

## Valid debris-flow models must avoid hot starts

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### Abstract

Debris-flow experiments and models commonly use “hot-start” initial conditions in which downslope motion begins when a large force imbalance is abruptly imposed. By contrast, initiation of natural debris flows almost invariably results from small perturbations of static force balances that apply to debris masses poised in steep channels or on steep slopes. Models that neglect these static balances may violate physical law. Here we assess how the effects of hot starts are manifested in physical experiments, analytical dam-break models, and numerical models in which frictional resistance is too small to satisfy static force balances in debris-flow source areas. We then outline a numerical modeling framework that avoids use of hot starts. In this framework an initial static force balance is gradually perturbed by increasing pore-fluid pressure that may trigger the onset of debris motion. Subsequent increases in pore-fluid pressure, driven by debris motion, may then reduce the debris frictional strength, leading to high flow mobility.

*Keywords:* debris flow, numerical model, hot start, initial conditions, dam break, experiments

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### 1. Introduction

Debris flows can begin to move in a variety of ways, but nearly all natural debris flows arise from mechanically balanced initial states in which stationary sediment is poised in steep channels or on steep slopes. The onset of debris-flow motion might entail wholesale landsliding or piecemeal sediment entrainment by running water, but in either case motion of sediment-rich debris begins when a static force balance is slightly perturbed. By contrast, many debris-flow experiments and models use “hot-start” initial conditions in which motion begins when a large force imbalance is abruptly imposed. (The term “hot start” has been used previously to describe tsunami simulations that begin by imposing an instantaneous—thus excessively energetic—uplift of the seafloor (*e.g.*, Grilli *et al.* 2012). We adopt the term here to describe excessively energetic onsets of simulated debris flows.)

One type of hot-start initial condition involves a dam break in which a barrier that impounds debris on a slope is instantaneously or rapidly removed. Instantaneous dam breaks provide important mathematical idealizations because they precisely represent end-member behavior that can be used to test the accuracy of numerical solution techniques (*e.g.*, Mangeney *et al.*, 2000). Rapid—but not instantaneous—dam breaks also serve an important purpose in physical experiments and model testing because they provide a convenient means of creating reproducible debris flows (*e.g.*, Iverson *et al.*, 2010) (Figure 1). On the other hand, use of dam-break initial conditions in simulations of natural debris flows generally involves an unwarranted artifice because it assumes that debris in steeply sloping source areas can remain in place only if held there by an imaginary dam.

An analogous type of hot-start initial condition is used in numerical models that do not explicitly consider a dam but which nevertheless assume that a static debris mass has too little strength to satisfy a static force balance (*e.g.*, Hungr, 1995; Moretti *et al.*, 2015). The modelled debris mass is held in place merely by withholding a computer command, and issuing the command triggers motion of the debris by abruptly imposing a large force imbalance. Like dam-break initial conditions, this type of hot-start initial condition is simple and convenient to use, but it conflicts with evidence from field observations. Moreover, by imposing an instantaneous transition from an equilibrium state to a far-from-equilibrium state without any physical cause, this type of hot-start condition violates physical law.

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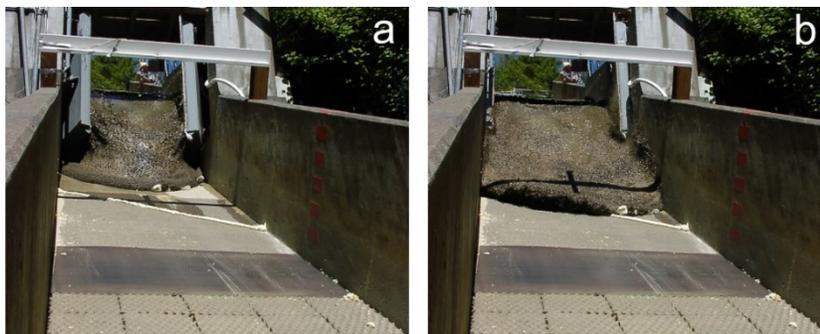


Fig. 1. Sequential photographs of a 10 m<sup>3</sup> debris flow discharging through the opening headgate at the U.S. Geological Survey debris-flow flume. (a) photo captured at  $t \approx 0.6$  s, and (b) photo captured at  $t \approx 0.8$  s, where  $t = 0$  denotes the time when the headgate began to open. A shadow visible on the flume bed and debris-flow surface is cast by a crossbar that suspends a laser depth-measurement gauge 2.5 downslope from the headgate.

