Velocity profiles and basal stresses in natural debris flows

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ABSTRACT: The internal deformation within debris flows holds essential information on dynamics and flow resistance of such mass-wasting processes. Systematic measurements of velocity profiles in real-scale debris flows are not yet available. Additionally, data on basal stresses of the solid and the fluid phase are rare. Here, we present and analyse measurements of vertical velocity profiles in two debris flows naturally occurring in the Gadria Creek, Italy. The method is based on cross-correlation of paired conductivity signals from an array of sensors installed on a fin-shaped wall located in the middle of the channel. Additionally, we measure normal stress and pore fluid pressure by two force plates with integrated pressure transducers. We find internal deformation throughout the flows. Only at the very front was some en-bloc movement observed. Velocity profiles varied from front to tail and between flows. For one debris flow, pore fluid pressure close to normal stress was measured, whereas the other flow was less liquefied. The median shear rates were mostly less than 5 s\(^{-1}\) and Savage numbers at the basal layer ranged from 0.01 to 1. Our results highlight the variable nature of debris flows and provide quantitative data on shear rate and basal stress distribution to help guide model development for hazard assessment and landscape evolution. © 2020 The Authors. Earth Surface Processes and Landforms published by John Wiley & Sons Ltd.

KEYWORDS: debris flow; velocity profile; normal stress; pore fluid pressure; field measurements; shear rate

Introduction

Debris flows are highly sediment-laden flows in steep channels with typically more than 40% solid concentration by volume (ASI, 2009). A characteristic of such flows is that the sediment is distributed over the whole flow height, with the sediment-fluid mixture at a certain height travelling at a similar speed. Their unpredictable initiation, tremendous destructive power and long run-out distance represent a challenging task for engineering risk management in alpine regions.

Observations of debris flows indicate altered characteristics during transient flow, with a steep front of merged boulders followed by a more fluid-like, dilute body, with lower density and infrequent visible boulders (e.g. Pierson, 1986; Marchi et al., 2002). A debris-flow event may occur as a single surge or as a sequence of multiple surges (e.g. Zanuttigh and Lamberti, 2007; Arai et al., 2013). Field monitoring and experiments underpin the observation of changing composition and flow properties between events (e.g. Hürlimann et al., 2003) as well as during an event (Berti et al., 2000; McCoy et al., 2013). For example, in-situ measurements of basal normal stress and pore-fluid pressure at the Illgraben Creek revealed low pressures at the coarse-grained front and excess fluid pressure in the body of the flow (McArdell et al., 2007). Here, excess fluid pressure refers to a pressure exceeding the theoretical hydrostatic pressure, defined as

\[ P_h = \rho_f g h \]  

where \( \rho_f \) is the density of the fluid, ranging from 1000 to about 1200 kg m\(^{-3}\) to compensate for fine sediment in suspension (Iverson, 1997), \( g \) is the acceleration due to gravity and \( H \) is the normal flow height assuming full saturation and neglecting any slope reduction. Data from field monitoring sites support these observations (Berti et al., 2000; McCoy et al., 2010, 2013) and highlight the influence of fluid pressure on travel distance by reducing the effective normal stress and with that the shear resistance due to particle friction. The heterogeneous sediment-fluid composition during the transient debris flow is expected to be the result of internal dynamics, which in turn may play an interdependent role for associated processes like erosion, levee formation or surge development (Iverson, 1997; Hsu et al., 2008; Berger et al., 2011; Johnson et al., 2012; de Haas et al., 2013; Kaitna et al., 2016).

Of overarching importance for the bulk flow behaviour are therefore the mechanics of movement (i.e. basal shear and the internal deformation of the flowing debris) (Walter and McArdell, 2015). Since systematic data on the deformation of natural debris flows are not yet available, we can define end-members (Hsu et al., 2008) based on experience from scaled laboratory experiments with various material mixtures at different boundary conditions (Figure 1).
The all-slip case (Figure 1a) represents a situation where all shear is concentrated at the bed and the material along the vertical profile travels at the same speed (no internal deformation). The all-flow case (Figure 1b) shows a typical fluid-flow profile over a rigid bed, at a decreasing shear rate with increasing distance from the bed (Savage, 1979). Figure 1c shows a combination of basal sliding and internal deformation. Finally, granular flows over an erodible bed typically show a linear to concave-up profile of the vertical velocity distribution (i.e. decreasing shear rate from the base to the surface) in the upper part and an exponential tail near the erodible base (Figure 1d) (GDR MiDi, 2004; Jop et al., 2006). Additionally, the relative proportion of either mechanism – basal sliding or internal shear – has never been measured. We hypothesize that vertical velocity profiles are strongly linked to flow characteristics such as pore-fluid pressure, grain size distribution and density variations.

