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Measurements of Velocity Profiles in Natural Debris Flows: A View behind the Muddy Curtain

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Key Terms: ***Debris Flow, Monitoring, Velocity Profile***

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 few attempts have been made to measure velocity profiles in natural debris flows due to the low predictability and high destructive power of these flows. In this contribution, we present recent advances to measure *in-situ* velocity profiles together with flow parameters like flow height, basal normal stress, and pore fluid pressure. This was accomplished by constructing a fin-shaped monitoring barrier with an array of paired conductivity sensors in the middle of Gadria Creek, Italy. We present results from two natural debris-flow events. Compared to the first event on July 10, 2017, the second event on August 19, 2017, was visually more liquid. Both debris flows exhibited significant longitudinal changes of flow properties like flow height 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. These measurements provide new insights into the dynamics of real-scale debris flows.

INTRODUCTION

Debris flows are gravitational mass flows that occur in steep channels, which characterize mountain landscapes. The high volumetric content of sediment together with grain sizes ranging over several orders of magnitudes, and velocities sometimes exceeding 15 m/s, make measuring velocity profiles in natural debris flows challenging. However, observations under natural conditions avoid scaling effects and provide some indication of the constitutive flow behavior of the mixture, both of which are useful for model development and testing. The aim of this study is to provide data on the internal deformation behavior of natural debris flows.

Measurements of velocity profiles in natural sediment-water mixtures are rare, but they mostly show a strong dependence on material composition (Arai and Takahashi, 1983; Mainali and Rajaratnam, 1994; Johnson et al., 2012; and Kaitna et al., 2014), which has also been observed in 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; and Theule et al., 2018). For example, internal deformation behavior was derived from paired shear force measurements on a vertical side wall at the Illgraben test site in Switzerland (Walter and McArdell, 2015). The importance of non-hydrostatic fluid pressure, which 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; and Kaitna et al., 2014, 2016), and it has also been measured in the field (McArdell et al., 2007; McCoy et al., 2010, 2013). Additionally, the runout length can be increased by the remobilization and deposit behavior of a residual layer due the pulsing nature of debris flows (Davies, 1990; Hu et al., 2011).

Herein, we present results of our efforts to measure the internal deformation behavior in natural debris flows at a monitoring station on Gadria Creek, Italy. We first give an overview of the test site and the installed setup. Subsequently, we show measurements of velocity profiles, normal stresses, flow heights, and basal pore fluid pressure for two debris flows observed in 2017.

METHODS

Field Site

The catchment for Gadria Creek is located in the Vinschgau valley in South Tyrol, Italy, and it occupies an area of 6.3 km² (Figure 1a). The highest point of the catchment is at 2,945 m above sea level (a.s.l.), and the

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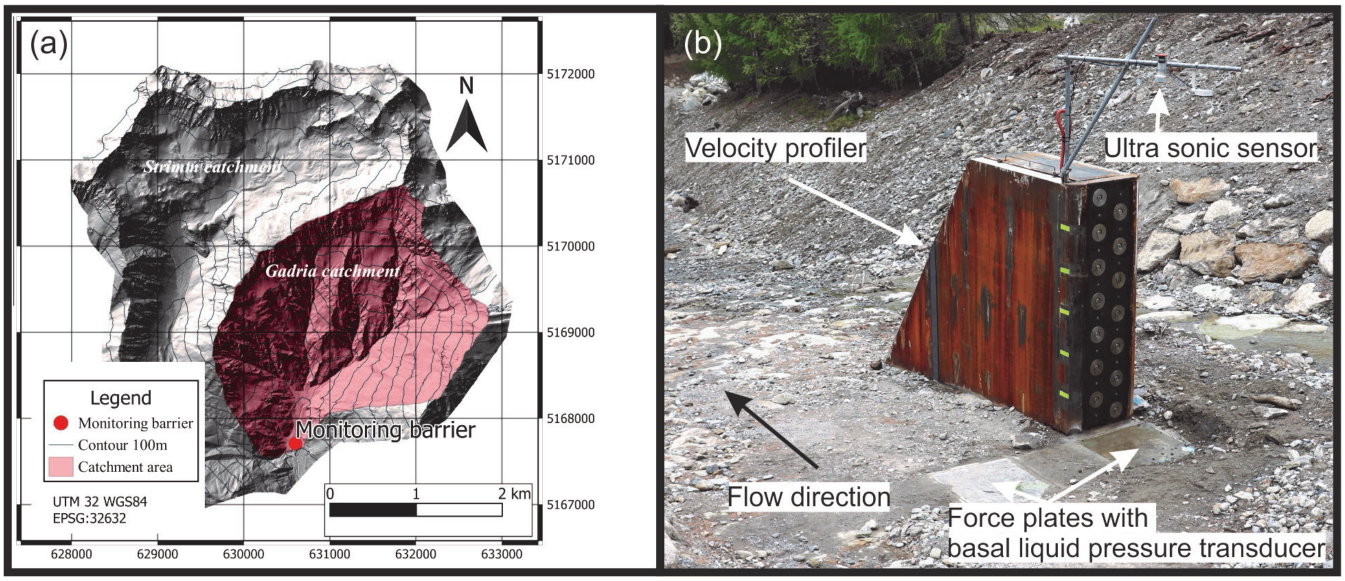