Some landslide and debris-flow modelers have attempted to rationalize use of hot-start initial conditions by claiming that the physics of motion onset has no consequential effect on debris behavior downslope or downstream (*e.g.*, Aaron *et al.*, 2018). This claim is contradicted not only by qualitative field observations but also by quantitative evidence from physical experiments (*e.g.*, Iverson *et al.*, 1997, 2000) and results of numerical simulations that account for the influence of varying debris porosities on the propensity for debris liquefaction (George and Iverson, 2014; Iverson and George, 2016). Indeed, these studies show that the behavior of debris masses can be extraordinarily sensitive to initial conditions and short-timescale ( $\sim 1$  s) dynamics that unfold as downslope motion begins.

In this paper we first examine some implications of hot-start initial conditions and then summarize an alternative modeling approach that avoids hot starts. This approach requires a debris-flow model that uses physical conservation laws, values of material properties, and numerical solution methods that allow statically balanced initial states to persist indefinitely in the absence of force-balance perturbations. A satisfactory model also must account for the effect of external agents such as rainfall in gradually perturbing the static force balance, and for a natural evolution of material strength that occurs as debris begins to move, liquefies, flows downslope, and eventually forms deposits (*e.g.*, Iverson and George, 2014; George and Iverson, 2014).

## 2. Hot starts in physical experiments

Although hot starts are primarily a property of mathematical models, hot-start initial conditions are also used in physical experiments that involve either dry granular avalanches or wet debris flows suddenly released from behind barriers that impound static material on a slope (*e.g.*, Savage, 1979; Iverson and LaHusen, 1993). These “dam-break” experiments are defensible scientifically because their goal is to abstract and simplify natural phenomena rather than to simulate their full complexity. Nevertheless, a physical dam break can introduce experimental artifacts that must be considered if the purpose of the experiments is to test models that are intended ultimately to explain or simulate the behavior of natural debris flows.

A set of six dam-break debris-flow experiments conducted at the U.S. Geological Survey (USGS) debris-flow flume in June 2016 revealed some important aspects of hot-start flow behavior. In these experiments either 10 m<sup>3</sup> or 8 m<sup>3</sup> of debris consisting almost entirely of sand and gravel-sized material was initially impounded to a depth of 1.9 m behind a vertical headgate, saturated with water, and then abruptly released on a 31° slope (Figure 1) (Logan *et al.*, 2007, revised 2018; Iverson and Logan, 2017). Opening of the side-by-side doors that formed the steel headgate required  $\sim 0.8$  s and was accompanied by rapid evolution of basal normal stresses, shear stresses, and pore-fluid pressures measured beneath mobilizing debris at locations 2.23 to 2.85 m upslope from the headgate (*e.g.*, Figure 2a and 2b). Although this stress evolution largely mirrored behavior measured in natural, gravity-driven failures of loosely packed wet debris (Iverson *et al.*, 2000), it also showed evidence of experimental artifacts.

One possible artifact resulted from a nearly instantaneous  $\sim 45$  kN force drop that occurred during unlatching of the flume headgate at  $t = 0$  s. The abrupt force drop radiated seismic energy into the concrete flume bed and generated conspicuous  $\sim 10$  Hz fluctuations in basal normal stress that persisted until  $t \approx 1$  s (*e.g.*, Figure 2a and 2b). These fluctuations may have facilitated the debris liquefaction process, much as cyclic loading can cause liquefaction of saturated soils during earthquakes (*e.g.*, Jefferies and Been, 2016). However, soil liquefaction during earthquakes