In this paper we present measurements of vertical velocity profiles, basal stress measurements, liquefaction ratio, density, sediment concentration, shear rates and stress fluctuation in two natural debris flows monitored at the Gadria Creek, Italy.

Methods

Field site

The Gadria Creek is located in the Vinschgau Valley in the Eastern Italian Alps and drains a catchment area of 6.3 km². The altitude difference between the highest peak (Weiße Riepl 2950 m a.s.l.) and the fan apex is about 1500 m. Here, the neighbouring Strimm Creek and the Gadria Creek unite (Figure 2). Downstream, an exceptionally large fan (10.6 km² and ~916 Mm³) has developed since the last ice age (Jarman et al., 2011). The geology of the watershed is dominated by metamorphic rocks, like paragneiss, mica-schist and quartz phyllit (Comiti et al., 2014). Due to a combination of vast amounts of highly fragmented rocks, glacial deposits and steep slopes, the Gadria catchment experiences one to two debris flows per year (Cavalli et al., 2013). A detailed description of the field side can be found in Cavalli et al. (2013) and Comiti et al. (2014). In this paper we focus on a monitoring barrier, which was built in 2016.

The monitoring barrier is located close to the fan apex, 200 m upstream of a retention basin with a slit dam, which was erected to protect the community of Allitz, its infrastructure and agricultural land on the fan (Figure 2). The channel reach upstream of the monitoring barrier has been artificially modified over a distance of about 2 km. The cross-section of the channel has a trapezoidal form with a rock riprap channel bank. The longitudinal profile upstream of the barrier was fixed by a series of (consolidation) check dams. The channel bed 40 m upstream of the monitoring structure has a constant slope of 6° with no disruptions by check dams (Figure 3a), and is secured against erosion with a concrete riprap bed.

To characterize the grain size distribution of debris flows at the Gadria Creek, we carried out pebble counts for the coarse material and a sieve analysis of the fine fraction (smaller than 63 mm). After a debris flow in 2017, pebble counts were carried out on freshly deposited levees at two positions near the...
monitoring barrier. The combined grain size distribution curves yielded a median grain size ($d_{50}$) of 150 mm, a $d_{10}$ of 6.3 mm and a $d_{90}$ of 420 mm. The clay and silt content of the samples was less than 2%.

**Monitoring barrier**

The monitoring barrier was built in collaboration with the Agency of Civil Protection South Tyrol, Italy and finalized in autumn 2016. The structure consists of two constructions, a transverse check dam and a barrier structure (Figure 3b). The transverse check dam is located upstream in front of the barrier structure, flush with the channel bed, and is not connected to the barrier. Two force plates are built in, with integrated pore-fluid pressure sensors. The barrier itself consists of a foundation plate (5 × 6 m and 1.4 m height) and a vertical concrete structure, flush with the channel bed, and is not connected to the barrier. Two force plates are built in, with integrated pore-fluid pressure sensors. The barrier itself consists of a foundation plate (5 × 6 m and 1.4 m height) and a vertical concrete element of 1 m width in the middle of the channel. The total height of this vertical element is 4.5 m, of which 3 m is above the channel bed (Figure 3b). At the orographic left side of the barrier an array of velocity sensors (velocimeter bar) was installed. In this paper we focus on measurements of the basal forces measured at the transverse structure and velocity measurements at the barrier, as explained later.

**Normal stress, flow height and density**

Two quadratic force plates of 1 m² are attached to the transverse barrier, flush with the channel bed. One force plate is located directly in front of the vertical, narrow side of the barrier (FP 2) and the other one 2 m aside (FP 1) (Figure 3b). Both plates measure forces in the normal direction, and FP 1 additionally in two tangential directions. Here, we focus only on the measurements in the normal direction (Figure 3b). Though the average slope of the channel reach is 6°, the force plates have been installed horizontally. Each plate is supported by four load pins with a maximum load capacity of 100 kN (Type MB927-100-x-A, Batarow Sensorik GmbH), each with a nominal resolution of ±0.5 kN. The surface of the steel plates is smooth compared to the channel bed, thus we assume only minor changes in flow behaviour during passing the plate, as the plate dimensions are small compared to the channel geometry (McCoy et al., 2013). The 4-mm gap between the plates and the steel frames is filled with soft cellular material and sealed with silicon. The force plates were calibrated before installation in the lab and regularly tested by stepwise increasing static loads in the field. From these tests we assessed an accuracy of ±0.2 kN. After each debris-flow event, the force plates were cleaned and tested.