Figure 1. (a) Study site of the Gadria Creek in South Tyrol, Italy. (b) Monitoring barrier with measurement system.

confluence of the receiving river Etsch is at 807 m a.s.l. With one to two debris flows per year in recent years, the area was considered to be well suited for debris-flow monitoring (Comiti et al., 2014; Coviello et al., 2019a, 2019b).

The steep terrain and frequent thunderstorm events, as well as metamorphic rock and thick glacial deposits, ensure a sufficient quantity of material available to be mobilized and transported. A grain size distribution of deposited debris-flow material carried out in autumn 2017 showed a wide range of grain sizes. A rigid combination of pebble counts on levées and sieving analysis of collected material less than 63 mm showed in the cumulative curve a median diameter (d_{50}) of 150 mm, a d_{10} of 6.3 mm, and a d_{90} of 420 mm (Figure 2). Less than 2 percent of the material was clay and silt.

Since the last ice age, Gadria Creek has developed a large fan, which is mainly used for agriculture and settlement (Brardinoni et al., 2018). 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 m^3. 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, including two radar sensors to measure flow height, rain gauges, geophones, and three

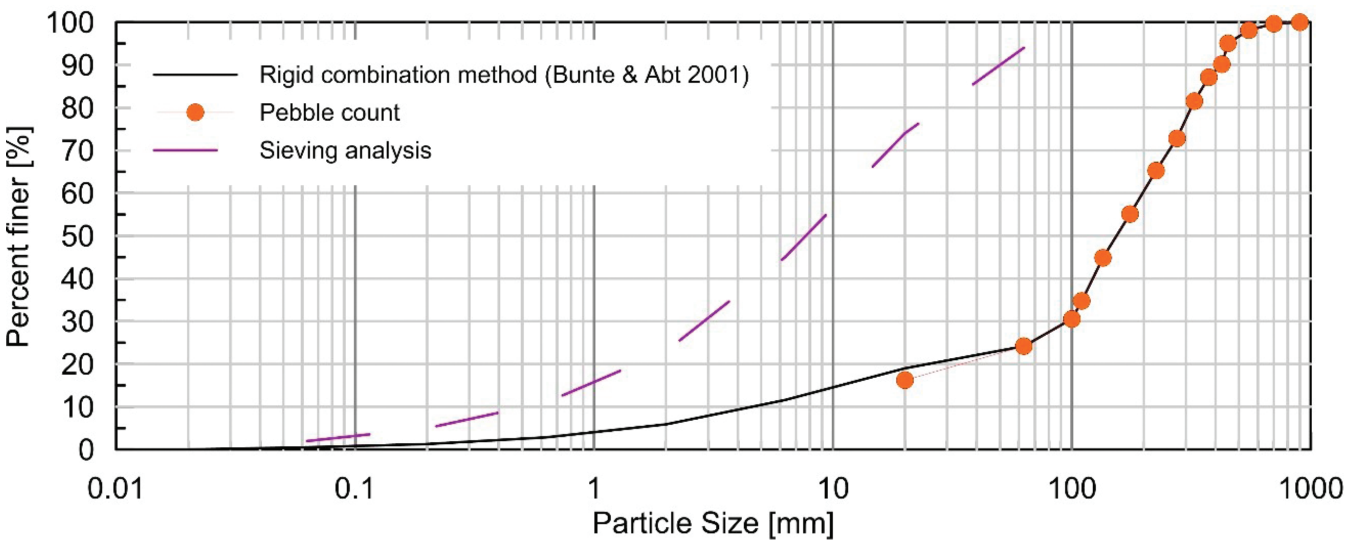

Figure 2. Rigid combination of sieving analysis and pebble count of debris-flow deposit provided by Bunte and Abt (2001).

