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ON THE DEVELOPMENT OF AN UNSATURATED FRONT OF DEBRIS FLOWS

R. KAITNA(*), L. HSU(**), D. RICKENMANN(***) & W.E. DIETRICH(****)

(*) University of Natural Resources and Life Sciences, Austria (Boku)
(**) University of California at Santa Cruz, USA
(***) Swiss Federal Institute for Forest, Snow and Landscape Research (WLS)
(****) University of California at Berkeley, USA

ABSTRACT

A visibly granular debris flow front, where large boulders accumulate, is often observed in nature. Although there is abundant evidence of particle sorting and solid-fluid segregation processes, little is known about the specific segregation mechanisms and what factors control the relatively dry coarse snout. To investigate the conditions associated with the development of an unsaturated front, experiments have been conducted with grain-fluid mixtures of different compositions. To create long-lived, accessible, stationary flows we used two vertically rotating drum setups with a diameter of 2.4 m and 4 m respectively. The presence of an unsaturated front was detected by pore pressure transducers installed at the base of the flows. Additionally normal stress and flow depth are measured. We carried out a series of runs with varying fluid viscosity, sediment concentration, channel bed roughness, and mean velocity. The unsaturated fronts developed in faster flows with higher sediment concentration. The dry fronts formed even in well-sorted coarse particles (hence differential particle inertia is not necessary). High fluid viscosity may favor dry front formation due to the tendency for the fluid to stick to the boundary but also reduce the front formation by retarding segregation processes at the front.

Key words: *granular front, pore fluid pressure, rotating drum*

INTRODUCTION

Debris flows are commonly described as surges of rapidly flowing mixtures of unsorted sediment and water, which are characterized by a granular front followed by a more dilute body (e.g. Stiny, 1910; Suwa, 1989; Costa, 1984). Pierson (1986), for example, provides a detailed description of the geometry of debris flow events at Mount St. Helens, Washington, USA. The flow fronts were steep and 'typically composed of the coarsest particles available for transport'. The coarse particles were transported on the surface to the front and tumbled down the steep leading edge where they partly accumulated (leading to an increasing boulder front length with flow duration) or were partly shouldered aside by the slurry pushing from behind (contributing to the formation of lateral levees). Pierson (1986) as well as other authors (e.g. Suwa 1988) report that the pore spaces of the front are not filled with the matrix slurry, resulting in an unsaturated front with assumed high internal friction. The formation of an unsaturated front lacking significant pore pressures was repeatedly measured in large scale debris flow experiments (Iverson *et alii,* 2010), in natural flows (McArdell *et alii*, 2007, McCoy *et alii,* 2010) as well as in small-scale flume experiments (Scotton & Deganutti, 1997). The damming action of the coarse front is assumed to cause peak discharge and flow depth to increase dramatically and friction concentrated at flow margins is considered to impede debris flow movement at lower gradients and may therefore be highly relevant for debris flow runout and deposition (Major & Iverson, 1999). Considering the large porosity of a front composed of large boulders it is interesting that the liquid matrix doesn't drain at the front in the course of an event, which typically has duration of several minutes (a debris flow front has often been described as a "moving dam" with more liquid material "pushing from behind"). For debris flows containing a significant fraction of clay, silt and fine sand, this can be explained by a relatively high concentration of fines in the body of the flow resulting from to particle segregation. Here the low hydraulic conductivity of the liquid matrix retards drainage over long time scales. For debris flows lacking a significant amount of fines post-depositional drainage within seconds to minutes was observed (Major & Iverson, 1999).

Engineering simulation tools model debris flows as homogeneous mixtures associated with an intrinsic rheologic flow behavior (e.g. O'Brien *et alii*, 1993,;McDougall & Hungr, 2004; Naef *et alii*, 2006; Begueria *et alii*, 2009). Sorting effects like the accumulation of large boulders at the front or the segregation of the fluid and solid phase are not taken into account. Newer concepts treat debris flows as two-phase mixtures; that is, the flow resistance of the solid and the fluid components are taken explicitly into account and are coupled via the pore pressure of the fluid (Iverson & Denlinger, 2001) or buoyancy and drag (Berzi & Jenkins, 2008). This approach allows simulating varying fluid pressure along a debris flow surge, but does not account for particle sorting.