The sampling frequency of the load pins was set to 2400 Hz. The resonance frequency of the force plates was determined within the range of 130–161 Hz. The recorded data were accordingly filtered using a band-stop filter. The total basal normal stress $\sigma_t$ is determined as

$$\sigma_t(t) = \frac{\sum N_{\text{pins}}(t)}{A_{\text{plate}}}$$  \hspace{1cm} (2)

where $N_{\text{pins}}$ is the sum of the normal force measured by four load pins (kN) and $A_{\text{plate}}$ is the area of the plate (m²) (Figure 4).

For later calculations, the effective normal stress is defined as $\sigma_{\text{eff}} = \sigma_t - P$, following Terzaghi’s (1925) approach, where $P$ is the pore-fluid pressure. The effective normal stress is assumed to decrease linearly towards the flow surface.

Since 2017, a vertically oriented ultrasonic sensor (Type UM300, SICK) measured the flow height $h(t)$ in front of the barrier, above FP 2 (Figure 3b). In 2018, a second sensor (Type UB4000, Pepperl+Fuchs) was installed above FP 1 (beside the barrier). For all plots and subsequent calculations, we use the measured vertical flow height as the bed normal flow depth, since the cosine correction at an inclination of 6° would be less than 1%. The sampling frequency of each sensor was set to 100 Hz.

From binned values (median value over 1-s bins) of normal stress and flow height, we calculated the bulk density $\rho_{\text{bulk}}$ during the flow as

$$\rho_{\text{bulk}}(t) = \frac{\sigma_t(t)}{gh(t)}$$  \hspace{1cm} (3)

Additionally, the volumetric sediment concentration $\phi$ was derived as

$$\phi(t) = \frac{\rho_{\text{bulk}}(t) - \rho_w}{\rho_s - \rho_w}$$  \hspace{1cm} (4)

assuming a density of the solid particles $\rho_s$ of 2630 kg m⁻³ (verified by five field samples of different sizes) and a density of water $\rho_w$ of 1000 kg m⁻³.

**Basal pore-fluid pressure and liquefaction ratio**

Two fluid pressure sensors were installed in the centre of each force plate. Each sensor consists of a pressure transducer (Model PR 25Y, Keller Inc., range ±1.5 bar), which is connected to a reservoir filled with hydraulic oil. A thin silicone membrane is used to close the reservoir at the head. Two metallic
The pressure transducers measured with a sampling frequency of 100 Hz. The measurement of basal pore-fluid pressure and normal stress allowed us to calculate the liquefaction ratio \( LR \), defined as

\[
LR(t) = \frac{\sigma_n(t)}{P(t)}
\]

If \( LR = 1 \), the flow is fully liquefied and there are no enduring inter-particle contacts that would lead to a rise of effective normal stress. Calculations were carried out with the median value of 1-s bins of the respective time series.

**Velocity profiles**

To measure the velocities of passing debris, an array of paired conductivity sensors has been installed in a PVC (polyvinyl chloride) bar of 2 m length and 0.2 m width, which is vertically attached to the monitoring barrier. This ‘velocimeter bar’ is situated laterally, 3 m behind the upstream end of the barrier to minimize the effect of lateral flow due to the interaction of impacting material and the structure (Figure 5a). The velocimeter bar carries 11 sensor pairs at different levels above the concrete channel bed, from 0.18 to 1.83 m (Figure 5a).

The conductivity sensors measure conductivity fluctuations of the passing saturated debris. When the internal structure of the grain–fluid mixtures does not change significantly between a sensor pair, the two time series are similar and can be cross-correlated to compute the time delay \( t \) (Kaitna et al., 2014). In this study the distance between the anodes and the cathodes was 4 cm and the distance \( s \) between two sensors was 6 cm. Hence, the velocity was determined with \( v = s/t \).

