Natural hazards explained

Debris flows: behaviour and hazard assessment

Debris flows are water-laden masses of soil and fragmented rock that rush down mountainsides, funnel into stream channels, entrain objects in their paths, and form lobate deposits when they spill onto valley floors. Because they have volumetric sediment concentrations that exceed 40 percent, maximum speeds that surpass 10 m/s, and sizes that can range up to ~10^9 m^3, debris flows can denude slopes, bury floodplains, and devastate people and property. Computational models can accurately represent the physics of debris-flow initiation, motion and deposition by simulating evolution of flow mass and momentum while accounting for interactions of debris' solid and fluid constituents. The use of physically based models for hazard forecasting can be limited by imprecise knowledge of initial and boundary conditions and material properties, however. Therefore, empirical methods continue to play an important role in debris-flow hazard assessment.

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Debris flows are common phenomena in mountainous regions world-wide. Their chief characteristics have long been apparent to astute observers:

> When a… slope of grit and shingle has been soaked like a sponge by rain or melting snows there may come a time when it… slides off… Slipping into channels and gullies this mass… attains a higher speed and carries away soft material as well as rocks which it finds on its way. It is during this descent that the mudspate generally acquires its characteristic composition, for only by movement can an even mixture of liquid and solids be maintained. …When left to itself… the middle of the mud runs faster because there is less friction, while at the sides, retarded by friction, deposition takes place giving rise to an embankment, so that the crawling leviathan builds its own track.
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> —W.R. Rickmers, *The Duab of Turkestan*, pp.194–197, Cambridge University Press, 1913.

Rickmers' colourful description shows that he appreciated the importance of solid–fluid interactions in debris flows, and that he recognized sediment entrainment and lateral levee formation as common features of debris-flow behaviour. Furthermore, although he focused his observations in a region comprising parts of modern-day Uzbekistan, Tajikistan, Kyrgyzstan and Kazakhstan, Rickmers remarked on the abundance of debris-flow deposits along mountain fronts elsewhere. He understood that these deposits were emplaced by recurrent prehistoric debris flows—with clear implications for debris-flow hazards in the future (Fig. 1).

While Rickmers' term 'mudspate' has faded from use during the past century, 'debris' and 'flow' have acquired precise geological meanings. 'Debris' indicates that sediment grains with diverse sizes and irregular shapes are present. This trait fundamentally distinguishes debris-flow mixtures from most man-made granular mixtures, because it implies that no characteristic grain size can be used to assess grain-fluid and grain-grain interactions. The term 'flow' indicates that rearrangement of grain contacts is pervasive during debris-flow motion. Indeed, wet, agitated debris consisting mostly of solid rock can sometimes appear to flow almost as fluidly as water. This remarkable mobility intrigues scientists today no less than it intrigued Rickmers.

Fig. 1. Oblique aerial photograph of source areas and runout paths of some of the devastating debris flows that were responsible for more than 20 000 fatalities in Vargas state, Venezuela, December 1999 (Photo by Matthew Larsen, US Geological Survey).

A modern perspective of debris-flow behaviour

Over the past 50 years, studies of debris flows have matured into rigorous scientific investigations combining field measurements, controlled experiments, and mechanistic analyses. This body of work has demonstrated that debris flows typically involve a characteristic sequence of events:

1. Most debris flows originate from discrete or distributed source areas where slopes steeper than about 25 to 30 degrees are mantled with low-cohesion soil and/or fragmented rock. This marginally stable debris becomes at least partly saturated through a rapid introduction of surface water or groundwater, commonly as a result of intense rainfall or snowmelt. Water-laden debris starts to shear and move downslope when at some depth frictional forces cannot resist driving forces—irrespective of whether the debris is positioned on slopes or in water-filled channels.
2. As it begins to move downslope, loosely packed debris contracts, driving up pore-water pressures and promoting runaway liquefaction and pervasive deformation that is recognizable as flow. Debris flows can also originate from densely packed debris, provided that sufficient water is available to fill dilating pores as motion commences. In some cases dilation can transition to contraction as a result of the mechanical breakdown of clay aggregates. Mobilization of dense debris is a relatively piecemeal process, however.
3. Downslope motion of a mass of debris converts some fraction of its translational kinetic energy into random kinetic energy (i.e. debris agitation). Consequent grain rearrangement and jostling can involve brief, inelastic collisions as well as enduring frictional contacts. As grains exchange momentum with one another, they simultaneously exchange momentum with adjacent pore fluid. Locally, lubrication forces develop as viscous fluid is squeezed between converging grains. On a bulk continuum scale comprising many grains and pores, the effects of solid–fluid momentum exchange are manifested as disequilibrium (i.e. nonhydrostatic) distributions of pore-fluid pressure.
4. Development and persistence of high pore-fluid pressures where debris contracts is promoted by sustained hydrodynamic suspension of mud-sized particles (< 63 μm), which increase the effective viscosity of the fluid fraction of the debris. This enhanced viscosity facilitates debris-flow motion by impeding pore-pressure relaxation and reducing energy dissipation that occurs when larger grains contact one another. Debris that retains high mobility for several minutes or more generally contains at least a few weight percent mud-sized particles, but it does not contain so much mud that the effects of mud shear strength outweigh the effects of mud on pore-fluid pressure. (If mud shear strength plays a dominant role, a debris flow might be better described as a mud flow, but true mud flows rarely occur in subaerial environments.)
5. Debris flows commonly grow in size by entraining sediment, water and miscellaneous flotsam as they descend steep slopes and channels. Entrainment can occur by scour of bed material or collapse of channel banks, and it can cause the volume of a debris flow to increase tenfold or more before deposition begins on flatter terrain downstream. Debris flows in forested regions commonly entrain a cargo of wood.
6. Abrupt, steep surge fronts form at the heads of moving debris flows. Large boulders (with diameters exceeding 10 m in some cases) and logs accumulate at surge fronts as a result of grain-size segregation and migration within the debris, but large clasts can also be scoured from the bed and retained at surge fronts.
7. Water-saturated debris that trails surge fronts commonly resembles wet, flowing concrete or roiling quicksand. Thus, as described by R.P. Sharp & L.H. Nobles in 1953, a debris-flow surge front commonly behaves as a 'bouldery dam... pushed along by the finer, more fluid debris impounded behind.'

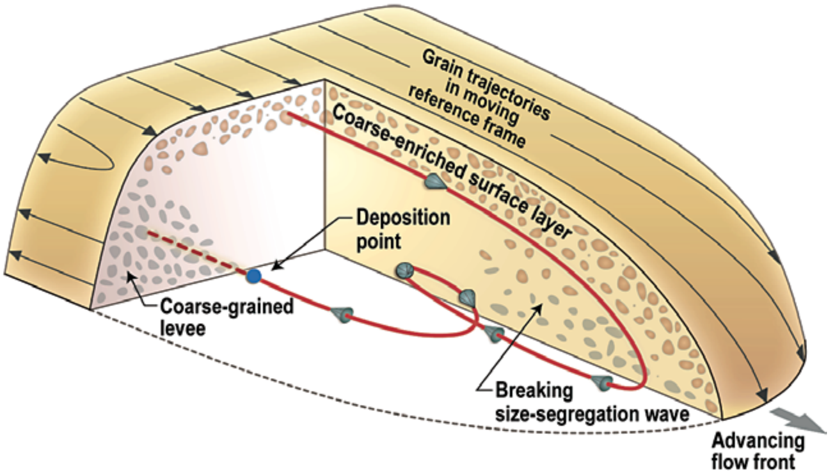

Fig. 2. Schematic cutaway illustration of the process leading to formation of a coarse-grained lateral levee behind an advancing debris-flow front. The path of a representative near-surface grain is shown in red. The reference frame moves forward at the speed of the advancing flow front, so that a grain moving forward less rapidly than the front appears to move backwards (for details see Johnson *et al.*, 2012).

