Measurements of velocity profiles in natural debris flows: a view behind the muddy curtain

Georg Nagla, Johannes Huebl, Roland Kaitna*

Abstract

The internal deformation behavior of natural debris flows is of interest for model development and model testing for debris-flow hazard mitigation. Up to now, only a view attempts were made to measure velocity profiles in natural debris flows due to low predictability and high destructive power of these flows. In this contribution we present recent advances of measuring in-situ velocity profiles together with flow parameters like flow depth, basal normal stress, and pore fluid pressure. For that a fin-shaped monitoring barrier was constructed in the Gadria creek (IT), laterally carrying an array of paired conductivity sensors. We present results from two debris-flow events with volumes of around 5,000 m³ each. Compared to the first event on July 10th, 2017, the second event on August 19th, 2017, was visually more liquid. Both debris flows exhibited significant longitudinal changes of flow properties like flow depth and density. The liquefaction ratios reached values up to unity in some sections of the flows. Velocity profiles for the July event were mostly concave up, while the profiles for the more liquid event in August were linear to convex. Though limited by boundary roughness at the wall and occasional sediment deposition on the force plates and pressure sensors, these measurements gain new insights of the dynamics of real-scale debris flows.

Keywords: velocity profile, pore fluid pressure, Gadria valley

1. Introduction

The high volumetric content of sediment together with grain sizes ranging over several orders of magnitudes, and velocities sometimes exceeding 10 m/s, form a challenging task to measure velocity profiles in natural debris flows. However, observations under natural conditions avoid all scaling effects and would provide some indication of the constitutive flow behavior of the mixture, which we regard as useful for model development and testing.

Measurements of experimental velocity profiles in natural sediment-water mixtures are rare, but mostly show a strong dependence on material composition (Arai and Takahashi, 1983; Mainali and Rajaratnam, 1994; Johnson et al., 2012; Kaitna et al., 2014), which has also been observed artificial solid-fluid mixtures (SanVitale et al., 2011; Chen et al., 2017). For natural flows measurements of mean velocity and surface velocity are available (Berti et al., 1999; Genevois et al., 2000; Marchi et al., 2002). Indication of the internal deformation behavior were derived from paired shear force measurements on a vertical side wall side at the Illgraben test site in Switzerland (Walter and McArdell, 2015). The importance of non-hydrostatic fluid pressure that reduces the shear resistance in debris-flow mixtures has been shown by different authors (e.g. Pierson, 1986; Iverson and LaHusen, 1989; Iverson, 1997; Major, 2000; Kaitna et al., 2014; Kaitna et al., 2016) and has also been measured in the field (McArdell et al., 2007; McCoy et al., 2010; McCoy et al., 2013).

Herein, we present first results of our efforts to measure the internal deformation behavior in natural debris flows at a monitoring station at the Gadria creek, IT. We first give an overview of the test site and the installed setup. Subsequently we show measurements of velocity profiles, normal stresses, flow depth and basal pore fluid pressure, and close with a short discussion of the outcomes and the limitations.

* Corresponding author e-mail address: roland.kaitna@boku.ac.at
2. Method

2.1. Field site

The catchment of the Gadria creek is located in the Vinschgau valley in South Tyrol, Italy, and occupies an area of 6.3 km². The highest point of the catchment is at 2,945 m a.s.l. and the confluence with the receiving river Etsch. With 1-2 debris flows per year in the recent years, the area was considered to be well suited for debris-flow monitoring (Comiti et al., 2014). The steep terrain, frequent thunderstorm events as well as metamorphic rock and thick glacier deposit ensure sufficient quantity of material to be mobilized and transported. Since the last ice-age, the Gadria creek developed a large fan, which is mainly used for agriculture and settlement. At the apex of the fan, at 1,390 m a.s.l., a slit check dam was built, providing a retention capacity of around 40,000 to 60,000 m³. Just upstream of the retention area, a monitoring station was installed by the Torrent Control Service of South Tyrol in cooperation with the Free University of Bozen-Bolzano in 2011 with two radar sensors for flow depth, rain gauges, geophones and three cameras (Comiti et al., 2014), Fig 1a). In 2016 the test site was extended with a sensor-equipped debris-flow breaker ("monitoring barrier") to measure impact pressures and investigate the process/barrier/ground interaction. In the course of the construction, also force plates, fluid pressure sensors, and a velocity profiler have been installed.