Before cross-correlation we low-pass filtered the 2400 Hz signals with 500 Hz, corresponding to the fixed hardware filter of the data logger. The resulting time series was normalized, as
suggested by McElwaine and Tiefenbacher (2003) and Tiefenbacher and Kern (2004), with
\[ a(t) = \frac{A(t) - \overline{A}}{\text{rms}(A)} \]  
where \( a(t) \) is the normalized signal, \( A(0) \) is the original (filtered) signal, \( \overline{A} \) is the average of \( A(t) \) over the interval \( T \) and \( \text{rms}(A) \) means the root mean square of \( A(t) \) over \( T \). Cross-correlation only gives an average time lag of the two signals; the best correlations are found for long time series. As we are interested in velocity variations over short time scales, we had to find an optimal time window for cross-correlating corresponding time series. We finally chose a window size of 2400 data points, corresponding to 1 s (Figure 5b). This time window was shifted stepwise by 24 values to obtain 100 velocity values per second. For the calculation of shear rate and Savage numbers, we computed a binned median and standard deviation for a duration of 1 s (Figure 6). Cross-correlation results with a correlation coefficient smaller than 0.8 were discarded. Additionally, negative velocities as well as unrealistic values which exceed twice the (independently derived) surface velocity were excluded from further analysis. Figure 6 shows an example of data processing for the debris-flow event on 10th July 2017.

Shear rates were calculated from the vertical velocity data by dividing the velocity difference between neighbouring sensor pairs and the elevation difference of respective sensors:
\[ \dot{\gamma}_{(i \leftrightarrow (i+1))} = \frac{v_{i+1} - v_i}{z_{i+1} - z_i} \]  
where \( z \) is the height of the sensor above the bed.

To assess the different stress-generation mechanisms of grain collision and Coulomb frictional sliding, a dimensionless number described by Savage and Hutter (1989) for granular flows, was computed a binned median and standard deviation for a duration of 1 s (Figure 6). Cross-correlation results with a correlation coefficient smaller than 0.8 were discarded. Additionally, negative velocities as well as unrealistic values which exceed twice the (independently derived) surface velocity were excluded from further analysis. Figure 6 shows an example of data processing for the debris-flow event on 10th July 2017.

Surface velocity
A digital video camera (Type M15, MOBOTIX) has been installed perpendicular to the barrier on the left channel bank. The video system is equipped with an infrared spot to capture events at night also. Depending on the illumination conditions, the frame rate varies between 15 and 25 frames per second. Due to the variation of the frame rate, it was necessary to determine the surface velocity manually by tracking particles near the profiler at a distance of up to 0.1–0.3 m from the barrier.

Results
Between July 2017 and July 2018, three debris flows were recorded by the monitoring station. All events were triggered by intense thunderstorms. In this paper we focus on the debris flows of 10th July 2017 and 21st July 2018.

On 10th July 2017, data collection started at 8:28 p.m., recording a debris flow travelling with a front velocity of about 1 m s\(^{-1}\). The flow had a distinct front and contained clasts with a size of around 0.5 m. On the flow surface after the front, interstitial fluid became visible with interspersed coarse boulders (see video [Data S1] in the online Supporting Information). At the tail, the flow changed to mud-rich slurries, with some boulders floating on top without rotational motion. Over the complete duration of the event, Froude numbers were smaller than 0.5.

In Figure 7a we plot the flow height against time (relative to the start of data collection at 7:29:13 p.m.), measured above FP 1 and 2. In the year 2017, an ultrasonic sensor at FP 1 was missing, so we back-calculated flow height from normal stress data according to Equation (8), using the bulk density derived from combined normal stress and flow height data of FP 2. We see that the debris flow consisted of one large surge of maximum 1.3 m depth and several small waves at the falling limb of the hydrograph. Flow height measured in front of the barrier (FP 2) displays higher values than FP 1 due to the run-up effect of the barrier. Since we are not interested in the interaction of the flow with a barrier structure, we will concentrate our further analysis on the measurements at the location of FP 1, which is less affected by the structure. The total event duration was less than 6 min.

**Figure 6.** (a) Derived velocity values and binned median at level 1 (0.18 m above the bed) for a 20-s sequence of the debris-flow event on 10th July 2017. (b) Corresponding time series of binned medians for five levels (0.18, 0.32, 0.48, 0.63 and 0.78 m above the bed). The error bars represent one standard deviation for each bin. [Colour figure can be viewed at wileyonlinelibrary.com]
The event in 2018 started as a sediment-laden flood with woody debris ($t = 70–250 \text{s}$, after initiation of data collection at 3:20:37 a.m.). The peak flow height was about 1.7 m, with large variations at the barrier due to the splashing nature of the process (Figure 7b). FP 1 (beside the barrier) was less affected. After the flow eased for about 150 s (with flow depth of $0.2–0.4 \text{m}$), a visually more fluid surge occurred and soon transformed into a debris flow with a patch of large boulders at the front (see video [Data S2] in the online Supporting Information). From this time on, flow height sensors 1 and 2 are in line ($t = 430 \text{s}$). After the main surge ($t = 440 \text{s}$), 10 subsequent surges with Froude numbers mostly between 0.9 and 1.5 followed. Between the surges, Froude numbers were smaller than 0.5. Video recordings reveal that for some surges a standing wave temporarily developed at the barrier.