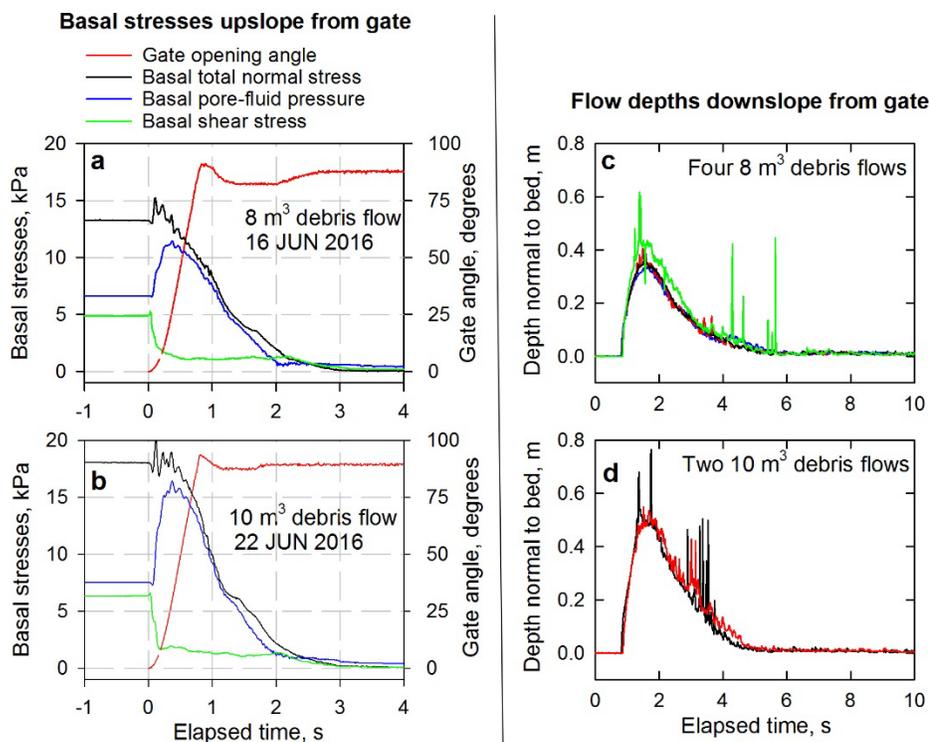


Fig. 2. Graphs of data collected in dam-break debris-flow experiments conducted at the USGS debris-flow flume in June, 2016. (a) and (b) basal stresses measured at locations 2.23 to 2.85 m upslope from the headgate as it opened in two typical experiments. (c) and (d) flow depths measured 2.5 m downslope from the headgate in six experiments. In each graph  $t = 0$  denotes the time when the gate began to open.

typically develops over tens of seconds, whereas liquefaction in our experiments was essentially complete within  $\sim 1$  s (as evidenced in Figure 2a and 2b by basal pore pressure becoming nearly equal to the total basal normal stress). Owing in part to this liquefaction, nearly all debris evacuated the area upslope from the headgate within  $\sim 3$  s (Logan *et al.*, 2007, revised 2018). However, we do not know whether similarly rapid liquefaction and debris acceleration would have occurred in the absence of radiation of seismic energy during opening of the headgate.

Despite differences in debris volumes, the six dam-break experiments conducted in June 2016 each produced flow fronts that initially traveled downslope at nearly identical speeds. At a position 2.5 m downslope from the headgate, flow-front arrival times ranged from  $t = 0.82$  s to  $t = 0.87$  s, where  $t = 0$  denotes the time the headgate began to open (Figures 2c and 2d). In comparison, a frictionless point mass released from the base of the headgate at  $t = 0$  would have required 0.995 s to travel 2.5 m downslope. Thus, the abrupt release of potential energy associated with collapse of the leading edge of the debris mass during the dam break boosted the speed of the flow fronts. On the other hand, the front speeds measured in the experiments were smaller than the front speeds predicted by analytical models of instantaneous dam breaks, which we consider next.

### 3. Hot starts in analytical models of instantaneous dam breaks

Exact analytical solutions that describe the start-up behavior of idealized, depth-averaged, dam-break flows illustrate some important mathematical properties of hot starts. We focus on 1-D dam-break solutions aimed at predicting downslope propagation speeds of flow fronts that are resisted by basal Coulomb friction, with a zero-friction case as an end member. Despite the effects of basal friction, these solutions predict flow-front speeds that exceed the speeds of frictionless point masses released from rest at the base of the dam. The high speeds reflect the influence of an idealized dam break in instantaneously converting potential energy to kinetic energy.

The first solution considers a dam that is oriented normal to the bed at  $x = 0$  and initially retains an infinite upslope reservoir of debris with uniform thickness  $h_0$  (Figure 3a). At time  $t = 0$  the dam vanishes, releasing a flow that descends a uniform slope inclined at an angle  $\theta$ . Mangeney *et al.* (2000) addressed this problem by generalizing a

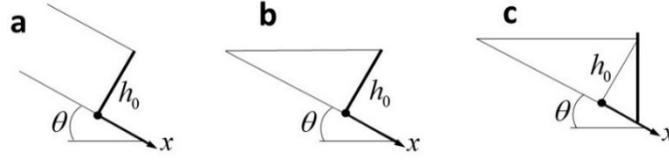


Fig. 3. Schematics illustrating different dam and debris configurations considered in analytical dam-break models. (a) bed-normal dam located at  $x=0$  with infinite, rectilinear debris reservoir upslope, (b) bed-normal dam located at  $x=0$  with finite, triangular debris reservoir upslope, (c) vertical dam located at  $x=h_0 \tan \theta$  with finite, triangular debris mass upslope. In each case the bed-normal thickness of debris at  $x=0$  is  $h_0$ .

