DOI: 10.4408/IJEGE.2011-03.B-042

ENTRAINMENT OF BED SEDIMENT BY DEBRIS FLOWS: RESULTS FROM LARGE-SCALE EXPERIMENTS

Mark E. REID(*), Richard M. IVERSON(**), Matthew LOGAN(**), Richard G. LAHUSEN(**), Jonathan W. GODT(***) & Julie P. GRISWOLD(**)

(*) U.S. Geological Survey, 345 Middlefield Road, MS 910 - Menlo Park - CA 94025 USA;
Email: mreid@usgs.gov; tel: +1-650-329-4891
(**) Cascades Volcano Observatory, U.S. Geological Survey, 1300 SE Cardinal Ct. #100 - Vancouver - WA 98683 USA
(***) U.S. Geological Survey, Denver Federal Center, Box 25046, MS 966 - Denver - CO 80225 USA

ABSTRACT

When debris flows grow by entraining sediment, they can become especially hazardous owing to increased volume, speed, and runout. To investigate the entrainment process, we conducted eight large-scale experiments in the USGS debris-flow flume. In each experiment, we released a 6 m^3 water-saturated debris flow across a 47-m long, ~12-cm thick bed of partially saturated sediment lining the 31º flume. Prior to release, we used low-intensity overhead sprinkling and real-time monitoring to control the bed-sediment wetness. As each debris flow descended the flume, we measured the evolution of flow thickness, basal total normal stress, basal pore-fluid pressure, and sediment scour depth. When debris flows traveled over relatively dry sediment, net scour was minimal, but when debris flows traveled over wetter sediment (volumetric water content > 0.22), debris-flow volume grew rapidly and flow speed and runout were enhanced. Data from scour sensors showed that entrainment occurred by rapid (5-10 cm/s), progressive scour rather than by mass failure at depth. Overriding debris flows rapidly generated high basal pore-fluid pressures when they loaded and deformed bed sediment, and in wetter beds these pressures approached lithostatic levels. Reduction of intergranular friction within the bed sediment thereby enhanced scour efficiency, entrainment, and runout.

Key words: debris flow, sediment entrainment, scour, large-scale experiment, pore-fluid pressure, soil moisture

INTRODUCTION

Debris flows that entrain sediment by scouring channel beds or undermining channel banks can become exceptionally mobile and destructive (Hungr *et alii*, 2005). They typically inundate larger regions than flows lacking entrainment, and they can originate in diverse geographic settings, including steep mountainous regions (Benda, 1990; Berti *et alii*, 2000; Berti & Simoni, 2005; Breien *et alii*, 2008), volcano flanks (Pierson *et alii*, 1990), denuded post-wildfire watersheds (Cannon & Reneau, 2000; Larsen *et alii*, 2006), and post-timber harvest hillslopes (Guthrie *et alii*, 2010). Moreover, debris flows that entrain sediment as they descend channels can initiate by diverse processes, including: mobilization of discrete landslides, coalescence of erosional rills, or exceptional concentration of surface-water flow (Cannon *et alii*, 2001; Wang *et alii*, 2003; Godt & Coe, 2007; Coe *et alii*, 2008).

Several hypotheses have been offered to explain the mechanics of bed sediment entrainment by debris flows. Takahashi (1978; 1991) proposed that saturated bed sediment fails en masse, rather than through progressive downward scour, when loaded by an overriding debris flow. He quantified his hypothesis by using an infinite slope-stability analysis that assumed steady, slope-parallel groundwater flow to calculate the depth of bed failure. In this approach, groundwater pressure in the sediment is in equilibrium with the sloping water table in the overriding debris flow, and no transient excess pore pressures develop. By contrast, Sassa and colleagues (Sassa *et alii*, 1985; Wang *et alii*, 2003; Sassa & Wang, 2005) suggested that loading by overriding debris flows could transiently increase pore pressures in saturated bed sediment. From results of laboratory ring-shear tests, they inferred that excess pore pressures might nearly liquefy the bed, greatly reducing bed-sediment shear strength and facilitating entrainment. A similar hypothesis was offered by Hungr & Evans (2004) to explain entrainment by rock avalanches. Analogous undrained loading has been observed in other mass movements (Hutchinson & Bhandari, 1971).