8 Lateral levees form where liquefied debris shoulders aside coarse, high-friction debris at surge fronts, most commonly where debris flows escape lateral confinement by overtopping stream banks or discharging onto broad alluvial fans or plains (Fig. 2). These self-formed levees can channelize flow and thereby increase distances of flow runout.

9 Depositional lobes form where the frictional resistance of coarse-grained flow fronts and margins is sufficient to halt motion of the trailing, liquefied debris. Bodies of fresh debris-flow deposits are generally too weak for people to traverse on foot, although coarse-grained lateral levees and distal margins of fresh deposits commonly afford more secure footing.

10 Following emplacement, debris-flow deposits gradually dewater and consolidate to a degree that allows secure passage on foot. As desiccation proceeds, deposits become nearly rigid, but this process commonly requires several days to months.

11 Recent debris-flow deposits are easily recognized owing to their distinctive surface morphology and composition (Fig. 3). More difficult to recognize are ancient deposits exposed only in stratigraphic cross-sections. Exposures of levee deposits may consist entirely of gravel and boulders, whereas other parts of the same debris-flow deposit may consist of matrix-supported gravel and boulders or of predominantly fine-grained sediment.

Physically based debris-flow models

Physically based mathematical models help codify our understanding of debris-flow behaviour, and they can also be used make testable predictions. Indeed, the ability of such models to predict the outcomes of diverse, controlled experiments serves as the best gauge of scientific understanding of debris-flow mechanics (Fig. 4). The simulation of natural debris flows provides an additional proving ground for physically based models, but it seldom provides decisive tests because natural events typically involve poorly constrained initial and boundary conditions, and unmeasured material properties. The effects of unresolved heterogeneities (such as a topography that is poorly represented in a DEM) can further bedevil model testing. Thus, even if a model is entirely sound physically, mathematically and computationally, it can fail to predict the behaviour of a natural debris flow if adequate knowledge of the initial conditions, terrain or material properties is lacking.

Sound physically based debris-flow models accurately represent the evolution of flow mass and momentum in response to net forcing. Forces that drive debris-flow motion are easy to determine because they are caused solely by gravity, but an evaluation of resisting forces is complicated by the fact that debris rheology evolves as static source material mobilizes, flows, and later regains rigidity in static deposits. Single-phase debris-flow models cannot represent these transitions without an *ad hoc* manipulation of rheological coefficients, but two-phase models can predict a natural evolution of debris rheology as the solid and liquid phases exchange momentum during debris dilation and contraction (Fig. 5). An evolution of rheology enables the use of realistic initial conditions with statically balanced forces—as opposed to dam-break initial conditions that assume an unstable mass is poised in a source area and then artificially released.

Most physically based debris-flow models employ depth-integrated mass- and momentum-conservation

Fig. 3. Panoramic image of multiple boulder levees and lobes in a debris-flow deposit formed in November, 2006, on Eliot Branch of the Middle Fork Hood River, Oregon, USA. Debris-flow source area was near treeline on snow-clad Mount Hood in the distance (Copyrighted image used by permission of Darryl Lloyd / LongshadowPhoto.com).

equations, which are similar to classical shallow-water equations that are often used to model flood waves and tsunamis. The depth integration of 3-D conservation laws absorbs basal and flow-surface boundary conditions into 2-D, depth-integrated evolution equations that describe behaviour of a debris flow as a whole. The boundary conditions are thereby satisfied automatically as part of the equations' solution. This property facilitates an incorporation of debris entrainment effects in models, and it also speeds computations. Further gains in computational efficiency result from the fact that depth-integrated models neglect or approximate one component of flow momentum (i.e. the vertical or bed-normal component). This simplification causes some loss of physical accuracy, however. Substantial efforts to correct for the effects of neglected or approximated momentum have been made in extended shallow-water theories, but in debris-flow modelling such efforts are only beginning.