2.2. Barrier

The monitoring barrier is located 200 m upstream to the retention basin at an altitude of 1,400 m a.s.l. The mean channel slope is 6° at the position of the barrier. The construction consists of two concrete parts, the barrier itself and an unconnected traverse check-dam in front of the barrier flush to the ground. For measuring normal stress and shear stress two force plates were installed on the transverse check-dam, one in front of the barrier and the second one two meter aside, both set to a sampling frequency of 2,400 Hz. The barrier is combined of a single concrete fin-shaped element in the middle of the channel connected to a foundation plate (Fig 1b).

2.3. Monitoring system

Two quadratic force plates of 1 m² were attached to the transverse check-dam. Each force plate is supported by four load pins with a maximum capacity of 10 kN each. In the middle of each force plate a pressure sensor is installed. Each sensor consists of a pressure transducer connected to a reservoir filled with hydraulic oil. The top of the sensor (flush with the force plate) is sealed with a thin silicone membrane and protected with two steel meshes of 0.5 and 2 mm grid sizes, similar as used in rotating drum experiments by Kaitna et al. (2014). Two ultra-sonic sensors for the flow depth measurement were installed above each force plate. The sampling frequency of the ultra-sonic sensors and the pressure transducer was set to 100 Hz. The velocity profiler is situated on the orographically left side of the barrier.
3 m behind the front to minimize the disturbance of the passing material, but still capable to capture a maximum flow height of 1.8 m. The profiler consists of eleven sensors at different heights (levels). The first level is located at 18 cm above the concrete bed; the next levels are equally stepped at 15 cm distance. Each velocity sensor consists of a pair of conductivity sensors at a distance of 6 cm apart. The normalized sensor signals were cross-correlated to determine the velocity of passing debris (Nagl and Huebl, 2017). The size of a moving correlation window for set to 1 second (2,400 data points) and the window was moved with a step size of 100 data points. Results with a correlation coefficient < 0.8 and unrealistic accelerations from adjacent values were excluded from further analysis (see discussion in Kern et al., 2010; Kaitna et al., 2014). Finally, a digital video system equipped with an infrared spot was installed on the orographic left side of the channel, which enabled us to assess the surface velocity near the profiler by particle tracking. Two data acquisition systems are integrated at the top of the barrier. First, a QuantumX HBM data acquisition system is in use to acquire signals from the load cells on the front of the barrier (impact measurements) with a sampling rate set to 19,200 Hz. The second system, which records the sensors described herein, is a MGCplus HBM data acquisition system with a sampling rate set to 2,400 Hz. Except for the velocity profiles, all signals were filtered with a Butterworth low-pass 500 Hz. The complete setup is powered by an uninterruptible power supply system (UPS).

3. Results

3.1. Event July 10th, 2017

On 10th of July 2017, a debris flow was triggered by intense rainfall. The front velocity was about 1 m/s and the maximum flow depth of around 1 m (Fig 2). Video recordings reveal that the flow had a steep bouldery front with rocks of around 0.5 m in diameter, followed by a mud rich tail with some boulders immerse in the flow. The main surge was followed by small waves. The complete event lasted around 240 seconds (4 minutes) and had a total volume of about 5,000 m³.

The normal stress $\sigma_N$ reached values up to 18,000 N/m² and the basal pore fluid ($P$) pressure peaks only slightly lower (Fig 2). The liquefaction ratio ($LR = P/\sigma_N$) were therefore very high throughout the flow and reached values close to unity at the tail. For comparison, an equivalent clear water pressure calculated from flow depth, the density of water (1,000 kg/m³) and the gravitational acceleration is peaks at about 9,000 N/m². Hence, except for the very front of the flow, an excess pore water pressure was observed during the whole event duration.

For the duration of the first surge, the median of the velocity profiles from the profiler exhibit a concave up form. The numbers Fig 2b-d are the number of successful correlations (see section 2). The independently derived surface velocity is in the same range but slightly higher as the uppermost velocity of the profiler. This might be connected to the non-existing effect of wall friction, as surface velocities were derived at some distant from the barrier. The 10/90 percentile of the box-whisker plot shows the highest variability on the upper levels. A closer look into the small waves, present a convex form of the velocity profile. Taking all velocity profiles into consideration, a concave up form exhibits.