Despite the importance of debris-flow entrainment to hazard assessment and landscape change, clear understanding of the basic process remains elusive, owing partly to a lack of high-resolution, field-scale data. Quantifying physical controls on entrainment through field measurements is difficult because of the sporadic, irreproducible character of natural events. To avoid the shortcomings of field investigations, some researchers have used small-scale laboratory flumes to examine debris-flow entrainment (Rickenmann *et alii*, 2003; Papa *et alii*, 2004). Direct application of results from small experiments to natural debris flows, however, is hampered by the scale-dependent properties of water-saturated debris (Iverson, 1997).

As an alternative to these approaches, we performed a series of debris-flow entrainment experiments in a unique, large-scale facility that minimized scaling problems. Our experiments used reproducible initial conditions with precisely placed instrumentation, and thus enabled thorough evaluation of factors influencing entrainment. The experiments focused on testing whether entrainment occurs by mass failure of the bed and whether deformation caused by overriding debris flows generates excess pore-fluid pressure in the bed sediments. To help isolate these processes, we controlled and systematically varied the water content of the bed sediment. Here we present experimental results, discuss the influence of bed water content on entrainment, and note that profound growth in debris-flow speed and runout can accompany entrainment of wet sediment.

EXPERIMENTAL CONFIGURATION

We performed our experiments using the U.S. Geological Survey debris-flow flume, located in the H.J. Andrews Experimental Forest in the Cascades Range of Oregon, USA (Iverson *et alii*, 2010). The flume, constructed on a 31° slope, consists of a concrete channel 95 m long and 2 m wide with a bumpy bed and a smoother, nearly horizontal concrete runout pad at the base (Fig. 1). Between 2006 and 2009, we conducted eight entrainment experiments and two control experiments without any erodible sediment in the flume (Iverson *et alii*, 2011).

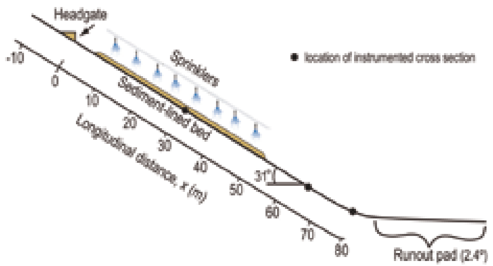

Fig. 1 - Schematic cross section of flume experiment configuration showing upper headgate area (containing initial debris-flow material), erodible sediment lining flume bed (between 6 and 53 m), overhead sprinkler system, instrumented cross sections, and runout area. Longitudinal distance is measured from the gate at the head of the flume. Thickness of bed sediment is exaggerated about 7X

In each entrainment experiment, we placed 11±1 m^3 of sediment on the flume bed between 6 and 53 m downslope of the headgate; this loose sediment formed a layer 47 m long and ~12 cm thick with a mean porosity of 0.45 ± 0.04. We determined *in-situ* porosity via a sediment excavation method. Using low-intensity overhead sprinklers, we then wetted the sediment and monitored its evolving volumetric water content, θ, and pore-fluid suctions with 1-Hz sampling of data from electrical capacitance soil-moisture sensors (Kizito *et alii*, 2008) and tensiometers. Using sediment from our experiments, we calibrated soil-moisture sensor response and found that variability in measured volumetric water content was about ± 0.02. In each experiment, we installed between 16 and 20 soil-moisture sensors in the bed sediment, distributed at 2.5 m spacing downslope. Typically, 3 locations contained nests of 2 sensors to monitor progression of the infiltration front. With this system, we controlled θ of the sediment layer so that its mean value ranged between about 0.15 ± 0.03 and 0.28 ± 0.04 at the time of debris-flow release. During sprinkling the bed sediment settled slightly, likely reducing porosity to ~0.4. We avoided fully saturating or generating positive pore-fluid pressures in the bed sediment prior to debris-flow release because such conditions led to premature failure of parts of the bed.

Fig. 2 - Photographs showing debris-flow behavior during an experiment with wet bed sediment (vol. water content, θ = 0.28). (a) Release of flow from headgate with bed sediment still in place. (b) Close-up showing debris flow entraining bed sediment; flow front is approaching measurement section at 32 m downslope from flume headgate, ~ 4 s after release. (c) Debris flow crossing runout pad, ~ 10 s after release. Grid squares are 1 m. Experiment date: 21 June 2007. Videos of experiments can be viewed at http://pubs.usgs.gov/of/2007/1315

Following bed-sediment wetting, we released 6-m^3 water-saturated debris flows from a steel headgate at the top of the flume (Fig. 2). Both the debris flows and bed sediment averaged 37% sand, 56% gravel, and 7% mud-sized (silt/clay) grains by dry weight. When in contact with the bumpy flume bed, this "SGM" mixture, extensively used in other USGS flume experiments, exhibits a static basal friction angle equal to its internal angle of friction of about 40º (Iverson *et alii*, 2010).

