and decreased during backfilling before the fan avulsed again (Fig. 4C).

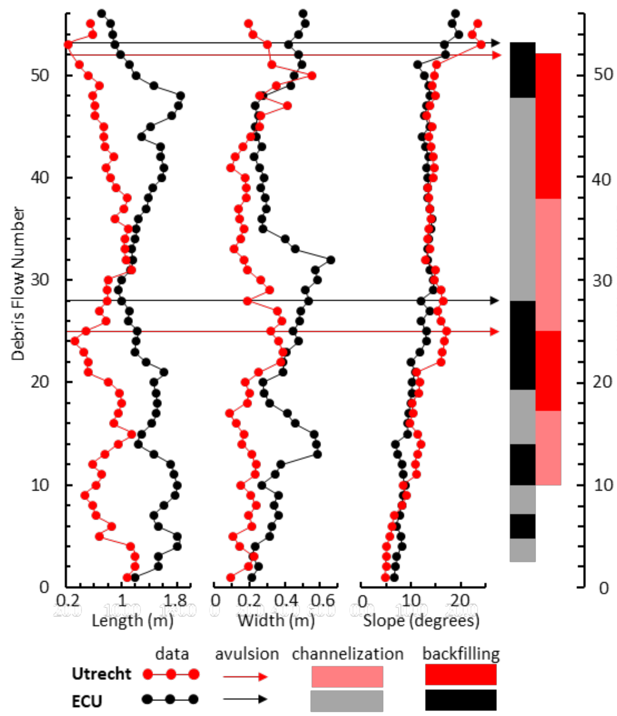

Fig. 4. Summary of debris-flow characteristics for the Utrecht and ECU fans. Light and dark boxes indicate phases of channelization and backfilling, respectively. Flow channelization starts at flow 2 in ECU fan and flow 10 in Utrecht fan. Arrows indicate instances of avulsion. (a) Debris-flow length measured from apex to maximum runout length. (b) Debris-flow width measured at the widest point of the flow. (c) Average fan slope measured along the active channel.

3.2. Autogenic behavior as reflected in deposition patterns

Both avulsion cycles observed on our experimental debris-flow fan exhibited flow channelization and channel backfilling. Fan avulsions occurred along the steepest flow path. First and second autogenic cycles were similar in length, consisting of 26 and 25 individual debris flows, respectively (Fig. 4). Minimum and maximum flow widths, lengths, and thicknesses were similar between the two distinct avulsion cycles. Additionally, debris-flow lengths and widths were inversely related, oscillating between long and narrow during phases of channelization and short and wide during phases of channel backfilling.

The phases of autogenic debris-flow fan evolution observed on our fan are demonstrated particularly well over the course of the first avulsion (Fig. 3). Flow channelization and channel backfilling alternated three times prior to the first fan avulsion phase at flow twenty-eight (Fig. 4). Flow channelization can be seen to develop as a result of constraining, coarse-grained lateral levees. Channel backfilling is shown as debris flows get progressively shorter, limited by the previous flow's thick, depositional lobe. The fan avulsion phase develops as the channel near the fan apex is backfilled and steepened until flow is preferentially diverted to the steepest flow path.

The major differences observed between the first and second autogenic cycles are in the number and length of sets of flow channelization and backfilling. The first autogenic cycle was initiated during flow three when flow was channelized following the first two debris flows. The first autogenic cycle consisted of three sets of channelization and backfilling. The second autogenic cycle exhibited only one set of channelization and backfilling. Following avulsion during flow twenty-eight, debris flows became progressively longer and slowly migrated from the left side of the fan. The sustained period of channelization observed during the second autogenic cycle compared to the first can be explained by debris-flow interaction with antecedent topography whereby debris flows preferentially deposited in topographically low areas. This resulted in debris flows that were progressively longer as previous deposit morphology guided, and effectively channelized, flow to the distal fan. Despite the channelizing effect of antecedent topography, individual flows in the second autogenic cycle still exhibited lateral levees typical of channelized flows.