Basal stresses

Figure 8 displays the temporal evolution of normal stress and pore-fluid pressure at FP 1, which is assumed to be less influenced by the barrier. We additionally plot theoretical hydrostatic fluid pressure from flow-height data assuming complete saturation and – without further knowledge – a fluid density of $1000 \text{kg m}^{-3}$ (Equation (1)).

For both debris-flow events the evolution of measured fluid pressure was mostly in line with independently measured normal stress. However, the magnitudes relative to normal stress were different.

For the event in 2017 (Figure 8a), pore-fluid pressure began to rise soon after the front passed the force plate. At peak flow, the normal stress was up to $20 \text{kN m}^{-2}$ and the basal pore-fluid pressure up to $16 \text{kN m}^{-2}$. The basal pore-fluid pressure was therefore approximately twice as large as the equivalent hydrostatic water pressure. At the end of the debris flow, excess fluid pressure approaches hydrostatic values. The largest fluctuations of both the normal stress and the fluid pressure were recorded at the front of the flow and decrease towards the tail.

The event in 2018 had a longer duration and larger flow heights. The normal stress peaked around $29 \text{kN m}^{-2}$, which is about twice the measured basal pore-fluid pressure (Figure 8b). In contrast to the event in 2017, fluid pressure close to hydrostatic was measured, even though the slurry flow appeared muddy. This might point to a very different composition of the flow, speculatively with less fines in suspension. However, we also have to consider the fact that the debris flow of 2018 was preceded by a sediment-laden flash flood, which deposited an unknown amount of material on the sensor, which may dampen the signal to some extent. We also have no information on any remobilization/redeposition of material at the location of the sensor. Moreover, the standing wave mentioned earlier might have affected the signals to an unknown extent.

Normal stress and fluid pressure variations due to subsequent surges go in line and are consistent with flow-height measurements (cf. Figures 7b and 8b). Towards the tail of the flow, basal pore-fluid pressure slightly lower than calculated hydrostatic pressure was measured, which points to a dampening of the signal by deposited material.

Velocity profiles

Figure 9 illustrates the evolution of velocity profiles for the event in 2017. As described, our analysis method yields 100 velocity estimates per second. In several cases, correlation quality and plausibility were not within the specified acceptable range, so the quantity of derived velocities available for the whisker plots varies (highlighted on the right side of each level). Surface velocities derived from particle tracking in video
analysis are presented in the upper white boxes. Additionally, we have to consider the fact that flow height varies over time, which results in a shorter period available for correlation computation in the upper levels.

In the front part (368–372 s, labelled b), a surface velocity of about 1 m s\(^{-1}\) and a small difference in velocity between each level indicate that the bulk of the debris was pushed over the channel bed, with highest shear or basal sliding at the front. The shape of the velocity profile changed to a linear or slight S-shaped form in the main body (372–399 s). The velocity at level 1 decreased from 0.6 to 0.25 m s\(^{-1}\) and remained constant during the flow. The surface velocity increased and reached a maximum value. In the next steps, the profile changed slightly but still kept constant in shape.

The first velocity profiles of the 2018 debris flow start at the rising surge front, from 428 to 441 s (Figure 10a). In this section, the debris flow contained a cluster of coarse boulders pushed down the channel and merged in a slurry matrix. The corresponding velocity profile shows an en-bloc movement with the highest slip velocity (Figure 10b). A more linear to
A concave-up profile form developed in the main body. At the descending part of the first surge, a linear profile to convex shape evolves (Figure 10c).

**Liquefaction ratio, density and sediment concentration**

To ensure no interference with the former deposit, we cleared the force plate before the 2017 event to ensure no influence of overlying material. We find the lowest values of LR at the very front of the flow (Figure 11a), indicating a region of low water content. Soon after the arrival of the front, the liquefaction ratio reaches values above 0.8. The highest liquefaction ratio close to 1 is reached in the middle part of the debris flow. In that case nearly all sediment is suspended and enduring particle contact is minimal. At the tail, the liquefaction ratio decreases to 0.8.