As the debris flows traveled down the flume, we sampled at 500 Hz the evolving flow height, *h*, normal to the bed (using overhead lasers), total normal stress, *σ*, on the bed (using force plates mounted in the bed), and pore-fluid pressure, *p*, on the bed (using pressure transducers mounted in the bed) at several cross sections in the flume (Fig. 1). Our instruments and methods of data processing are described in detail by Iverson *et alii* (2010). We used time-stamped video recordings, synchronized with the sensor data, to precisely determine flow-front speeds. The video recordings, indexed by experiment date, can be viewed on-line at *http://pubs.usgs.gov/of/2007/1315* (Logan & Iverson, 2007).

At locations between 13 and 43 m, we installed nests of scour sensors within the bed sediment. These sensors consisted of artificial gravel-sized clasts, buried at depths from 2 to 10 cm (normal to the slope) with a typical spacing of ~4 cm, connected by short leashes to contact switches mounted in the flume bed. Electronic circuits were broken as the clasts were entrained, thereby signaling the time and depth of scour. We also surveyed the bed sediment surface using either graduated surface-contact probes or, later, a laser ranging device (at minimum intervals of 0.2 m across the flume and 2.5 m down the flume) before and after each experiment. Using differences in the isopach surfaces generated from these surveys, we obtained estimates of the net sediment volume entrained by the debris flows.

RESULTS

Our experiments demonstrated that the water content of the bed sediment had a profound effect on entrainment and resulting debris-flow behavior. With wetter bed sediment, conspicuous entrainment (> 60% of the bed sediment) occurred and debris-flow runout was enhanced (Figs. 3 and 7). With drier bed sediment, minimal net entrainment (20-30%) occurred and debris-flow runout was hindered. We found a roughly linear positive relation (over the range examined) between overall bed-sediment volumetric water content, *θ*, and normalized volume of sediment entrained, V_E, defined as the ratio of entrained volume to the control debris-flow volume of 6 m^3 (Fig. 3). We also found that if $\theta > 0.22$, then $V_E > 1$, indicating that the entrained volume exceeded the control debris-flow initial volume.

To understand the differences in behavior caused by variable bed-sediment water contents, we first examine scour and loading effects within wetter and

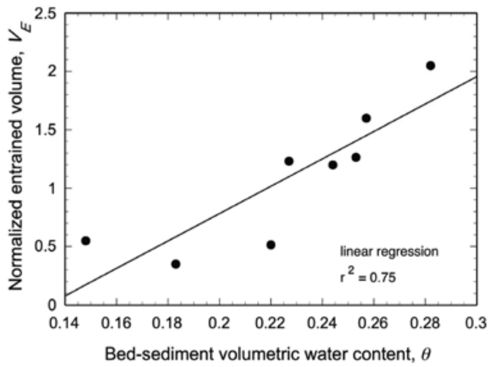

Fig. 3 - Normalized volume of sediment entrained, V_E, (entrained volume/control debris-flow volume of 6 m^3) as a function of bed-sediment volumetric water content, . Normalization differs from that of IVERSON, *et alii (2011)*

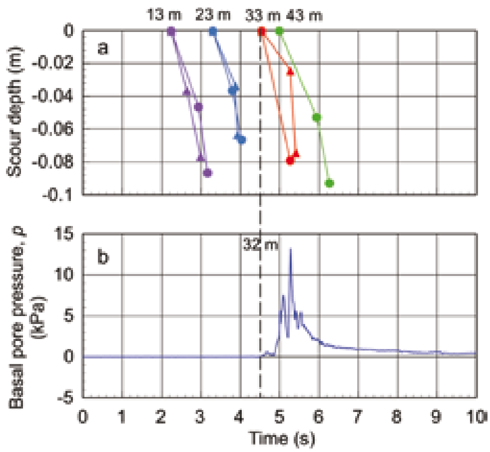

*Fig. 4 - (**a**) Scour depth detected at 4 measurement sections down the flume (13, 23, 33, and 43 m) during an entrainment experiment with wet bed sediment (θ = 0.25). Each measurement section had a left- (triangle symbols) and right-side (circle symbols) nest consisting of two sensors at different depths. Left- and right-side sensor nests were located 0.5 m from the left and right flume walls, respectively. (**b**) Basal pore-pressure responses at the 32-m measurement section. Vertical dashed line denotes arrival of debris-flow front at 32-m section. Experiment date: 13 May 2008*

drier bed sediments as they were overridden by debris flows. Then, we summarize large-scale effects of bed entrainment on overall debris-flow behavior, including flow-front speeds and runout distances.