Different mechanisms have been suggested to explain the formation of a typical debris flow front:

Dispersive pressure, that causes large particles to move vertically upward (*"inverse grading"*, e.g. Bagnold, 1968; Takahashi, 1991). Due to higher velocities in the upper layers of the flow profile these particles are regularly transported to the front where they accumulate. Legros (2002) presents a theoretical analysis that dispersive pressure is less important for inverse grading in grain flows and might be therefore not the dominant mechanism responsible for boulder accumulation at the front of debris flows.

In an agitated granular mass large particles tents to migrate to the upper regions of the flow profile by the mechanism of "*kinetic sieving*", and are subsequently transported to the front (e.g. Savage & Lun ,1988; Pouiquen *et alii,* 1997). The effect of kinetic sieving represents a possible mechanism to cause inverse grading in granular flows, but may be less important in flows where the size ratio of particles is large (Thomas, 2000). The magnitude of this effect in grain-fluid mixtures needs to be assessed.

Frontal focusing is a result of a force balance between the downslope component of the gravity force of a particle, the frictional force on the channel bottom and the drag force of the surrounding flow (Suwa, 1988). In steep reaches of a channel large boulders reach a higher terminal velocity compared to smaller ones due to a higher downslope component of gravity force. Consequently large boulders tend to migrate to the front. The proposal of Suwa (1988) is based on a simplified analysis of a particles dragged by a fluid and is supported by small-scale laboratory experiments of a bore of water entraining glass particles of different sizes. Effects due to high overall sediment concentration and the presence of other particles are not taken into account. A concentration of boulders at the front has also been observed at lower gradients (McArdell *et alii*, 2007).

In summary, current explanations for the formation of a typical debris flow front concentrate on different mechanisms for the frontal focusing of large boulders rather than solid-fluid segregation processes. In this contribution we aim to investigate the conditions that favor the formation of an unsaturated front. Is segregation by large particles (relative to the median size) necessary to develop an unsaturated front of a flowing grain-fluid mixture? Is the formation of a typical debris flow front a combination of the separate processes of particle sorting (accumulation of larger particles at the front) and phase segregation (particles preceding the fluid)? What is the role of the viscosity of the intergranular fluid (water and fines)? Is it possible to create an unsaturated front in grain-fluid mixtures composed of uniform sediment? We explore these questions by conducting laboratory experiments in a rotating drum apparatus, where it is possible to establish stationary flows of grain-fluid mixtures of varying composition at different mean flow velocities.

METHODS

We conducted a first series of experiments in a rotating drum with a diameter of 2.4 m and a channel width of 0.45 m ('small drum', Fig. 1). The curved channel bottom was roughened with a synthetic mesh of 10x10 mm spacing and a height of around 5 mm. In an initial step we tested artificial grain-fluid mixtures of varying volumetric concentration (*Cv = volume solids / total volume* = 0.26 to 0.62), fluid viscosities, bulk volume (V = 0.028 to 0.046 m³), and mean velocity (v_m = 0.1 to 2.8 m/s). The particles used were cylindrical PVC grains of 10 mm in diameter and 10 mm height, with a specific density $\boldsymbol{\rho}_s$ of 1.42. The fluid was either water ($\mu \sim 0.001$ Pa.s) or a transparent synthetic polymer as used in chemical industry (see Kaitna & Rickenmann, 2007 for details). The polymer exhibited a shear thinning flow behavior which may be roughly characterized by a Bingham model over a limited range of shear rates. The viscosities (due to polymer in the water) were varied over one order of magnitude (μ = 0.02 to 0.2 Pa.s) and the yield stress was kept relatively small (τ_y = 0.5 to 20 Pa). Bulk volumes in our experiments ranged between 0.028 and 0.046 m³, corresponding to a total mass of 19 to 55 kg.