cameras (Comiti et al., 2014) (Figure 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, force plates, fluid pressure sensors, and a velocity profiler were also installed.

Barrier

The monitoring barrier is located 200 m upstream of 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, and it is protected against erosion. 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 2 m to the side, both set to a sampling frequency of 2,400 Hz. The barrier was combined into a single concrete fin-shaped structure in the middle of the channel and connected to a foundation plate (Figure 1b).

Monitoring System

Two quadratic force plates of 1 m^2 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 fluid pressure sensor was 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 to those used in rotating drum experiments by Kaitna et al. (2014). Two ultra-sonic sensors for flow height 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 sensor data recorder is a MGCplus HBM data acquisition system with a sampling rate set to 2,400 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 it is still capable of capturing a maximum flow height of 1.8 m. The profiler consists of 11 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 intervals. Each velocity sensor consists of a pair of conductivity sensors at a distance of 6 cm apart.

All signals were filtered with a Butterworth low-band-pass 500 Hz filter. The normalized sensor signals were cross-correlated to determine the velocity of passing debris (Nagl and Hübl, 2017). We set the size of the correlation window to 1 second (2,400 data points) and moved the window with a step size of 24 data points to derive continuous velocity estimates over time for each level. Results with a correlation coefficient <0.8 and unrealistic accelerations from adjacent values were excluded from further analysis, following the argumentation of Kern et al. (2010) and 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.

RESULTS

Debris Flow of July 10, 2017

On July 10, 2017, a debris flow was triggered by intense rainfall. The front velocity was about 1 m/s, and the maximum flow height was around 1 m (Figure 3d). Video recordings revealed that the flow had a steep front with rocks around 0.5 m in diameter, followed by a mud-rich tail with some boulders immersed in the flow (see video snapshots in Figure 3a). The main surge was followed by small waves. The complete event lasted around 288 seconds (4.8 minutes) and had a total volume below 1,000 m^3.

The normal stress, σ_N, reached values up to 19,000 N/m^2, and the basal pore fluid (P) pressure peaked only slightly lower (Figure 4). The liquefaction ratio ($LR = P/\sigma_N$) was therefore very high throughout the flow and reached values up to 0.9 at the tail. Hence, except for the very front of the flow, 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 exhibited a concave-up form. The numbers beside the boxes (Figure 3e–g) are the number of successful correlations (see Methods). The independently derived surface velocity (red box) is in the same range but slightly higher than the uppermost velocity of the profiler. This might be connected to the non-existent effect of wall friction, as surface velocities were derived at some distance from the barrier. The 10/90 percentiles of the box-whisker plot shows the highest variability on the upper levels. A closer look into the small waves shows a convex form of the velocity profile (Figure 3f). Taking all velocity profiles into consideration, a concave-up form dominates. During the July 10th event, no deposition of sediment was observed at the sensor location.

Debris Flow of August 19, 2017

The second event on August 19, 2017, again followed a heavy rainfall event, and it began with