SEDIMENT SCOUR DURING DEBRIS-FLOW LOADING

Results from two experiments, one with relatively wet (θ = 0.25) and one with relatively dry (θ = 0.18) bed sediments, illustrate the disparities in sediment entrainment. With θ = 0.25, bed material was rapidly and progressively scoured as the debris-flow front moved down the flume (Fig. 4a). In this case, shallow scour sensors (at 2-4 cm depth) at the upslope section (13 m downslope from the flume headgate) were eroded first, and scour proceeded rapidly downward into the sediment at a rate of 5-10 cm/s. Complete erosion of the bed sediment occurred within 1-2 seconds without *en masse* failure at depth, and sensor nests located within the right and left sides of the bed sediment responded almost identically. As the debris flow traveled down the flume, scour occurred in a similar manner farther downslope (Fig. 4a). Pore-fluid pressures at the base of the sediment were transiently elevated during the 1-2 s of intense scour. (Compare, for example, scour data with basal pore-pressure response at the 32-m section (Fig. 4b)). In contrast, 16 scour sensors located within drier bed sediment (θ = 0.18) remained undisturbed as the debris flow overrode them. In this case, our post-flow excavation of the bed sediment revealed that only 1-2 cm of scour of the uppermost bed sediment had occurred.

Detailed data from our sensors illuminate the interactions between sediment entrainment and debris-flow behavior with θ = 0.25 and θ = 0.18. At the 32-m measurement section, the height, h (encompassing both the debris flow and bed-sediment thickness), increased rapidly in both experiments as the debris-flow front passed (Figs. 5a and b). With θ = 0.25, h subsequently decreased to a level less than the pre-release bed level, reflecting removal of bed material (Fig. 5a). With θ = 0.18, h ultimately returned to approximately the pre-debris-flow bed level, indicating minimal net erosion (Fig. 5b). In both cases, the primary flow front was followed by a series of roll waves evidenced by small transient increases in h (Figs. 5a and b).

With both θ = 0.25 and θ = 0.18, increased just after the passage of the flow front (Figs. 5c and d). Similarly, in both cases basal pore-fluid pressure, p, increased when σ increased, but p increased significantly only with θ = 0.25 (Figs. 5e and f). In our control experiments, as well as other field and laboratory observations without entrainment, the increase in p and σ is typically delayed slightly as the drained, dilated, coarse-grained debris-flow snout passes, and the increase in p typically lags behind that of σ (IVERSON, 1997; MCARDELL *et alii*, 2007; IVERSON *et alii*, 2010; MCCOY *et alii*, 2010). Results shown in Fig. 5 do