classical dam-break analysis to obtain a solution for the downslope velocity of the flow front  $u_f$  that can be expressed as

$$u_f = Sgt + 2\sqrt{h_0 g \cos \theta} \quad (1)$$

where  $g$  is the magnitude of gravitational acceleration and  $S$  is defined as

$$S \equiv \sin \theta - \cos \theta \tan \phi_{bed} \quad (2)$$

The value of  $S$  is proportional to the difference between the downslope gravitational driving force and the upslope resisting force produced by basal Coulomb friction, which depends on the effective basal friction angle  $\phi_{bed}$ .

The two terms on the right-hand side of (1) have distinct physical implications. The term  $Sgt$  describes the growth of velocity due to steady downslope acceleration of a Coulomb point mass that begins from a position of rest at the base of the dam (i.e.,  $u_f = 0$  at  $t = 0$ ). By contrast, the term  $2\sqrt{h_0 g \cos \theta}$  describes an instantaneous velocity boost that lacks any dependence on time or frictional resistance. In the case of debris-flow flume experiments with debris initially impounded 1.9 m deep against a vertical dam face on a  $31^\circ$  slope (Figure 1), use of the formula  $2\sqrt{h_0 g \cos \theta}$  and the bed-normal debris thickness  $h_0 = 1.9 \text{ m} \times \cos \theta = 1.629 \text{ m}$  predicts that a velocity boost of 7.4 m/s applies for all  $t > 0$ .

The flow-front propagation solution (1) also applies to cases in which the reservoir of debris upslope from a bed-normal dam has a horizontal upper surface and finite length (Figure 3b). This solution can easily be obtained from an analogous dam-break solution for frictionless fluids by inserting (2) in place of  $\sin \theta$  in the derivation of Ancy *et al.*, (2008). A key implication of this solution is that the presence of a finite reservoir does not modify the terms  $Sgt$  or  $2\sqrt{h_0 g \cos \theta}$  in (1). The sum of these terms describes flow-front propagation even after an upslope-traveling wave of disturbance arrives at the upper end of the finite debris reservoir, thereby resulting in downslope motion of the entire mass of debris (Ancy *et al.*, 2008).

If a vertical rather than bed-normal dam impounds a finite mass of debris with a horizontal upper surface, then a different solution describes flow-front propagation following the dam break. In this case the base of the dam is positioned at  $x = h_0 \tan \theta$ , in which  $h_0$  is the debris thickness measured normal to the bed where  $x = 0$  (Figure 3c). Relative to the geometries discussed previously, this geometry better approximates the initial geometry used in our debris-flow flume experiments described in section 2. For this geometry an analytical solution obtained by Fernandez-Feria (2006) describes the dam-break behavior of frictionless fluids, but only for a short time following the dam break (i.e.,  $t \leq 2\sqrt{h_0/g} \left[ \tan \theta / \sqrt{\cos \theta} \right]$ , indicating the interval  $0 < t \leq 0.53 \text{ s}$  in our debris-flow flume experiments. The solution of Fernandez-Feria (2006) can be generalized to account for the effect of basal Coulomb friction by using (2) in place of  $\sin \theta$  in his analysis, thereby yielding the result

$$u_f = Sgt + \frac{\cos \theta}{\tan \theta} gt \quad (3)$$

This solution implies that the flow front behaves as an accelerating Coulomb point mass that is subject to a persistent force imbalance proportional to  $[S + (\cos \theta / \tan \theta)]g$ , which exceeds the force imbalance implied in (1). However, the flow-front speed predicted by (3) is not subject to an explicit dependence on  $h_0$  or to a time-independent velocity

boost like that described by the term  $2\sqrt{h_0 g \cos \theta}$  in (1). This key difference between (1) and (3) exists because the bed-normal thickness of impounded material adjacent to a vertical dam vanishes for all  $\theta > 0$ .