To compare the results of these artificial mixtures with more realistic material we conducted another set of experiments in a larger rotating drum using gravel and water and gravel and mud, respectively. The second drum had a diameter of 4 m and a channel width of 0.8 m ('big drum', Fig. 1). The material tested comprised uniform gravel of 4, 10, and 13 mm (ρ_s = 2.65). For all experiments the total mass of solids was 455 kg. For the gravel-mud experiments we added a clay-silt-fine sand mixture. The densities of the muddy fluid ranged between 1136 and 1205 kg/m³, representing volumetric sediment concentrations between 0.09 and 0.14 in the fluid. Fluid viscosities measured in a co-axial cylinder rheometer (Bohlin Visco88) ranged from 0.008 to 0.09 Pa.s over the estimated shear rate range of relevance (0-150 s^{-1}). We estimated the maximum shear rate based on surface velocity and mean flow depth during our experiments. The mean diameter of fine components of the mixture was determined to be 0.008 mm (Hsu, 2010).

Fig. 1 - Photographs showing the drum setup of 2.5 m diameter (left) and 4 m diameter (right)

In both setups the fluid pressure was monitored by two pressure transducer installed at the centerline of the rotating channel bed. The transducer measured the pressure in an oil filled reservoir, which was connected to the channel bed by a flexible membrane. The membrane was protected from being affected by particle impacts by a steel mesh (2 mm spacing). Additionally both drums were instrumented with load plates to measure bed normal total stress in the centerline of the flow. The measurement frequency was set to 400 Hz for the runs in the small drum and 1000 Hz for the runs in the big drum. The experiments were continuously monitored with digital video cameras from the top and with digital photo cameras through the transparent side walls. To measure the flow geometry, ultra-sonic sensors were used for the experiments in the small drum and a 2-D laser profiler was employed for the runs in the big drum. Details about the experimental setups and the instrumentation can be found in Kaitna & Rickenmann (2007) and in Hsu (2010). In the following, all information about the presence and length of an unsaturated front are based on the comparison between normal stress and pore fluid pressure data. Since we investigate only uniform particle mixtures with relatively large pore spaces, we assume tension saturation (suction pressure within the pores) to be negligible. In most cases it was possible to qualitatively confirm the measurements with observations through the transparent side walls.

RESULTS

PVC-FLUID MIXTURES

The tests with this artificial material showed that it is possible to establish stationary flows for all tested mixtures in the small drum. Though the sidewalls were rather smooth (stainless steel on one side and acrylic glass on the other) inducing less friction than the bottom of the drum, the effect of the sidewall was not negligible and a symmetric, three-dimensional flow pattern developed. At high velocities this flow pattern sometimes turned asymmetric. The direction of asymmetry varied. Strong asymmetric flows were excluded from further analysis. Some fraction of the fluid was stripped from the bulk mixture due to adhesive forces on the boundary. It is noted that this effect was enhanced with increasing rotation velocity and by

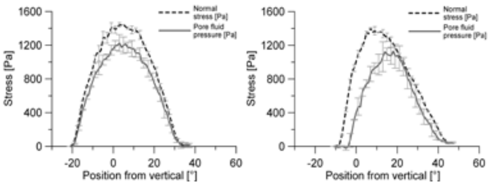

Fig. 2. - Longitudinal normal stress and pore fluid pressure profiles for a PVC – fluid mixture (μ = 0.09 Pa.s, Cv = 0.58) at Vm = 0.1 m/s (left) and 1.1 m/s (right)

	$v_m <$ 0.5 m/s	$0.5 < v_m$ < 1.0 m/s	$1.0 < v_m$ < 1.5 m/s
V=45L, μ=0.001Pa.s	no	no	yes
V=30L, μ=0.02Pa.s	no	no	yes
V=29L, μ=0.09Pa.s	no	yes	yes
V=28L, μ=0.20Pa.s	no	yes	yes

Tab. 1 - Presence of an unsaturated front for mixtures of varying fluid viscosity at different mean flow velocities v_m

the fact that the mesh attached to roughen the bed increased the specific channel surface area significantly. Using the bulk volume calculated form geometric data and the known volume of the solids and fluid dumped into the drum, we were able to calculate the *Cv* value for each run separately. *Cv*-values varied by ± 0.05 for a given mixture.

We observed an unsaturated front for mixtures with *Cv* values larger than 0.35. The onset of the formation as well as the length of a dry front was directly related to mean flow velocity. For mixtures with *Cv* – values smaller than 0.35 the front region was fluidized at all speeds.