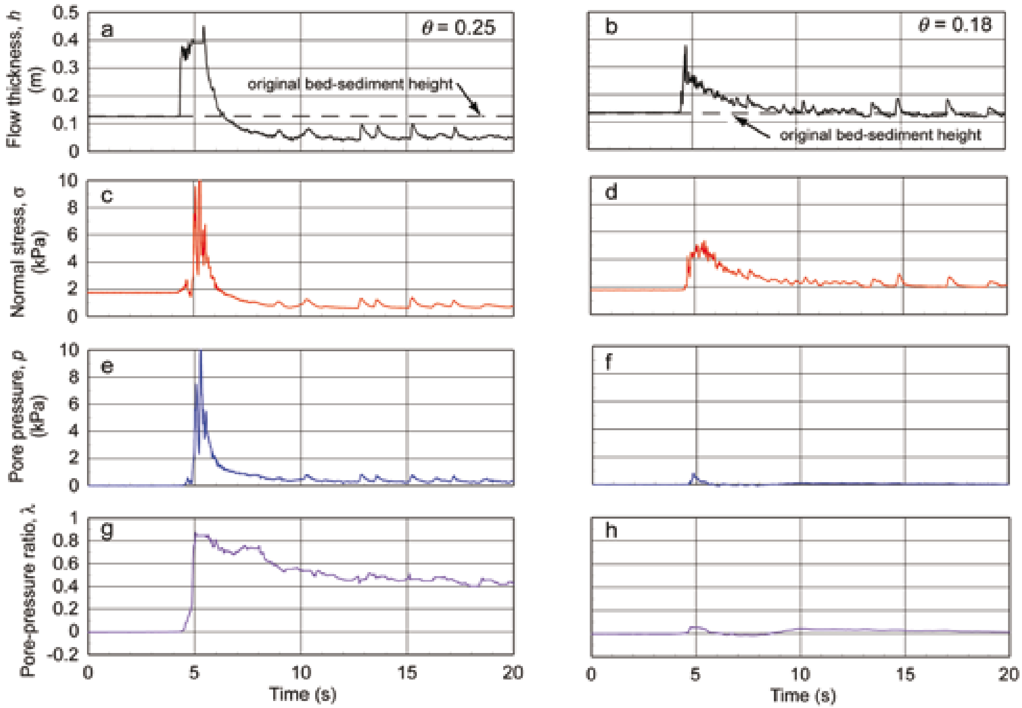

Fig. 5 - Responses measured at the cross section 32 m downslope from headgate during wet (θ = 0.25) and dry (θ = 0.18) entrainment experiments. (a) and (b) Flow thickness, h. Horizontal dashed lines represent original bed-sediment heights. (c) and (d) Total normal basal stress at the flume base, σ (e) and (f) Basal pore-fluid pressure, p. (g) and (h) Basal pore-pressure ratio, λ (ratio of p/σ). Wet experiment date: 13 May 2008. Dry experiment date: 2 June 2009

not illustrate such a lag, because they depict conditions at the base of the bed sediment - which do not necessarily mirror those at the base of the debris flow.

The pore-pressure ratio, λ, (commonly used in groundwater analyses and defined as p/σ) specifies the amount of the total normal load offset by basal pore-fluid pressure; $\lambda = 1$ indicates a fully liquefied state in which the pore pressure equals the lithostatic load, such that the effective frictional strength is reduced to zero. In our experiment with $\theta = 0.25$, λ hovered around 0.9 during scour (Fig. 5g). In the drier bed experiment, λ remained quite low (Fig. 5h). Thus, rapid loading and deformation due to an overriding debris flow provoked elevated basal pore-fluid pressures in wetter bed sediment, but had little effect in drier bed sediment.

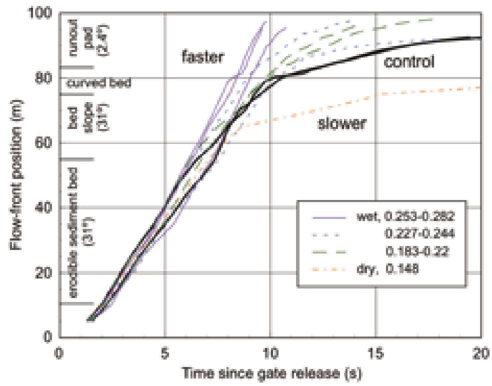

Fig. 6 - Debris-flow front position as a function of time since flow release during 8 entrainment experiments (solid and dashed lines) and 2 control experiments (thick black lines)

EFFECT OF ENTRAINMENT ON DEBRIS-FLOW BEHAVIOR

Our experimental debris flows that entrained wet bed sediment traveled faster and farther than our control debris flows on bare concrete beds. In all of the experiments, the speeds of the debris-flow fronts exiting from the gate at the head of the flume were similar for about 3 s (Fig. 6). Flows interacting with wetter bed sediment became greatly agitated compared to those overriding drier sediment. Notable differences in flow-front speeds occurred after the flows traveled beyond the extent of the bed sediment (at ~7-8 s). Flows that overrode wetter bed sediment

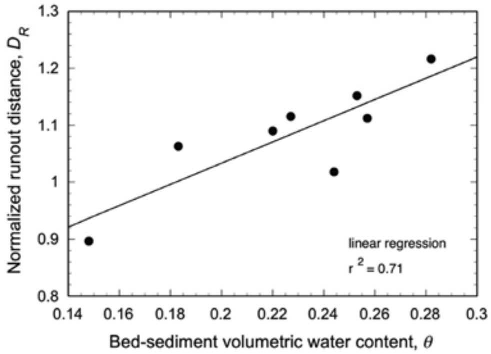

Fig. 7 - Normalized maximum debris-flow runout distance, D_R (runout distance relative to that of the control experiments), as a function of bed-sediment volumetric water content, θ