Numerical methods used to solve depth-integrated debris-flow equations must be robust enough to simulate the development of shocks (e.g. hydraulic jumps) that can arise when rapidly moving debris flows encounter obstacles or abrupt changes in topography. Some traditional numerical methods lack this capability, making it impossible to test the veracity of underlying mathematical models. On the other hand, modern shock-capturing numerical methods such as the finite-volume method can provide accurate solutions because they can evaluate discontinuous fluxes of conserved quantities (e.g. mass and momentum) as they are transferred between adjacent computational cells. A key challenge when using finite-volume methods arises from the complicating effects of source terms that summarize the driving and resisting forces, however. These effects must be well balanced numerically, or else the computation will be unable to preserve a static state in debris that is poised on a slope prior to the onset of debris-flow motion. Indeed, the ability to simulate statically balanced states as well as flowing states can serve as a benchmark test for all physically based debris-flow models.

Fig. 4. Photograph of an 18 m^3 experimental debris flow discharging from the mouth of the 95-m-long USGS flume near Blue River, Oregon, USA (for details see Iverson *et al.*, 2010, 2011).

Debris-flow hazard assessment

Debris-flow hazard assessments must address two kinds of questions. First, where and when will debris flows occur, and how large will they be? And second, how fast will debris flows travel, and what areas will be impacted downstream? Answers to the first type of question require knowledge of hydrological conditions favouring the development of debris flows, whereas answers to the second type require a knowledge of behaviour during flow runout.

The most obvious factor influencing the propensity for debris-flow initiation is the presence of slopes steeper than about 25 to 30 degrees, because flatter terrain has little potential for spawning debris flows. Another obvious contributing factor is geology. Lithologies and structures that weather to produce an abundance of soil and scree provide conditions favourable for debris flows. Therefore, early debris-flow hazard maps identified prospective debris-flow source areas where steep slopes coincided with susceptible geological units. In later efforts, the influences of slope and geology were considered in a more mechanistic way, commonly by representing the effects of slope angle and strength in an infinite-slope stability model and assuming some distribution of pore-water pressure. Additional refinements involved estimating the influence of topographic curvature on groundwater (especially in hillslope hollows), and estimating maxi-

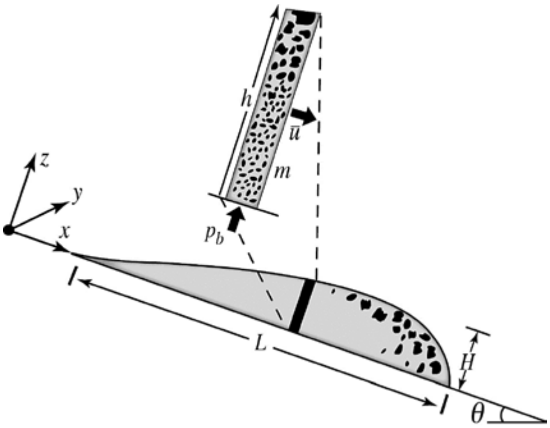

Fig. 5. Schematic vertical cross section illustrating a depth-integrated debris-flow model in which flow velocity, $\bar{u}$, flow depth, h, solid volume fraction, m, and basal pore-fluid pressure, p_b evolve as functions of position and time. Depth-integrated models are commonly applicable if $H/L \ll 1$, where H and L are the characteristic flow thickness and length (for details see George & Iverson, 2011).