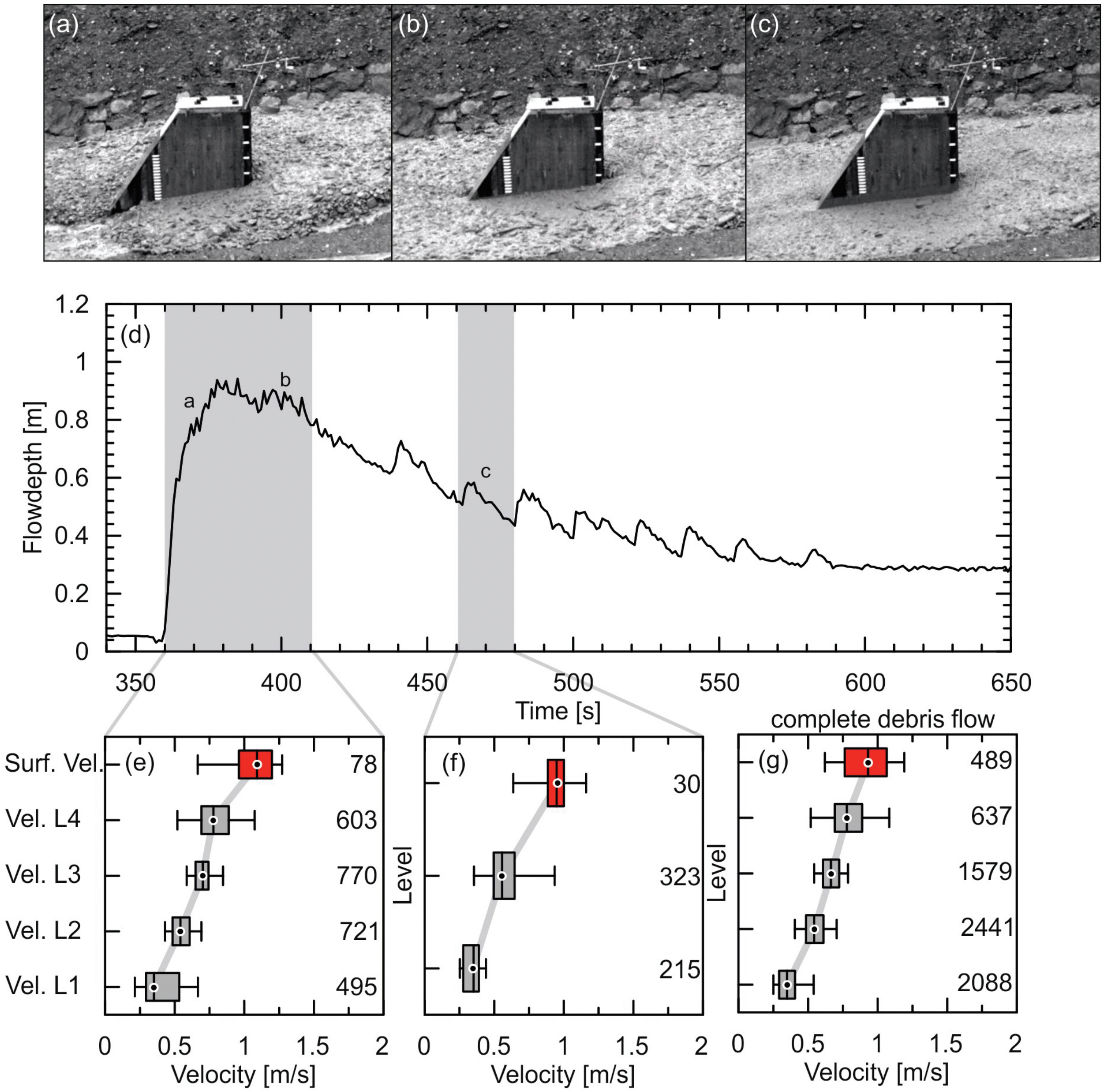

Figure 3. Data of the debris flow from July 10, 2017. (a-c) Picture series. (d) Flow height (m) of the ultra-sonic sensor of force plate 1 beside the barrier. (b) Velocity profile of the first surge (360–410 seconds). (c) Velocity profile of a small wave (460–480 seconds). (d) Collective velocity profile of the complete debris flow. The gray boxes represent the 10th and 90th percentiles, and the whiskers are the minimum and maximum values. The points in the boxes stand for the median values. Red color box on top presents the surface velocity.

a sediment-laden flood that included woody debris, which later transformed into a debris flow with a less pronounced front and a maximum flow height of 1.8 m. The maximum surface velocities up to 4 m/s (Figure 5d) were much higher compared to the event in July 2017. Additionally, the hydrograph differed significantly. The August 2017 event consisted of two main surges with no characteristic bouldery front; the second surge included six small waves. A mud-rich tail with no visible boulders finalized the debris flow. The complete event lasted 1,200 seconds (~20 minutes).