Figure 2 gives an example of normal stress and pore fluid pressure data for a PVC – fluid mixture (μ = 0.09 Pa.s, *Cv* = 0.58) at flow velocities of 0.1 m/s and 1.1 m/s, respectively. In this study we concentrate only on the averaged values, thus the data was smoothed and represent values averaged over ten rotations (i.e. the sensors which are installed at the channel bed are passing underneath the surge ten times). It can be seen that the mixture is well saturated throughout the flow length at a very low velocity, whereas the front region is clearly unsaturated at a velocity of 1.1 m/s. The length of the unsaturated front increased gradually with flow velocity. This pattern was observed for most of our tested mixtures.

The sample volume had some influence on the development of a dry front because fluid loss due to adhesive forces at the boundary is more pronounced for small volumes, but is less relevant for larger volumes. For this reason we kept the sample volume constant for most experiments.

We tried to assess the influence of fluid viscosity on the formation of a dry front by comparing four mixtures with *Cv* – values of 0.48±0.05 and volumes between 0.028 and 0.048 m³ (Tab. 1). Though fluid viscosity was varied over two orders of magnitude (μ = 0.001–0.2 Pa.s) a dry front formed depending on mean flow velocity v_m to some extent in all mixtures.

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GRAVEL-WATER MIXTURES

The experiments in the big drum reveal that solid-fluid segregation processes are also an important feature of natural grain-fluid mixtures. Figure 3 depicts an example of the longitudinal stress profiles of a mixture with a well sorted gravel with median size of 7 mm and water (C_v = 0.63) at (1) 0.41 m/s, (2) 0.83 m/s, and (3) 1.46 m/s. The load plate sensor and the pore fluid pressure sensor are located in different quadrants in the drum, but given the steady flow conditions we shifted the data by 86.3° to allow direct comparison. Since we are not interested in the fluctuating components of the signal, the load cell and fluid pressure data were low-pass filtered at 5 Hz and averaged over a window size of one degree for three rotations. Therefore the error bars do not represent the fluctuation around a mean value but the standard deviation of the mean values for three rotations.

It can be seen that flow velocity strongly controls the formation and length of an unsaturated front in the experiments as in the small drum. Figure 3a shows that at low velocities water drains out at the front and a bore of fluid precedes the not fully saturated mass of gravel (note dark color of the unsaturated gravel). The fluid pressure in the bore exceeds total normal stress measured by the load cell at the front, which is not possible for a fluid flow (normal stress should equal fluid pressure). This disagreement (also observed in the faster flow shown in Fig. 3b) is primarily due to the fact that the load cell and the fluid pressure sensor are not located at the position in the drum and data had to be shifted for comparison. It is noted that in the vicinity of the normal stress load cell some roughness elements had to be taken out to guarantee an undisturbed measurement.

As a consequence the flow surface was slightly reduced in this region and explains some inconsistencies in the different datasets at the front and the tail of our experimental flows. Figure 3b shows total normal stress and pore fluid pressure rising together, but soon total stress significantly exceeds fluid pressure. The mean flow velocity v_m in this situation was 0.83 m/s, which is around twice the velocity of (a). We conclude that the mixture is relatively well mixed over the whole length of the flow. As can be seen in the photos, only the uppermost region close to the flow surface at the deepest part of the flow is not fully saturated. Further increase of flow velocity induces a progressive development of an unsaturated front. At v_m = 1.46 m/s the first ~ 20 cm of the front were clearly not saturated but saturation increased linearly within the flow following the unsaturated front (Fig. 3c). Visually the deepest part of the flow became completely saturated.