Equations (1) and (3) can be used to calculate the theoretical positions of advancing flow fronts for circumstances like those in the debris-flow flume experiments summarized in Figures 1 and 2. Predicted flow-front positions  $x_F(t)$  are obtained by integrating the equation  $dx_F/dt = u_F$ . Use of (1) and the initial condition  $x_F(0) = 0$  in this integration yields the prediction

$$x_F = (1/2)Sgt^2 + 2t\sqrt{h_0 g \cos \theta} \quad , \quad (4)$$

whereas use of (3) and the initial condition  $x_F(0) = h_0 \tan \theta$  yields the prediction

$$x_F = (1/2)[S + (\cos \theta / \tan \theta)]gt^2 + h_0 \tan \theta \quad . \quad (5)$$

Inserting  $t = 0.5$  s along with the experimental values  $\theta = 31^\circ$  and  $h_0 = 1.9 \text{ m} \times \cos \theta = 1.629 \text{ m}$  in (4) and (5) yields results that are summarized in Table 1 for limiting cases with no basal friction (i.e.,  $S = \sin \theta$ ) and with basal friction that is sufficient to counteract the entire downslope driving force (i.e.,  $S = 0$ ). For reference, the table also lists  $x_F$  values calculated for a point mass that is released at  $x = 0$  and obeys  $x_F = (1/2)Sgt^2$ . The tabulated values show that the distances of flow-front advance predicted for a bed-normal dam are larger than those predicted for a vertical dam, and that each of these predictions greatly exceeds the prediction for a point mass released at  $x = 0$  in the absence of a dam of finite height.

The predicted flow-front arrival time  $t_F$  at a specified downslope distance  $x$  can be calculated by performing some simple algebraic manipulations of (4) and (5). Table 1 lists  $t_F$  values calculated for  $x = 2.5$  m. For this location, data collected in our June 2016 debris-flow flume experiments yielded flow-front arrival times with a mean and standard deviation  $t_F = 0.846 \pm 0.016$  s (Figure 2c and 2d). All predictions of  $t_F$  listed in Table 1 differ significantly from this measured value. Indeed, the most accurate prediction of  $t_F$  is provided by the simplest and most naïve model, the frictionless point-mass model. This finding reveals the limitations of hot-start dam-break solutions in evaluating physical scenarios, even if those scenarios are as highly idealized as they are in our dam-break debris-flow experiments.

Table 1. Analytical predictions of flow-front position  $x_F$  at  $t = 0.5$  s and flow-front arrival time  $t_F$  at  $x = 2.5$  m.

Basis of prediction	$S = 0$ (maximum friction)		$S = \sin \theta$ (frictionless)	
	$x_F$ at $t = 0.5$ s	$t_F$ at $x = 2.5$ m	$x_F$ at $t = 0.5$ s	$t_F$ at $x = 2.5$ m
equation (4), bed-normal dam	3.70 m	0.338 s	4.33 m	0.306 s
equation (5), vertical dam	2.73 m	0.483 s	3.36 m	0.414 s
point mass with no dam	0 m	$\infty$	0.63 m	0.995 s

#### 4. Hot starts in numerical models of natural debris flows

Rather than simulating dam breaks, numerical models commonly implement hot starts by using a computational artifice in which the specified geometry of an initially static debris mass is intentionally mismatched with the debris frictional resistance. In such models resistance typically is set to a value far smaller than is necessary to statically balance forces in debris-flow source areas, but motion of the modeled debris is held in check by withholding a computer command (e.g., Hungr, 1995; Moretti *et al.*, 2015; Aaron *et al.*, 2017). Then, when a command is issued, the debris mass is instantaneously released with a great excess of net driving force, analogous to launching it downslope with a slingshot.

The implications of this hot-start tactic can be illustrated by considering a very simple model that lies at the quantitative heart of many complicated debris-flow dynamics models. The simple model stipulates that the downslope velocity  $u$  of a debris flow's center of mass obeys Newton's second law as summarized by the equation of motion  $du/dt = Sg$ , which can be rewritten as

$$\frac{du}{dt} = g \sin \theta \left[ 1 - \frac{\tan \phi_{bed}}{\tan \theta} \right], \quad (6)$$

where  $\phi_{bed}$  is an effective basal friction angle that implicitly accounts for any effects of pore-fluid pressure. For physically valid initial states in which static debris is poised to begin downslope motion, (6) indicates that  $\tan \phi_{bed} = \tan \theta$  must be satisfied. This condition places an unambiguous constraint on the value of  $\phi_{bed}$ , yet numerical models that use hot starts ignore this constraint and commonly use values similar to  $\tan \phi_{bed} \approx 0.5(\tan \theta)$  instead (e.g., Moretti *et al.*, 2015; Aaron *et al.*, 2017).