As mentioned earlier, woody debris was transported during the precursory sediment-laden flood as well as during the debris flow. Video recordings revealed that

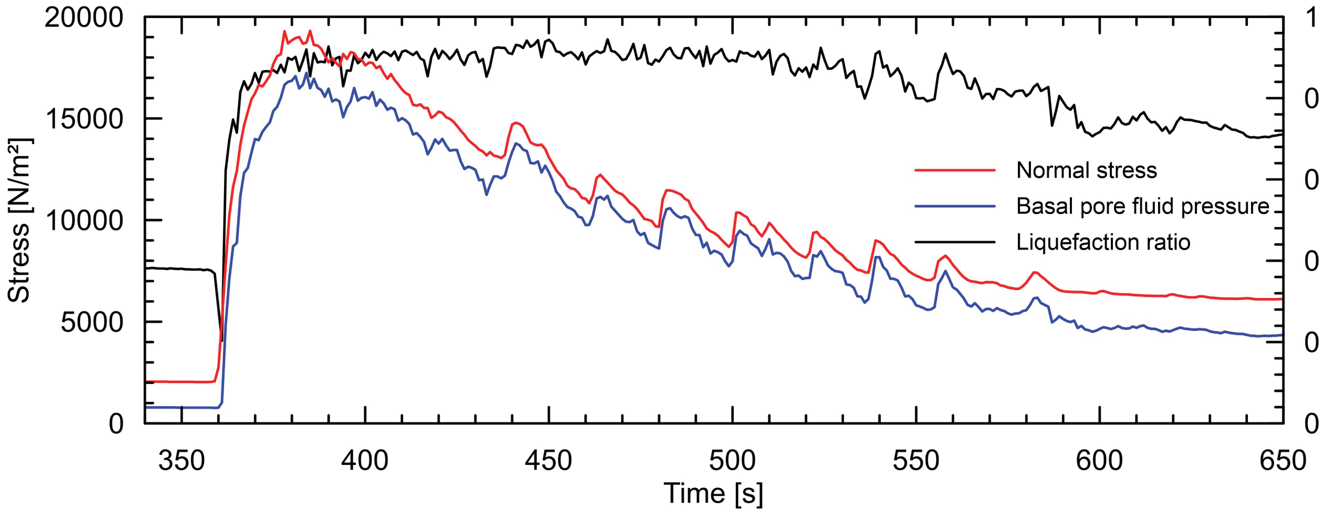

Figure 4. Normal stress (red line), basal pore fluid pressure (blue line), and liquefaction ratio (black line) in running average values of 1 Hz.

a log got caught for 164 seconds at the front of the barrier, causing (1) sediment to deposit in the vicinity of the force plates, and (2) diversion of the flow to some extent in the cross-channel direction. This affected the force plate in front of the barrier significantly and probably also the second plate at the side of the barrier. Here, we measured normal stresses up to 36,000 N/m^2 during the first surge.

The corresponding basal pore fluid pressure achieved values to 20,000 N/m^2, and as a result, the liquefaction ratio reached values of 0.5 to 0.6 (Figure 6). For the second surge, an excessive pore pressure was observed, but it did not reach values as measured for the flow on July 10th. We found a linear to slightly convex velocity profile for the first surge and for the complete event from the profiler (Figure 5e and g). For the debris-flow event of August 19, 2017, some fluvially transported channel sediment was deposited up to a height of 0.2 m before the first surge arrived at the barrier. The first incoming surge eroded the deposited layer at the front of the surge at the measurement time of 150 seconds, as shown in Figure 5e with the black bars. The second surge (700–1,200 seconds) showed no mobilization of the first sensor level. For the periods in which the debris was stationary between the surges, no velocities were measured with the velocity profiler.

DISCUSSION

The velocity profiles shown here represent the first results from our monitoring site at Gadria Creek. Despite the fact that differences in the median velocity values over the height of the flow are larger than the 10 and 90 percentile data, the derived data are subject to some uncertainties that must be taken into account. First, there are uncertainties that are connected to shortcomings of the experimental field setup. It is likely that we measured 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 measured only particle velocity and not fluid velocity, and the geometry of the paired conductivity sensors captured only flow variations in the flow direction. Second, 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 could not 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, the deposition pattern may influence the flow along the barrier, as can be seen for the second event in August 2017. This seems unavoidable for a field study, as we cannot regulate the flow hydrograph or the flow composition.