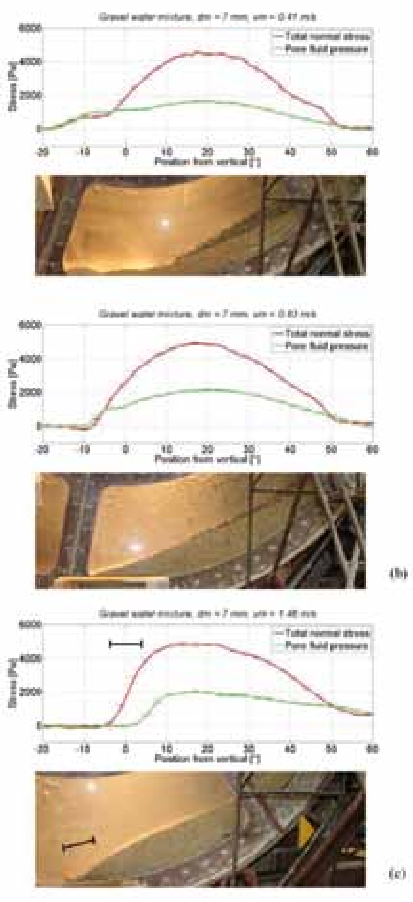

Fig. 3 - Stress distribution and photographs through the transparent side walls of a gravel-water mixture (Cv = 0.62, d_m = 7 mm) at rotation velocities 0.41 m/s (a), 0.83 m/s (b), and 1.46 m/s (c). Sensor position 0° represents 6 o'clock position in the drum. Photos are flipped for comparison. Black bar delineates the "dry front". Lines of pore fluid pressure have been smoothed

Experiments with gravel-water mixtures of mean diameter of 4 mm and 13 mm and varying water content resemble measurements with the 7 mm gravel and support the results from the small drum: for a given mixture the onset and the length of a dry front is closely related to flow velocity.

To investigate the effect of fines on the formation of a dry front we conducted some runs with gravel-mud mixtures of varying mud sediment concentration. The results from the experimental runs showed a similar pattern as the gravel-water runs, however, the effect of increased fluid viscosity was more pronounced than found in the experiments in the small drum: an unsaturated front formed in all mixtures above a critical velocity, but developed over only a short distance (limited length) and did not increase proportional to an increase of mean flow velocity as observed with the PVC-fluid mixture.

DISCUSSION AND CONCLUDING REMARKS

Our experiments show that segregation processes are an important feature of grain-fluid mixtures. Since we used only uniform grain-fluid mixtures we conclude that neither the mechanism of kinetic sieving nor the effect of dispersive pressure is necessary for the development of an unsaturated front. However, we cannot exclude these mechanisms of being important for frontal focusing of large boulders. Three different regimes can be identified for our uniform particle mixtures of a given water content and fluid

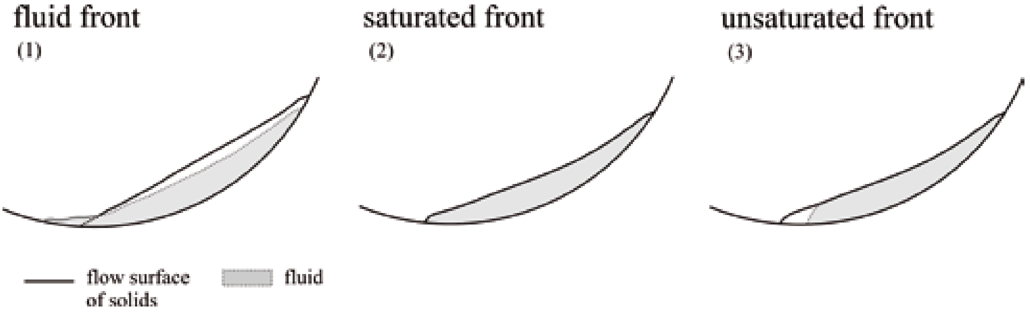

Fig. 4 - Three regimes of grain-fluid flow observed in the rotating drums

viscosity, which are separated only by different mean velocities of the flow (Fig. 4): (1) at low velocities and low viscosities the fluid precedes the solid particles which are concentrated in the body and tail of the flow; (2) at 'medium' velocity the bulk mixtures are visually homogeneously mixed; and (3) at 'high' velocities an unsaturated front develops. All these regimes formed rapidly (duration of seconds) after the start of the experiment and stayed relatively constant for the time of observation. Regime (2) and (3) may resemble dynamics in natural debris flows. Regime (1) on a straight slope would cause the flow to drain and stop motion.