The motion predicted by (6) depends strongly on whether there is a small perturbation of a statically balanced initial state (e.g.,  $\tan \phi_{bed} / \tan \theta = 0.9999$ ) or a large perturbation like that implied by  $\tan \phi_{bed} / \tan \theta = 0.5$ . Integration of (6) shows that the predicted instantaneous speed ( $u$ ) in either case is proportional to  $[1 - (\tan \phi_{bed} / \tan \theta)]t$  and that the predicted distance travelled ( $x$ ) is proportional to  $[1 - (\tan \phi_{bed} / \tan \theta)]t^2$ . Table 2 lists numerical values of such predictions for motion down a uniform slope inclined at the angle  $\theta = 31^\circ$  (the angle of the USGS debris-flow flume).

The results listed in Table 2 illustrate why it is tempting for modelers to use hot-start initial conditions rather than physically valid initial conditions that involve small perturbations of statically balanced initial states. Flow speeds and travel distances obtained by assuming that  $\tan \phi_{bed} / \tan \theta = 0.5$  applies may be far more realistic than those obtained by using  $\tan \phi_{bed} / \tan \theta = 0.9999$ . Indeed, the predictions obtained by using  $\tan \phi_{bed} / \tan \theta = 0.9999$  are more suitable for a slowly creeping landslide than for a fast-moving debris flow, whereas those obtained by using  $\tan \phi_{bed} / \tan \theta = 0.5$  indicate that after 100 s, a debris flow has traveled nearly 500 m and reached a speed of nearly 10 m/s—values that are quite plausible in many circumstances. However, while the numerical results obtained by using a hot start with  $\tan \phi_{bed} / \tan \theta = 0.5$  may seem pleasing, the underlying physics are deeply flawed. The large speeds and travel distances attained by modeled debris flows with  $\tan \phi_{bed} / \tan \theta = 0.5$  are merely artifacts of using physically implausible hot-start initial conditions and inappropriate parameter values.

Table 2. Dynamic responses to different perturbations of a balanced initial state, as indicated by solutions of (6).

Elapsed time (s)	Small perturbation, $\tan \phi_{bed} / \tan \theta = 0.9999$		Large perturbation, $\tan \phi_{bed} / \tan \theta = 0.5$	
	Speed, $u$ (m/s)	Distance traveled, $x$ (m)	Speed, $u$ (m/s)	Distance traveled, $x$ (m)
1	1.981e-5	$9.906 \times 10^{-6}$	0.09906	0.04953
4	7.925e-5	$1.584 \times 10^{-4}$	0.3962	0.7925
10	1.981e-4	$9.906 \times 10^{-4}$	0.9906	4.012
20	3.962e-4	$3.962 \times 10^{-3}$	1.981	19.81
50	9.906e-4	0.02476	4.953	123.8
100	1.981e-3	0.09906	9.906	495.3

## 5. An alternative to hot starts

Physically valid models of natural debris flows must avoid hot starts, but how can this be accomplished? The basic requirements are that such a model must be compatible with a statically balanced initial state and must simulate an evolution of debris strength that occurs after motion is triggered by a small perturbation of the static balance. A simplistic way to accomplish this goal is through arbitrary adjustments of debris strength. For example, a model might stipulate that the static debris strength decays gradually until downslope motion commences, and that the strength then continues to decline to emulate a transition to a more mobile, flowing state. With a sufficient number of adjustments of flow resistance, this model-tuning approach could yield results that match observations quite precisely. However, such an approach is essentially an elaborate curve-fitting exercise that has no explanatory power and limited value for making useful predictions. It merely mimics observed physical behavior rather than explaining it.

A requisite feature of a physically based debris-flow model that has both explanatory power and value as a predictive tool is that it accounts for natural transitions in debris strength through solution of evolution equations that are integral components of the model. Indeed, the central scientific problem in understanding and predicting the dynamics of landslides and debris flows is to quantify not only the effects but also the physical causes of strength evolution that occurs naturally during downslope motion. As noted by Johnson (1970), the most remarkable property of debris is its ability to flow fluidly in some circumstances and behave almost rigidly in others. From a scientific perspective, this property demands explanation, and not merely emulation.

Our depth-averaged numerical model D-Claw explains and simulates natural transitions in debris strength by solving differential equations that describe evolving distributions of solid volume fraction and pore-fluid pressure. These differential equations are strongly coupled to additional differential equations that describe the evolving distributions of debris mass and momentum (Iverson and George, 2014, 2016; George and Iverson, 2014). The system of coupled equations shows how pore-fluid pressure responds to dilation or contraction of the granular solid phase, such that contractive deformation drives up the fluid pressure. In turn, increases in fluid pressure reduce the intergranular effective normal stress and thereby reduce the effects of intergranular Coulomb friction, which provides most of the resistance to debris motion.