Despite these limitations, the monitoring site provided detailed information on the deformation behavior, erosion, and deposition pattern of the natural debris flows. For example, the first debris flow (July 10, 2017) showed concave-up profiles and velocities at the first level and then changed to a convex profile. Instead, the front of the second debris flow (August 19, 2017) showed some erosion on the deposited first level during the very first part of the front and showed a

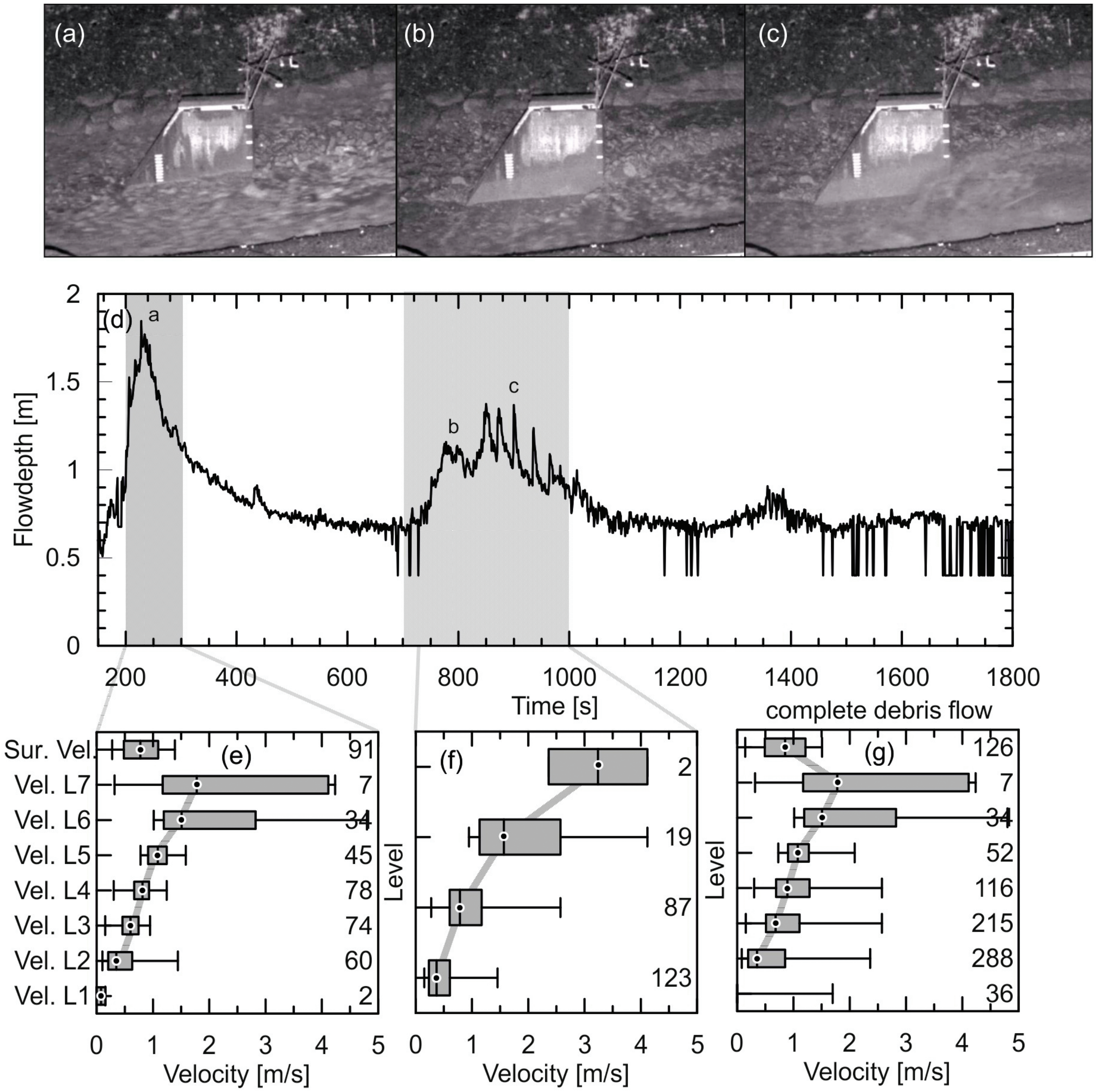

Figure 5. Data of the debris flow from August 19, 2017. (a-c) Picture series. (d) Flow height (m) of the ultra-sonic sensor of force plate 1 beside the barrier. (b) Velocity profile of the first surge (200–300 seconds). (c) Velocity profile of the second surge (700–1,000 seconds). (d) Collective velocity profile of the complete debris flow. The gray box represents the 10the and 90th percentiles, and the whiskers are the extreme values. The points in the boxes stand for the median values.