A much lower liquefaction ratio was calculated for the debris flow in 2018, but it still reached values above 0.6 during the passage of the first surge at $t\sim450$ s. Note that LR systematically increases when the secondary surges arrive, indicating that the sudden loading by such surges may decrease bulk-flow resistance and ease the remobilization of slower or deposited debris.
In both flows, the densities mostly ranged from 1800 to 2000 kg m\(^{-3}\). For the 2018 flow, densities were high even before the debris-flow front arrives (t~450 s), which we attributed to fluvial activity, including strong non-steady flow and deposition at the force plate. In both debris-flow events the highest density values were calculated at the front and decreased towards the tail (Figures 11a and b). This observation is in line with the video recordings, which show a visually higher concentration of sediment including large clasts at the front.

Shear rate and Savage number

For better visualization of the shear-rate time series in Figure 12, we computed a moving average over 5 s. Level 0 to 1 denotes the shear rate between the concrete base and level 1 of the velocity meter bar (z\(_1\) = 0.18 m). Level 1 to 2 denotes the shear rate between level 1 and level 2 at z\(_2\) = 0.33 m, and so on (cf. Figure 3).

In general, we find averaged shear-rate values less than 5 s\(^{-1}\), due to the moderate mean velocity of both debris flows (Figure 12). For both flows the time series of shear rates reveals a complex deformation behaviour, indicating variations of material composition along the flow.

Focusing on the 2017 event, we find the highest shear rates at the front between the base and level 1 of 4 s\(^{-1}\). It is unclear whether there is a sliding component along the concrete channel bed. The shear rates in the upper layers are relatively low. Over time, the basal shear rate decreases to about 1.5–2.0 s\(^{-1}\) in the middle part of the flow (t = 380–500 s). This is where the shear rate between level 1 and 2 is similar to the basal shear rate. Interestingly, at t~410 s and later at t~445 s and t~465 s, the basal shear rate drops below that of level 1 to 2. In this section of the flow a highly sheared central layer travels on a less sheared layer at the base and is overridden by debris at the surface. This may indicate the initiation of deposition of the near-bed debris.

The time series of shear rates for the 2018 debris flow is even more variable (Figure 12b). Video recordings show that the event transformed from a fluvial flood into a debris flow with high shear rates at the base and at the debris front. At later stages, the basal shear rate again increased. The shear rate between level 1 and 2 is consistently smaller than the basal shear rate. After the main surge (t~460 s), shear rates at level 2 to 3...
have similar or even higher values than at level 1 to 2. The most striking observation, however, is that the deformation caused by surges that followed the peak flow (t=460 s) was consistently translated through the material and is visible in the shear-rate time series at the basal layer (level 0 to 1) and the layer between level 1 and 2. This was not observed for the debris flow of 2017.

For the flow of 2017, the Savage number tends to be larger than 0.1, indicating a limited effect of particle friction on total flow resistance. The highest Savage numbers can be found at the base level at the flow front, and at levels 1 to 2 at the tail of the flow. The reason for these relatively high values is a very low effective normal stress. The high content of fine particles increased fluid pressure and speculatively the viscosity of the muddy fluid, which in turn may reduce collisional interactions of the particles.

In 2018, measured fluid pressures were significantly lower, resulting in Savage numbers below 0.1 for most parts of the flow. After the passage of the first surge, the Savage number increased at the top of the flow. At the tail, all levels and both debris flows rise above 0.1. Compared to the flow of 2017, and keeping in mind that fluid pressures in 2018 were rather low, there might be a frequent transition between frictional and collisional effects in both the longitudinal and vertical direction of the flow.

Discussion

Our observations of basal stresses and pore fluid pressure are in line with other field studies, where excess fluid pressures have been measured in sections of the flow (e.g. Berti et al., 2000; McArdell et al., 2007). The fluid pressure at the very front lags behind, as was also observed in the field (McArdell et al., 2007) and in experiments (Iverson et al., 2010; Leonardi et al., 2015). Further, the measurements of the density support the observations of Berti et al. (2000), McArdell et al. (2007) and McCoy et al. (2010), and show a longitudinal heterogeneity. This heterogeneity is reflected in the velocity profiles, which we found are not uniform during the flow and between flows. Before further interpretation of our measurements, we briefly review the challenges of our field observations.