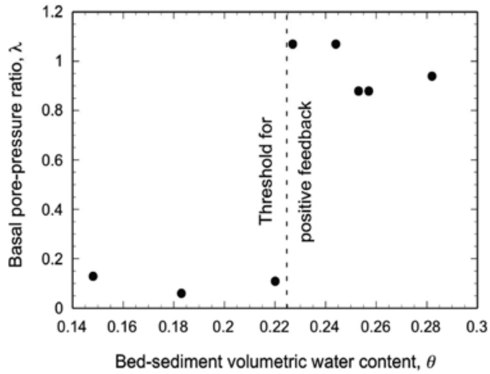

Fig. 8 - Peak basal pore-pressure ratio, λ (= p/σ), as a function of bed-sediment volumetric water content, θ

generally increased in speed (by 10-20%), whereas those that overrode drier bed sediment had speeds similar to or slower than the speeds measured in control experiments (Fig. 6). Speeds of the flows that entrained wet sediment exceeded those of the control flows even across the gently sloping runout pad. Debris flows that entrained wet bed sediment traveled farther as well. There is a roughly linear positive relation between overall bed-sediment volumetric water content, θ, and normalized maximum runout distance, D_R, defined as the furthest runout distance relative to that of the control experiments (Fig. 7). If $D_R > 1$, then the maximum runout exceeded that of the control experiments with no entrainment.

DISCUSSION

CONTROLS ON ENTRAINMENT

In our experiments, bed sediment entrainment by overriding debris flows occurred through rapid progressive downward scour, rather than by mass failure at depth. Progressive scour by debris flows has also been documented in field settings (Berger *et alii*, 2010). It is possible, however, that very thin, finite-thickness layers of bed sediment could have failed in rapid succession without detection in our experiments, because the vertical spacing of our sensors typically was ~4 cm. Nevertheless, initial failure did not commence at the base of the bed sediment.

Our experiments revealed a remarkable sensitivity of entrainment to the water content of the bed sediment. Wet sediments (here θ > 0.22) responded to debris-flow loading with rapidly elevated pore-fluid pressures that promoted entrainment, whereas drier sediments did not (Figs. 3 and 5). This acute sensitivity to bed-sediment water content is quantified by the peak λ (ratio of pore pressure to total normal load) response during scour (Fig. 8). We observed an abrupt transition in behavior between wet bed sediment, where approached 1 and the sediment could liquefy, and dry sediment, where remained quite small (~0.1). Elevated pore pressures and associated liquefaction effects reduced effective frictional strength and encouraged sediment entrainment.

Rapid pore-pressure increase within the wet bed sediment was likely caused by two mechanisms. As a debris flow traveled over the sediment, its weight directly compressed the sediment pores. Because compression was considerably more rapid than the rate of equilibration of pore-fluid pressure, undrained loading occurred. In addition, the loose sediment in the bed likely contracted as it approached a critical-state density during shear deformation. Our sensors indicated that scour, and therefore shear deformation, occurred with increased pore-fluid pressures (Fig. 4). Contraction and collapse during shear failure can help transiently elevate pore-fluid pressures and promote debris-flow mobilization (Iverson *et alii*, 1997; Iverson *et alii*, 2000; Iverson, 2005).

We observed that increased pore pressures developed in bed sediment without the pores being fully saturated prior to loading by debris flows. Initial sediment porosity after sprinkling was ~ 0.4 and rapid pressure increases occurred if θ > 0.22. In such cases, water in sediment pores was likely mostly continuous with air mainly confined to isolated, entrapped bubbles. With drier sediment (more air spaces), escape of air as the sediment was compressed probably thwarted substantial pore pressure increases. For our loose sediment, θ > ~ 0.22 appears to be a threshold for rapid pressure response and substantial sediment entrainment.

IMPLICATIONS FOR DEBRIS-FLOW HAZARDS

Experimental debris flows that entrained wet bed sediment traveled faster and farther than control flows without bed sediment. The combination of increased speed and flow volume implied increased flow momentum. Simple physical reasoning dictates that entraining sediment adds flow mass with zero velocity, which should reduce flow speed if momentum is conserved and frictional resistance remains the same (Iverson *et alii*, 2011). This behavior was clearly evident when flows encountered dry bed sediment and slowed. On the other hand, in the wet-bed sediment experiments, elevated pore-fluid pressures in the bed sediment diminished frictional resistance (to almost zero) and stimulated growth of both flow mass and speed. This positive feedback promoted sustained entrainment and further growth. Increased flow speed likely resulted from the development of a steeper and deeper debris-flow front, as documented in our video recordings. These processes combined to generate faster flows with longer runouts (Iverson *et alii*, 2011).