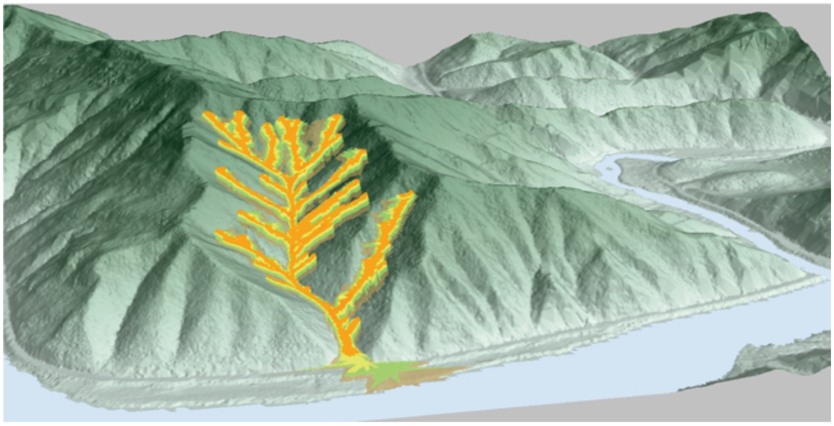

Fig. 6. Oblique aerial perspective of statistically computed debris-flow hazard zones in a watershed adjacent to the Umpqua River, Oregon, USA. Warmer colors denote higher relative hazard (for details see Griswold & Iverson, 2008).

mum probable debris-flow volumes originating in prospective source areas. Similar strategies are still used today, and have been automated through the use of digital map-manipulation tools such as geographical information systems (GIS). However, traditional map-based approaches to hazard assessment do not attempt to identify the timing of debris-flow onset.

Forecasting of debris-flow timing is crucial for issuing hazard warnings, and has focused largely on rainfall as a triggering agent. The earliest approaches to this problem emphasized an empirical identification of combinations of rainfall intensity and duration that provoke widespread debris flows. Still in use today, rainfall intensity-duration thresholds for debris-flow triggering have been identified for the entire Earth, and more-specialized thresholds have been identified for geographic regions characterized by specific combinations of geology, topography, hydrology and land use. Recently, refinements in evaluating the role of rainfall have been made through the application of Bayesian statistical methods that use data from prior events to identify the probabilities (and not merely the triggering thresholds) of future events.

Another recent advance involves the development of physically based models of transient rainfall infiltration and its effect on evolving pore-pressure distributions that may instigate debris flows. The most sophisticated models combine digital map-based methods of hazard-zone delineation with spatially distributed hydrologic and slope-stability models. However, such physically based debris-flow initiation models demand considerable input data. Like physically based flow-dynamics models, their predictions can fail as a result of unresolved geological heterogeneities—even if a mathematical representation of the underlying physical processes is flawless.

Forecasting debris-flow speeds and inundation areas commonly entails a use of physically based, deterministic flow-dynamic simulations, with all of their associated benefits and detriments. Flow-dynamic models hold one clear advantage over flow-initiation models, however: they exploit Newton's second law relating accelerations to net forces. (An error of 10 percent in the evaluation of net forces will cause commensurate errors in computed flow accelerations, but such errors do not render results 100% fallacious. In contrast, a 10 percent error in the evaluation of the static force balance that governs flow initiation can make a deterministic prediction of debris-flow onset unequivocally wrong). Like flow-initiation models, flow-dynamic models can incorporate probabilistic components by adopting a range of plausible values for material properties and initial conditions, and computing a corresponding range of possible outcomes. Such methodology can place errors and uncertainties in their proper context.

Probabilistic debris-flow inundation forecasts can be accomplished in a less detailed way by exploiting statistical patterns exhibited by prior events. For example, several studies have shown that both channel cross-sectional areas and planimetric areas inundated by debris flows in diverse settings are commonly proportional to flow volume raised to the 2/3 power. Statistically calibrated relationships of the form $area \propto volume^{2/3}$ thus be used in computational algorithms that employ a range of hypothetical flow volumes and initiation sites to compute the limits of prospective inundation areas and display them on DEMs. Such algorithms can thereby generate gradational hazard-zonation maps (Fig. 6). The modest data requirements of these methods gives them lasting value, even as physically based forecasting models become more realistic, reliable and accessible.

Conclusions

Debris flows have attracted the attention of scientists for more than 100 years, and over the past half-century, great advances have been made in understanding debris-flow behaviour and hazards. Current understanding of debris flows is codified most succinctly in physically based mathematical models. Further testing and refinement of these models will likely lead to improvements in predictive power and a more widespread use in practical applications. On the other hand, empirical methods of hazard assessment will continue to have utility owing to their relatively modest data requirements, ease of use, and suitability for probabilistic forecasting.

Suggestions for further reading

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