Challenges of field measurements

Gravitational mass flows are sensitive to boundary conditions. Therefore, the new measurement method used here for vertical velocity is subject to a number of limitations. Foremost among them is the influence of wall friction due to the barrier in the middle of the flow. Laboratory studies have highlighted the crucial role of side-wall friction on velocity profiles in granular flows and granular suspensions (Savage, 1979; Jop et al., 2005). There are experimental indications that the shape of the velocity profiles close to the side walls is similar to that in the centre of the flow, and only the magnitudes are diminished due to wall friction (Azanza et al., 1999; Schaefer et al., 2010; Kaitna et al., 2014). In the current field study the channel banks are very rough and the width is great compared to the median diameter d50 of the debris (w/d50 > 60). The boundary of the barrier structure is smooth compared to that of the channel. We therefore expect that the velocity profiles measured at the side wall of the barrier are influenced by friction, but still representative.

Independently measured surface velocity may serve as a plausibility check for the derived velocity profiles. For that we have to keep in mind that the surface velocity was calculated from video analysis of pixels 0.1–0.3 m distant from the vertical wall. Hence, we expect the surface velocity values to be higher than the velocity derived from the conductivity sensors below. This expectation is supported by the results shown in Figures 9 and 10. We find that the magnitude of this effect is small since there is mostly an overlap of the uncertainty ranges.

Video analysis of the free surface flow sometimes shows cross-stream trajectories, which we assign not only to the natural diversion around the barrier but also to local deposition and remobilization of sediment and woody debris in front and on the side of the structure. We observed this especially for the flow in 2018 where, during some sections of the flow, a standing wave formed. From visual assessment of the video (see Supporting Information), this was due to variations in mixture composition and high Froude numbers, together with the liquid nature of the 2018 flow and also deposition and erosion, which we cannot control in this natural setting.

The conductivity sensors work best at saturated conditions. The signal noise increases when the material is only partially saturated. In case of an unsaturated or only partially saturated debris flow, we expect an increase of noise and larger uncertainty of the derived velocities, which might explain the larger variations of velocities at the front of the 2017 debris flow. Another issue connected to velocity measurements at the very front might be particle trajectories towards the bed, which cannot be resolved by the applied method.

Flow profiles

Velocity profiles in experimental granular suspensions depend strongly on the particle concentration (Takahashi, 1991; Armanini et al., 2005), grain size distribution (Kaitna et al., 2014; Sanvitale and Bowman, 2016), presence of an erodible layer (e.g. Egashira et al., 2001; Armanini et al., 2005) and non-hydrostatic pore-fluid pressure (Kaitna et al., 2016).

In a recent study, Sanvitale and Bowman (2016) found that well-graded Duran glass particles flowing down a small-scale flume form a plug flow type with high shear rates at the bottom and low velocity gradient at the top. Similarly, velocity profiles for natural sediment with a high content of fines showed the highest shear concentrated at the base in large-scale rotating drum flows (Kaitna et al., 2016). For these mixtures, basal pore-fluid pressure was close to the total normal stress (lithostatic). The 2017 debris flow reported here had a distinct flow front with a plug-like movement. During the passage of the flow, the velocity profiles changed to a more linear or slightly concave profile, with the highest shear in the lowest layers and basal fluid pressure measurements close to lithostatic.

Note that we do not measure sliding directly at the base. Considering the relatively high velocities at the lowest sensor and that the distance between the channel bed and this sensor is of the same order as the d50 of the material (0.18 and 0.15 m), we assume that the calculated velocity at the lowest sensor is representative of a basal slip velocity. Iverson (1997) mentioned the role of agitation of particles, which can induce sliding and rolling of grains along the bed. The visual observation of coarse boulders at the front, together with a high fluctuation of normal force and low basal pore-fluid pressure, indicated en-bloc movement of the front.

The event in 2018 evolved from a sediment-laden flow into a debris flow. The first surge showed a concave-up velocity profile. During the falling limb of the hydrograph the profiles transformed to convex, with the highest shear rates at the top. Such shapes were observed in experiments with suspended PVC pellets over an erodible bed, which evolve into a layered
structure of the flow with a frictional flow regime at the base and a collisional flow above (Armanini et al., 2008). The co-existence of a frictional–collisional regime was also observed in dense granular suspensions by Ancey and Evesque (2000). The 2018 debris flow was visually rather liquid, with pore-fluid pressures close to hydrostatic. Here, Savage numbers above 0.1 were calculated, pointing to a collisional flow regime. However, we must remember that this metric does not represent other forces (e.g. viscous forces). We assume that during the falling limb of the flow, particle velocities decreased due to sustained frictional contacts and were overflown by the less concentrated layer above.