An unsaturated front has been reported in large-scale debris flow experiments (e.g. Major & Iverson 1999; Iverson *et alii,* 2010) and field measurements (McArdell *et alii*, 2007, McCoy *et alii,* 2010). One of the main differences between our laboratory experiments and natural flows is that we impose a mean flow velocity through drum rotation. The flows have to adjust flow height and surface slope accordingly. For this reason it is possible to keep a granular suspension in constant motion, though the fluid drains out at the front (regime 1). In a stationary flow driving forces have to balance resisting forces. Therefore the mean surface slope increases as the flow resistance of the experimental mixtures increases. Comparison of the mean surface slope based on flow depth measurements showed that the partially drained condition of the flow body in regime (1) leads to increased flow resistance compared to regime (2) and (3). The loss of water from the bulk mixture in regime (1) results in an increase of effective normal stress and subsequently to an increase of Coulomb grain shear stress. Regime (1) may represent the final phase of a debris flow event, when the mass reduces its speed due to reduction channel slope and/or spreading on the fan.

Observation of grain-fluid segregation processes raises the question of grain velocity vs. fluid velocity. Most two-phase debris flow models assume that grains travel with the same velocity as the fluid (e.g. Iverson, 1997). Regime (1) and (3) clearly show that the fluid and particles must follow different trajectories.

Fluid viscosity can affect unsaturated front development in two opposing ways: boundary resistance due to the no slip condition and drag resistance to particle motion. The fluid experiences adhesive forces on the boundary. This non-slip condition applies for a fluid, but is not necessarily expected for an intensively sheared grain flow, since particle slip occurs in granular experiments (e.g. Louge & Keast, 2001; Bartelt *et alii*, 2005) including in our big drum experiments. High fluid viscosity could enhance the bottom flow to 'stick' to the base even as the inertia of the coarse particles carries them past the flow to the front.

High fluid viscosity could, however, also reduce the tendency for coarse particles to segregate from the flow. Consider a situation as in regime (2), where the grain-fluid mixture is relatively well mixed. The density ratio between the solid (ρ_{PVC} = 1.42, ρ_{gravel} = 2.65) and the fluid components (ρ_{water} = 1.0, $\rho_{mud} \sim 1.2$) is larger than unity, resulting in higher inertia of the solids than the fluid. Particles and fluid of the upper layers where velocity is larger than the absolute mean velocity (which is zero in case of the drum) travel towards the front at a relative high speed. At the front the bulk mass has to turn towards the bed, and particles – owing to their high inertia – may have the tendency to escape from the fluid. High fluid viscosities would dampen this effect because of higher drag resistance. Similar to the analysis of Suwa (1988), larger particles should be preferentially expelled from the grain-fluid assembly. The relative importance of these processes should depend on mean velocity of the flow.

The experiments in the small drum show that the development of a dry front depends both on the velocity and the viscosity of the intergranular fluid. This was also observed in small-scale flume experiments of Scotton & Deganutti (1997) and the experiments in the big drum support this observation. The runs with natural material in the big drum showed in addition, that the presence of fines dampens the formation of a dry front. An additional influence on dry front formation is the net loss of material during the flow, which in the case of drums is influenced by the bed roughness and specific surface area created. The effect of stripping of fines from the leading edge and sequestering them into the flume bed has been discussed by Parson et al. 2001. They conclude that this effect may contribute to the concentration of coarse sediment at the front, but is not sufficient to explain the rapid formation of a granular snout in their experiments. This effect may be more significant in our experiments in the small drum than in the big drum which has larger roughness elements, but a low specific surface area.

Taken together, our drum experiments show that both flow velocity and fluid viscosity influence the degree of development of the unsaturated front in debris flows. Even in well sorted material, where there is no size dependent differential behavior of the coarse particles, a dry front develops in sufficiently viscous and rapidly moving flows. The fluid and particle paths differ. Losses to the bed and walls in a debris flow can contribute to drying of the flow, but the unsaturated front requires neither losses nor segregation of a coarse fraction to occur.

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REFERENCES

Bagnold R.A. (1968) – *Deposition in the process of hydraulic transport.* Sedimentology, **10**: 45-56.

Bartelt P., Buser O. & Kern M. (2005) - *Dissipated work, stability and the internal flow structure of granular snow avalanches.* Jounal of Glaciology, **51**(172): 125-138.

Beguería S., Van Asch T.W.J., Malet J.P. & Gröndahl S. (2009) - *A GIS based numerical model for simulating the kinematics of mud and debris flows over complex terrain.* Nat Hazards Earth Syst Sci, **9**: 1897-1909. Disponible en el siguiente registro: http://digital.csic.es/handle/10261/20650.