In D-Claw simulations, the highest flow mobility develops when debris becomes fully liquefied (*i.e.*, has zero effective normal stress). In this case the only resistance to motion is provided by viscous shearing of the debris' fluid phase. The lowest degree of mobility develops when all positive pore-fluid pressure has dissipated and the debris behaves as a Coulomb granular solid. The conceptual and mathematical framework of this model generalizes the Coulomb mixture-theory framework presented by Iverson and Denlinger (2001) by accounting for dilatancy and its coupling to debris motion. The D-Claw framework also generalizes some key principles of critical-state soil mechanics (*e.g.*, Wood, 1990) by considering the effects of inertial forces.

D-Claw simulations begin by specifying a statically balanced initial state and then perturbing the static balance by gradually increasing the basal pore-fluid pressure—as might occur naturally in response to rainfall or snowmelt. Pore-pressure increases can be either spatially uniform or nonuniform, but in all cases debris motion begins locally when the pore pressure in some computational cell becomes large enough to destabilize the static force balance there. The local force balance is, however, influenced by lateral stresses imposed by neighboring computational cells. Motion thereby begins in the weakest finite sector of a debris mass, which may or may not set off a chain reaction of motion in adjacent sectors as momentum is transferred from moving debris to static debris. If motion is accompanied by contractive deformation that drives up the pore pressure, then it can instigate a positive feedback process in which further motion yields even higher pore pressure and ultimately leads to liquefaction. If the feedback is strong, a complete transformation from slow, rigid-body motion to highly fluid flow can occur within seconds—leading to a style of debris-flow onset like that observed in physical experiments (*e.g.*, Iverson *et al.*, 1997, 2000).

## 6. Conclusion

Hot starts arise from use of initial conditions in which a large force balance is abruptly imposed on a static debris mass. Debris-flow models that rely on hot starts to simulate high flow mobility lack a sound scientific basis. Indeed, numerical models that use hot starts impose an instantaneous transition from equilibrium to far-from-equilibrium states, which is inconsistent with physical principles as well as field observations. A possible exception to this inconsistency exists when debris flows are triggered by strong earthquakes, but even in those circumstances, the onset of debris motion begins when a static force balance is infinitesimally violated.

Hot starts can serve useful scientific purposes in other contexts, as when dam-break debris-flow onsets are used to create reproducible experiments or analytical dam-break solutions are used to test the accuracy of computational algorithms. Dam-break behavior nevertheless fails to represent the behavior exhibited during the early stages of motion of most natural debris flows. Indeed, results we report in this paper indicate that analytical dam-break solutions can yield poor predictions of measured flow-front speeds—even under the idealized circumstances of our dam-break debris-flow experiments.

Use of hot starts can be avoided in properly formulated debris-flow models that account rigorously for statically balanced initial states. In these models motion is triggered by an infinitesimal perturbation of the balanced state, but the subsequent force balances and flow accelerations can evolve rapidly during the early stages of motion. Evidence from our debris-flow flume experiments indicates that a requisite feature of these models is representation of the pore-pressure feedback process that allows a nearly rigid granular mass to transition into a flowing, liquefied mass, and then transition back to a nearly rigid mass following pore-pressure dissipation.