Hazards may increase when debris flows entrain wet bed sediment and travel faster and further. Flows that gain mass commonly have more destructive impact force and inundate larger areas while delivering more sediment downstream. Estimating the likelihood of sediment entrainment in a natural channel prior to a debris flow may be difficult, but mapping the distribution and quantity of saturated (or potentially saturated) channel sediment capable of being liquefied when loaded by overriding debris flows could aid regional debris-flow hazard analyses.

CONCLUSIONS

Using a series of well-controlled, large-scale experiments, we investigated entrainment of bed sediment by overriding debris flows. Results from our experiments support the following conclusions:

(1) Sediment entrainment is very sensitive to the volumetric water content of the bed sediment. Wetter sediment is readily entrained, whereas drier sediment is not.
(2) Entrainment occurs through rapid (5-10 cm/s) progressive downward scour rather than by mass failure at depth.
(3) Rapid loading by an overriding debris flow quickly increases pore-fluid pressures within loose, wet bed sediment, typically increasing basal pressures to nearly lithostatic levels.
(4) Flows that entrain wet sediment can travel faster and farther, and can be more hazardous, than flows without entrainment. Rapid elevation of pore-fluid pressures and the ensuing reduction of intergranular friction (to near zero) within the bed sediment facilitate this behavior.

ACKNOWLEDGEMENTS

We thank Kelly Swinford, Roger Denlinger, Scott Henderson, David George, Cate Fox-Lent, Jeff Coe, Bill Schulz, Brian McArdell, and Catherine Berger for their assistance in performing entrainment experiments. We also thank Scott McCoy and Kevin Schmidt for helpful reviews.

REFERENCES

Benda L. (1990) - T*he influence of debris flows on channels and valley floors in the Oregon Coast Range, USA*. Earth Surface Processes and Landforms, **15**: 457-466.

Berger C., McArdell B.W., Frtischi B. & Schlunegger F. (2010) - *A novel method for measuring the timing of bed erosion during debris flows and floods.* Water Resources Research, **46**, doi: 10.1029/2009WR007993.

Berti M., Genevois R., LaHusen R.L., Simoni A. & Tecca P.R. (2000) - *Debris flow monitoring in the Acquabona watershed on the Dolomites (Italian Alps)*. Physics and Chemistry of the Earth, Part B: Hydrology, Oceans and Atmosphere, **26**(9): 707-715.

Berti M. & Simoni A. (2005) - *Experimental evidences and numerical modelling of debris flow initiated by channel runoff.* Landslides, **2**: 171-182.

Breien H., F.V. D.B., Elverhoi A. & Hoeg K. (2008) - *Erosion and morphology of a debris flow caused by a glacial lake outburst flood*, Western Norway. Landslides, **5**: 271-280.

Cannon S.H., Kirkham R.M. & Parise M. (2001) - *Wildfire-related debris-flow initiation processes, Storm King Mountain, Colorado.* Geomorphology, **39**: 171-188.

Cannon S.H. & Reneau S.L. (2000) - *Conditions for generation of fire-related debris flows, Capulin Canyon, New Mexico*. Earth Surface Processes and Landforms, **25**: 1103-1121.

Coe J.A., Kinner D.A. & Godt J.W. (2008) - *Initiation conditions for debris flows generated by runoff at Chalk Cliffs, central*

Colorado. Geomorphology, **96**: 270-297.

Godt J.W. & Coe J.A. (2007) - *Alpine debris flows triggered by a 28 July 1999 thunderstorm in the central Front Range, Colorado.* Geomorphology, **84**: 80-97.

Guthrie R.H., Hockin A., Colquhoun L., Nagy T., Evans S.G. & Ayles C. (2010) - *An examination of controls on debris flow mobility: Evidence from coastal British Columbia*. Geomorphology, **114**: 601-613.

Hungr O. & Evans S.G. (2004) - *Entrainment of debris in rock avalanches: An analysis of a long run-out mechanism*. Geological Society of America Bulletin, **116**(9/10): 1240-1252, doi: 10.1130/B25362.1.

Hungr O., McDougall S. & Bovis M. (2005) - *Entrainment of material by debris flows*. In: Jakob M. & Hungr O. (eds.) - *Debris-flow Hazards and Related Phenomena*: 135-158, Springer, Berlin.