4. Discussion

4.1. Replicability of debris flow physical models

The results of our experimental debris-flow fan are very similar to those reported in de Haas et al. (2016) despite the differences in experimental design. Both fans experienced two full autogenic avulsion cycles driven by phases of channelization, backfilling, and avulsion in a similar number of debris flows (55 and 56, respectively, Fig. 4). During these phases, both fans grew in length through flow channelization and expanded laterally as a result of preferential deposition toward the steepest flow path and topographically low areas. Individual debris flows on the ECU fan displayed the same morphology corresponding with these phases as those on the Utrecht fan (de Haas et al., 2016; Fig. 5). Additionally, all flows had well-defined depositional lobes; long, narrow flows constrained by coarse-grained lateral levees characterizing phases of channelization; and short, wide flows dominating during phases of backfilling. These experimentally observed patterns of debris-flow evolution also mimic those observed on natural debris flow fans (e.g., Suwa and Okuda, 1983; Imaizumi et al., 2016; Wasklewicz and Scheinert, 2016; de Haas et al., 2018b).

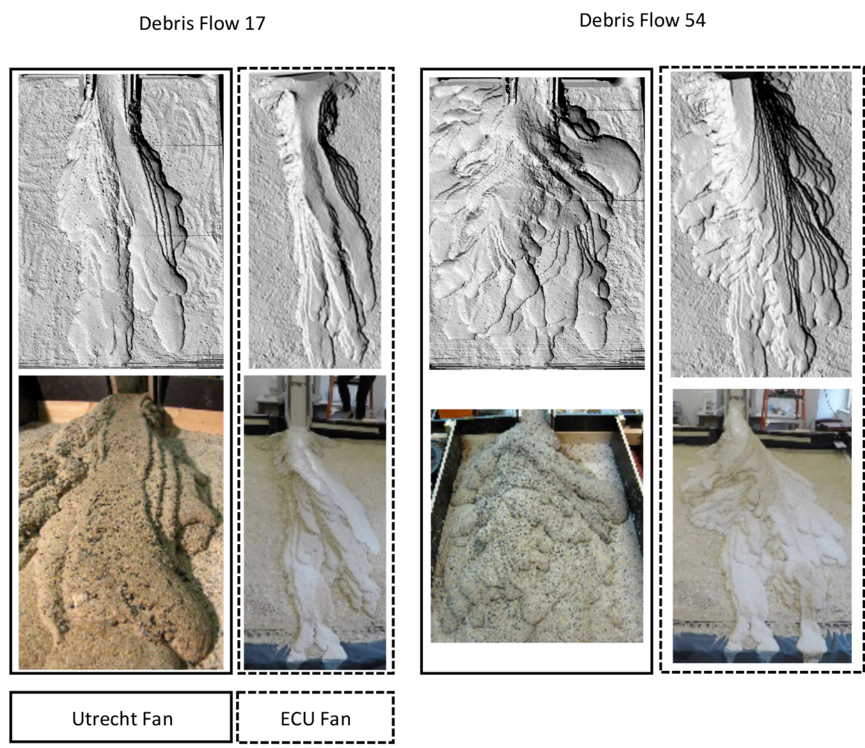

Fig. 5. Examples of fan morphology similarities between the Utrecht and ECU fans. Hillshades (top panel) and pictures (bottom panel) of debris flow numbers seven and fifty-four for the Utrecht and ECU fans.

The major differences between our results and those reported in de Haas et al. (2016) are the observed flow lengths, fan slopes, and deposit thicknesses. ECU debris flows were longer, fan slopes were gentler, and debris-flow deposits were less thick than those measured on the Utrecht fan. All of these differences can be attributed to the larger volume of water used to make the debris flows in the ECU fan. This assertion has been clearly articulated in previous research and graphically displayed in Fig. 6 of de Haas et al. (2015). Regardless of the aforementioned differences associated with the larger volume of water used in the ECU fan, the processes driving autogenic evolution of both debris-flow fans were the same and both fans were formed by morphologically similar debris flows.