3.2. Event 19th of August 2017

The second event on August 19th, 2017, resulted again from heavy rainfall and started as a sediment-laden flash flood with woody debris, and developed into a debris flow with a less pronounced peak with a maximum flow depth of 1.8 m and a velocity of 4 m/s (Fig 3a). The event consists of two main surges with no characteristic bouldery front; the second surge was characterized by six small waves. A muddy rich tail with no visible boulders finalized the debris flow. The complete event lasted 1,600 seconds (~ 27 minutes). A log clocked the force plate in front of the barrier and affected the measurement of this force plate. The second force plate aside of the barrier measured normal stresses up to 36,000 N/m² at the first surge.
Fig 2. Data of the debris flow from July 10th, 2017. (a) Flow depth [m] of the ultra-sonic sensor of the force plate 1 aside the barrier. (b) Velocity profile of the first surge (360-410 sec.) (c) Velocity profile of a small wave (460-480 sec.) (d) Collective velocity profile of the complete debris flow, (e) normal stress (red line), basal pore liquid pressure (blue line), liquefaction ratio (black line), and equivalent clear water pressure (green line) in running average values of 1Hz.

Here, the basal pore liquid pressure achieved values to 20,000 N/m², and as a result, a liquefaction ratio reached values of 0.5 to 0.6. At the first surge, the equivalent clear water pressure was similar to the basal pore liquid pressure; at the second surge, an excessive pore pressure was observed, but did not reach values as observed for the flow on July 10th. We find a linear to slightly convex velocity profile for the first surge and for the complete event from the profiler (Fig 3b and Fig 3d). Surface velocity values are not yet available. For the fast flowing and rather liquid middle part of the event (Fig 3c), the derived velocity profiles shows a clear convex profiles, with very low velocities at the base, indicating that material that eventually would deposit was overridden by a surge from behind, similar as for the small wave in the first event. For the average profile of the complete flow the lowest level shows very few (124, compared to 3910 in the level above), but surprisingly high values compared to the upper layers. Here, close to the base, material might have decelerated, eventually deposited and remobilized. In that case, the correlation coefficient decreases and when the velocity approaches zero, ultimately no cross-correlation is possible. This missing information of very low, respectively zero velocity values, over a long reference period yields biased median values towards higher velocities.
4. Discussion

The velocity profiles shown here represent the original results from the monitoring barrier. Despite the fact that differences of velocities over the height are larger than the scatter of the data, the derived data, several sources of uncertainties have to be considered: (1) Firstly, there are uncertainties that are connected to shortcomings of the experimental field setup. That is, we unavoidably measure velocities of particles passing and probably sliding along a rigid wall, i.e. there is the effect of wall friction (cf. Jop et al., 2005; Kaitna et al., 2014). Additionally, we measure only particle velocity and not fluid velocity and the geometry of the paired conductivity sensors captures only flow variations in flow direction. (2) Secondly, there are uncertainties associated with the data analysis. For example, the choice of a threshold for the correlation coefficient is to some extent arbitrary. We tried to avoid misleading correlation results by defining a high correlation coefficient of 0.8. Another source of error arises from the comparison of velocities derived from the profiler with a surface velocity derived from video recordings. Due to the resolution of the camera, we cannot derive surface velocities at the boundary of the barrier, but only in a region some 5-20 cm distant. Additionally, we found that for natural flows, including large boulders and woody debris, deposition pattern may influence the flow along the barrier as can be seen for the second event in August 2017, where surface velocity was often smaller than the velocities at the barrier.

![Graph showing flow depth, velocity profiles, and normal stress vs. time for a debris flow event.](image)

Fig. 3. Data of the debris flow from August 19 2017 (a) Flow depth [m] of the ultra-sonic sensor of the force plate 1 aside the barrier. (b) Velocity profile of the first surge (200-300 sec.). (c) Velocity profile of the second surge (700-1000 sec.) (d) Collective velocity profile of the complete debris flow. (e) Stress [N/m²], normal stress (red line), basal pore liquid pressure (blue line), liquefaction ratio (black line), and equivalent clear water pressure (green line) in running average values of 1Hz.
5. Conclusion

Two debris flows were observed in the Gadria torrent in South Tyrol in the year 2017 by the new monitoring barrier. Additionally to the internal velocity profile, the normal stress, basal liquid pore pressure, and the flow depth were recorded. The minimum temporal resolution for the velocity profiles at this stage is around 1 second. Our measurements demonstrate that natural debris flows undergo different states of deformation during the flow and indicate no constant velocity profile throughout the flow. Velocity profiles are strongly affected by surges and deposition of material between surges. We assume that the general shape of the derived profiles may be representative for the respective section of the flow, but there are several sources of errors that might affect the results. We think that especially the connection between excess pore liquid pressure and the velocity profiles need to be further investigated.

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References