Hutchinson J.N. & Bhandari R.K. (1971) - *Undrained loading, a fundamental mechanism of mudflows and other mass movements*. Geotechnique, **21**: 353-358.

Iverson R.M. (1997) - *The physics of debris flows.* Reviews of Geophysics, **35**: 245-296.

Iverson R.M. (2005) - *Regulation of landslide motion by dilatancy and pore-pressure feedback.* Journal of Geophysical Research, **110**: doi: 10.1029/2004JF000268.

Iverson R.M., Logan M., LaHusen R.G. & Berti M. (2010) - *The perfect debris flow? Aggregated results from 28 large-scale experiments.* Journal of Geophysical Research, **115**(F03005), doi: 10.1029/2009JF001514.

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, **290**(5491): 513-516.

Iverson R.M., Reid M.E. & LaHusen R.G. (1997) - *Debris-flow mobilization from landslides*. Annual Review of Earth and Planetary Sciences, **25**: 85-138.

Iverson R.M., Reid M.E., Logan M., LaHusen R.G., Godt J.W. & Griswold J.P. (2011) - *Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment*. Nature Geoscience, **4**, doi: 10.1038/NGEO1040.

Kizito F., Campbell C.S., Campbell G.S., Cobos D.R., Teare B.L., Carter B. & Hopmans J.W. (2008) - *Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor*. Journal of Hydrology, **352**: 367-378.

Larsen I.J., Pederson J.L. & Schmidt J.C. (2006) - *Geologic versus wildfire controls on hillslope processes and debris flow initiation in the Green River canyons of Dinosaur National Monument.* Geomorphology, **81**: 114-127.

Logan M. & Iverson R.M. (2007) - *Video documentation of experiments at the USGS debris-flow flume, 1992-2009.* U.S. Geological Survey Open-file Report 2007-1315, version 2.0.

McArdell B.W., Bartelt P. & Kowalski J. (2007) - Field observations of basal forces and fluid pore pressure in a debris flow. Geophysical Research Letters, **34**, doi: 10.1029/2006GL029183.

McCoy S.W., Kean J.W., Coe J.A., Staley D.M., Wasklewicz T.A. & Tucker G.E. (2010) - *Evolution of a natural debris flow: In situ measurements of flow dynamcis, video imagery, and terrestrial laser scanning*. Geology, **38**(8): 735-738, doi: 10.1130/G30928.1.

Papa M., Egashira S. & Itoh T. (2004) - *Critical conditions of bed sediment entrainment due to debris flow*. Natural Hazards and Earth System Sciences **4**(3): 469-474.

Pierson T.C., Janda R.J., Thouret J.-C. & Borrero C.A. (1990) - *Perturbation and melting of snow and ice by the 13 November 1985 eruption of Nevado del Ruiz, Columbia and consequent mobilization, flow and deposition of lahars.* Journal of Volcanology and Geothermal Research, **41**: 17-66.

Rickenmann D., Weber D. & Stepanov B. (2003) - *Erosion by debris flows in field and laboratory experiments*. In: Rickenmann D. & Chen C.-l. (eds.) - *Debris-flow Hazards Mitigation: Mechanics, Prediction, and Assessment:* 883-894, Millpress, Rotterdam.

Sassa K., Kaibori M. & Kitera N. (1985) - *Liquefaction and undrained shear of torrent deposits as the cause of debris flows*. In: Takei A. (ed.) - *Proceedings of the International Synposium on Erosion, Debris Flows and Disaster Prevention*: 231-236, The Erosion-control Engineering Society, Japan, Tokyo.

Sassa K. & Wang G. (2005) - *Mechanism of landslide-triggered debris flows: Liquefaction phenomena due to the undrained loading of torrent deposits.* In: Jakob M. & Hungr O. (eds.) - *Debris-flow Hazards and Related Phenomena*: 81-104, Springer, Berlin.

Takahashi T. (1978) - *Mechanical characteristics of debris flow*. Journal of Hydraulics Division, ASCE, **104**(HY8): 1153-1169.

Takahashi T. (1991) - *Debris Flow*. IAHR Monograph. A. A. Balkema, Rotterdam

Wang G., Sassa K. & Fukuoka H. (2003) - *Downslope volume enlargement of a debris slide-debris fow in the 1999 Hiroshima, Japan, rainstorm*. Engineering Geology, **69**: 309-330.