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## References

- Aaron, J., Hungr, O., Stark, T.D., and Baghdady, A.K., 2017, Oso, Washington, Landslide of March 22, 2014: Dynamic Analysis, *J. Geotech. Geoenviron. Eng.*, v. 143, 05017005. doi: 10.1061/(ASCE)GT.1943-5606.0001748.
- Aaron, J., Stark, T.D., and Baghdady, A.K., 2018, Closure to "Oso, Washington, Landslide of March 22, 2014: Dynamic Analysis" by Jordan Aaron, Oldrich Hungr, Timothy D. Stark, and Ahmed K. Baghdady, *J. Geotech. Geoenviron. Eng.*, v. 144, 07018023, doi: 10.1061/(ASCE)GT.1943-5606.0001748.
- Ancey, C., Iverson, R.M., Rentschler, M., and Denlinger, R.P., 2008, An exact solution for ideal dam-break floods on steep slopes. *Water Resources Research*, v. 44, W01430, doi:10.1029/2007WR006353.
- Fernandez-Feria, R., 2006, Dam-break flow for arbitrary slopes of the bottom, *J. Engineering Mathematics*, v. 54, p. 319–331, doi: 10.1007/s10665-006-9034-5.
- George, D.L., and Iverson, R.M., 2014, A depth-averaged debris-flow model that includes the effects of evolving dilatancy. II. numerical predictions and experimental tests, *Proc. Royal Society London, Ser. A*, v. 470, doi: 10.1098/rspa.2013.0820
- Grilli, S.T., Jarris, J.C., Bakhsh, S.T., Masterlark, T.L., Kyriakopolous, C., Kirby, J.T., and Shi, F., 2012, Numerical simulation of the 2011 Tohoku tsunami based on a new transient FEM co-seismic source: comparison to far- and near-field observations, *Pure and Applied Geophysics*, v. 170, 1333-1359. doi: 10.1007/s00024-012-0528-y.
- Hungr, O., 1995, A model for the runout analysis of rapid flow slides, debris flows, and avalanches, *Canadian Geotech. J.*, v. 32, p. 610-623, doi: 10.1139/t95-063.
- Iverson, R. M., and LaHusen, R.G., 1993, Friction in debris flows: Inferences from large-scale flume experiments, *Hydraulic Engineering '93* (Proceedings of the 1993 Conference of the Hydraulics Division of the American Society of Civil Engineers), v. 2, p. 1604–1609, *Am. Soc. of Civ. Eng.*, New York.
- Iverson, R.M., Reid, M.E., and LaHusen, R.G., 1997, Debris-flow mobilization from landslides: *Annual Rev. Earth and Planetary Sciences*, v. 25, p. 85-138.
- Iverson, R.M., Reid, M.E., Iverson, N.R., LaHusen, R.G., Logan, M., Mann, J.E., Brien, D.L., 2000, Acute sensitivity of landslide rates to initial soil porosity, *Science*, v. 290, p. 513-516.
- Iverson, R.M., and Denlinger, R.P., 2001, Flow of variably fluidized granular masses across three-dimensional terrain: 1. Coulomb mixture theory, *J. Geophys. Res. Solid Earth*, v. 106, B1, p. 537-552. doi: 10.1029/2000JB900329.
- Iverson, R.M., Logan, M., LaHusen, R.G., and Berti, M., 2010, The perfect debris flow? aggregated results from 28 large-scale experiments. *J. Geophys. Res. Earth Surface*, v. 115, F03005, doi:10.1029/2009JF001514.
- Iverson, R.M., and George, D.L., 2014, A depth-averaged debris-flow model that includes the effects of evolving dilatancy. I. physical basis, *Proc. Royal Society London, Ser. A*, v. 470, 20130819, doi: 10.1098/rspa.2013.0819
- Iverson, R.M., and George, D.L., 2016, Modeling landslide liquefaction, mobility bifurcation and the dynamics of the 2014 Oso disaster. *Geotechnique*, v. 66, p. 175–187, doi: 10.1680/jgeot.15.LM.004.
- Iverson, R.M., and Logan, M., 2017, Sensor data from debris-flow experiments conducted in June, 2016, at the USGS debris-flow flume, HJ Andrews Experimental Forest, Blue River, Oregon: U.S. Geological Survey Data Release, doi: 10.5066/F7N58JKH.
- Jefferies, M., and Been, K., 2016, *Soil Liquefaction a Critical-state Approach*, 2<sup>nd</sup> Edition, CRC Press, Boca Raton, Florida, 690 p.
- Johnson, AM., 1970, *Physical Processes in Geology*, Freeman, Cooper and Company, San Francisco, 577 p.
- Logan, M., Iverson, R.M., and Obryk, M.K., 2007 (revised 2018), Video documentation of experiments at the USGS debris-flow flume, 1992-2017. U.S. Geological Survey Open-file Report 2007-1315 (<http://pubs.usgs.gov/of/2007/1315/>).
- Mangeney, A., Heinrich, P., and Roche, R., 2000, Analytical solution for testing debris avalanche numerical models, *Pure and Applied Geophysics*, v. 157, p. 1081-1096.
- Moretti, L., Allstadt, K., Mangeney, A., Capdeville, Y., Stutzmann, E., and Bouchut, F., 2015, Numerical modeling of the Mount Meager landslide constrained by its force history derived from seismic data, *J. Geophys. Res. Solid Earth*, v. 120, p. 2579–2599, doi:10.1002/2014JB011426.
- Savage, S.B., 1979, Gravity flow of cohesionless granular materials in chutes and channels, *J. Fluid Mechanics*, v. 92, p. 53-96, doi: 10.1017/S0022112079000525.
- Wood, D.M., 1990, *Soil Behavior and Critical State Soil Mechanics*, Cambridge University Press, Cambridge, 465 p.