4.2. Implications of the debris-flow physical model replicability for alluvial fan evolution

Our experiment provides a successful independent test of the results identified in de Haas et al. (2016). Reproducibility is clearly achieved here as we designed our own physical model in a different lab, used different researchers to conduct the experiments, and the media used (water and sediment) varied slightly from the original design. All of these items meet the widely accepted standard for observation conditions having independent measurement in a different test/measurement facility with different operators using different equipment (ISO, 2017). The implications of these results are several fold. Church et al. (2017) highlighted the importance of reproducibility in the field of Earth sciences as a vital component preventing incorrect or biased inferences. Our findings provide strong support for the physical modeling methods presented by de Haas et al. (2016) and corroborate the role of autogenic processes in promoting flow avulsion that lead to semi-conical form of debris-flow fans with “unlimited” accommodation. Our findings provide further support to the broader literature for autogenic controls on alluvial fan development, especially as they relate to debris-flow fan formation in unlimited accommodation space. The achievement of reproducing the equipment, methods and findings of de Haas et al. (2016) speak broadly to the credibility of the approach to capturing 4D information on the debris flows and debris-flow fan dynamics, which provides greater confidence for the employment of this approach to advance science.

The ability to reproduce this type of experiment with an independent test also has implications for moving forward with physical modeling. This opens the opportunity to run large-scale experiments at many institutions and produce a large sample size. Information gathered from numerous simulations as opposed to a single simulation lends itself to unravelling process-form relations with a much greater degree of certainty because the scientific research would be based on multiple repeated results. This will provide the potential to advance conceptual and theoretical scientific knowledge and lead to more authoritative scientific communications. Advances might come in the areas of bajada development or limited accommodation space, impacts of base-level lowering, and interactions between endogenic and autogenic processes There will also be opportunities to simulate multiple scenarios in landscape evolution. This would involve starting models at various evolutionary stages, or slightly modifying the flow characteristics or materials to examine how these differences would impact the outcome. What would normally take months or years to accomplish could be done in a matter of a month or less with multiple cooperative labs simulating the various aspects of the experiment. The ability to develop simulations in this fashion will provide a deeper understanding of the processes driving long-term landform and landscape development as well as begin to incorporate the role of and the impacts on humans in these experimental settings, in particular how built structures modify and are in turn impacted by debris flows. The ability to test multiple scenarios simultaneously would also provide scientists with the ability to inform numerical modeling and corroborate results that will assist the numerical modeling community to advance more rapidly. This synergy opens opportunities for integrative research whereby multiple labs could work cooperatively integrating numerical and physical models in a manner that could lead to greater insights into bajada formation, role of base-level in fans, external and internal factors leading to fan forms and how fans impacted humans living on and adjacent to fans.

5. Conclusions

The use of physical models to study processes acting on the Earth’s surface has helped to advance our knowledge of a myriad of geomorphological, scientific, and engineering questions. However, heretofore independent physical modeling experiments of debris-flow fans have seldom been designed with the goal of reproducing or validating the previous modeled experiments. Our findings, based upon a physical debris-flow fan model designed by and the associated experimental results reported in de Haas et al. (2016), provide clear evidence for the reproducibility of the previous simulations, despite experimental design differences. Our debris-flow fan evolved by channelization, backfilling, and avulsion of many individual debris flows, displaying the same scale-independent morphology of natural debris-flow fans. These results not only corroborate previous findings specific to autogenic debris-flow fan evolution, but they speak to the importance and value of replicating physical modelling experiments. The ability to reproduce physical modelling experiments could foster collaborations between research scientists from different laboratories internationally to advance theoretical and applicable knowledge.

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