Berzi D., Jenkins J.T. (2008) - *A theoretical analysis of free-surface flows of saturated granular-liquid mixtures.* Journal of Fluid Mechanics, **608**: 393-410 (doi:10.1017/S0022112008002401).

Costa J.E. (1984) - *Physical Geomorphology of Debris Flows*. In Costa J.E.; Fleischer P.J. (eds.): *Developments and Applications of Geomorphology.* Berlin: Springer: 268-317.

Hsu L. (2010) - *Bedrock Erosion by Granular Flow.* Dissertation submitted at the University of California at Berkeley, USA.

Iverson R.M. (1997) - T*he physics of debris flows.* Reviews of Geophysics, **35**(3): 245-296.

Iverson R.M.; Denlinger R.P. (2001) - *Flow of variably fluidized granular masses across three-dimensional terrain: 1. Coulomb mixture theory.* Journal of Geophysical Research, **106**(B1): 537-552.

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** (doi:10.1029/2009JF001514).

Kaitna R., Rickenmann D. (2007) - *A new experimental facility for laboratory debris flow investigation.* Journal of Hydraulic Research, **45**(6): 797-810.

Legros M.Y. (2002) – *Can dispersive pressure cause inverse grading in grain flows?* Journal of Sedimentary Research, **72**(1): 166-170.

Louge M.Y. & Keast S.C. (2001) - *On dense granular flows down flat frictional inclines.* Physics of Fluids, **13**(5): 1213-1232.

Major J.J. & Iverson R.M. (1999) - *Debris-flow deposition: Effects of pore-fluid pressure and friction concentrated at flow* *margins*. Geological Society of America Bulletin, **111**(10): 1424-1434.

McArdell B.W., Bartelt P. & Kowalski J. (2007) - *Field observations of basal forces and fluid pressure in a debris flow*. Geophysical Research Letters, **34**, L07406 (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 dynamics, video imagery, and terrestrial laser scanning.* Geology, **38**: 735-738 (doi: 10.1130/G30928.1)

McDougall S. & Hungr O. (2004) - *A model for the analysis of rapid landslide motion across threedimensional terrain.* Can Geotech J, **41**: 1084-1097.

Naef D., Rickenmann D., Rutschmann P. & McArdell B.W. (2006) - *Comparison of flow resistance relations for debris flows using a one-dimensional finite element simulation model.* Natural Hazards and Earth System Sciences, **6**: 155-165.

O'Brien J.S., Julien P.Y. & Fullerton W.T. (1993) - *Two-dimensional water flood and mudflow simulation.* J. Hydraulic Engineering, **119**(2): 244-261.

Parson J.D., Whipple K.X. & Simoni A. (2001) - *Experimental study of the grain-flow, fluid-mud transition in debris flows*. Journal of Geology, **109**: 427-447.

Pierson T.C. (1986) - *Flow behavior of channelized debris flows, Mount St. Helens, Washington.* In Abrahams A.D. (ed.): *Hillslope Processes*. Boston: Allen and Unwin: 269-296.

Pouliquen O., Delour J. & Savage S. (1997) - *Fingering in granular flows*. Nature, **386**: 816–817.

Savage S.B. & Lun C.K.K. (1988) - *Particle size segregation in inclined chute flow of dry cohesionless granular solids*. Journal of Fluid Mechanics, **189**: 311-335.

Scotton P. & Deganutti A.M. (1997) – *Phreatic line and dynamic impact in laboratory debris flow experiments*. In Chen C. (edt.): *Debris-flow hazard mitigation: Mechanics, Prediction, and Assessment.* ASCE, USA.

Suwa H. (1988) - *Focusing mechanism of large boulders to a debris flow front.* Trans. Japan. Geomorph. Union, **9**: 151-178.

Suwa H. (1989) - *Field observation of debris flow. Proceedings of the Japan-China (Taipei).* Joint Seminar on Natural Hazard Mitigation, Kyoto, Japan, July 16-20: 343-352.

Stiny J. (1910) - *Die Muren [Debris flows]*. Wagner. Innsbruck.

Takahashi T. (1991) - *Debris Flow.* IAHR Monograph Series, Balkema Publishers, The Netherlands.

Thomas N. (2000) - *Reverse and intermediate segregation of large beads in dry granular media*. Physical Review E(62): 961-974..