linear velocity profile with a lower liquefaction ratio than the first debris flow. For the fast-flowing and rather fluid middle part of the second event (Figure 5f), the derived velocity profiles were convex, with very low velocities at the base, indicating that material that was deposited earlier was overridden by a surge from behind, similar as for the small waves during the second event.

We note that the average profiles for the total duration of the event contain very different velocity values. This is due to the fact that at some levels, positive correlations of conductivity signals were only possible for

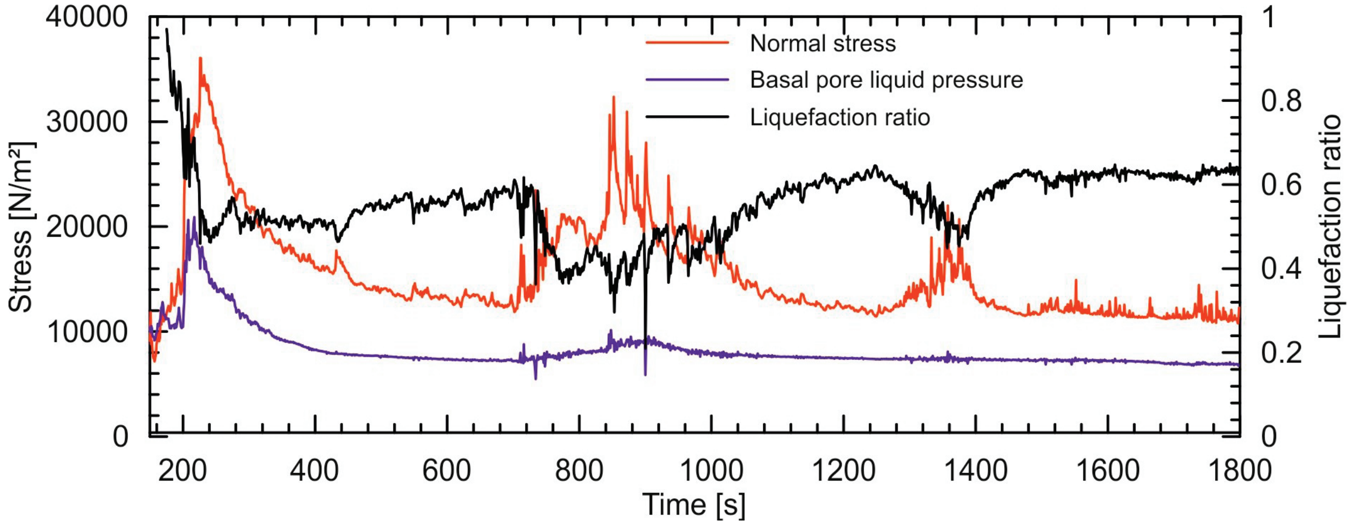

Figure 6. Normal stress (red line), basal pore fluid pressure (blue line), and liquefaction ratio (black line) in running average values of 1 Hz.

a limited duration. The physical interpretation is that either no debris-flow material passed the sensor (this happened typically in the uppermost layers), or there was material touching the sensor, but it did not move. The latter occurred for the debris flow in August 2017 (Figure 5), where we detected no movement at the lowermost layer during most of the flow.

CONCLUSIONS

Two debris flows occurred at Gadria Creek in South Tyrol in the year 2017, and they provided a successful test of the recently installed monitoring site. At this "monitoring barrier," we measured the vertical velocity profiles when the debris flows passed the concrete structure. Close to the structure, basal normal stress, pore fluid pressure, and flow height were recorded. The minimum temporal resolution for the velocity profiles at this stage of our analysis 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. The connection between excess pore fluid pressure and the velocity profiles needs to be further investigated.

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