Figure 13 shows binned values averaged over 5 s. The colour of the circles indicates the event time, with $t$−350 and $t$−400 representing the front of the respective flows and $t$−520 and $t$−500 the tails. We find that there is a positive correlation between normal stress fluctuations and the basal shear rate (which exerts strong control on the Savage number) for both debris-flow events (Figures 13a and b). The dependence of the 2018 event is more pronounced than that of the 2017 event. Note that for the latter, energy dissipation was probably strongly mediated by the muddy pore fluid. We speculate that for the 2018 event, frictional and collisional particle interactions were relevant and the transition between these flow regimes was governed by the shear rate. For the 2017 event, shear-rate variations were limited at our measurement location and showed a smaller effect on basal normal stress fluctuations. To assess whether persistent excess fluid pressure results from granular agitation of the particles or from internal deformation of the sediment fluid mixture, we compare normal force fluctuations and shear rate with $P - P_0$. We find a weak correlation between excess fluid pressure and normal force fluctuations (Figures 13c and d). However, the colour markers indicate a consistent temporal component. During the first stages of the events, there are high fluctuations and low excess fluid pressure at the very front (dark blue markers). Soon, normalized stress fluctuations decrease and excess fluid pressure increases to the highest values at the main body of the flow (light blue markers). Towards the tail there is a weak decrease of normalized stress fluctuations and a strong decrease of excess fluid pressure (yellow markers). Shear rate and excess fluid pressure, however, do not seem to be related. Our measurements support the experimental evidence that material composition (i.e. grain size distribution) is a first-order control of excess fluid pressure development (Kaitna et al., 2016), rather than shear rate or collisional particle interactions.

Stress fluctuations, shear rate and fluid pressure

Combined measurements of total normal stress, pore-fluid pressure and shear rate allow us to test whether there is a relationship between normal force fluctuations, shear rate and excess fluid pressure. Figure 13 shows binned values averaged over 5 s. The colour of the circles indicates the event time, with $t$−350 and $t$−400 representing the front of the respective flows and $t$−520 and $t$−500 the tails. We find that there is a positive correlation between normal stress fluctuations and the basal shear rate (which exerts strong control on the Savage number) for both debris-flow events (Figures 13a and b). The dependence of the 2018 event is more pronounced than that of the 2017 event. Note that for the latter, energy dissipation was probably strongly mediated by the muddy pore fluid. We speculate that for the 2018 event, frictional and collisional particle interactions were relevant and the transition between these flow regimes was governed by the shear rate. For the 2017 event, shear-rate variations were limited at our measurement location and showed a smaller effect on basal normal stress fluctuations. To assess whether persistent excess fluid pressure results from granular agitation of the particles or from internal deformation of the sediment fluid mixture, we compare normal force fluctuations and shear rate with $P - P_0$. We find a weak correlation between excess fluid pressure and normal force fluctuations (Figures 13c and d). However, the colour markers indicate a consistent temporal component. During the first stages of the events, there are high fluctuations and low excess fluid pressure at the very front (dark blue markers). Soon, normalized stress fluctuations decrease and excess fluid pressure increases to the highest values at the main body of the flow (light blue markers). Towards the tail there is a weak decrease of normalized stress fluctuations and a strong decrease of excess fluid pressure (yellow markers). Shear rate and excess fluid pressure, however, do not seem to be related. Our measurements support the experimental evidence that material composition (i.e. grain size distribution) is a first-order control of excess fluid pressure development (Kaitna et al., 2016), rather than shear rate or collisional particle interactions.

Summary and Conclusion

In this study we use combined measurements of vertical velocity profiles, flow height as well as basal normal stress...
and pore-fluid pressure to derive continuous information on shear rates, bulk density, liquefaction ratio and stress fluctuations for two debris flows that occurred naturally at the Gadria Creek, Italy. Both flows showed rather contrasting flow mechanics, from close to hydrostatic conditions to highly liquefied states. The velocity profiles varied from front to tail and between flows. The 2017 flow event had a distinct front and we determined the highest basal velocity gradients at the base and an en-bloc movement in the upper layers. Subsequently, the liquefaction ratio increased to 0.8 and the volumetric sediment concentration varied from 0.5 to 0.6. The corresponding bulk density was around 2000 kg m$^{-3}$ and decreased towards the tail. In the body, the liquefaction ratio had peaks up to unity and a volumetric sediment concentration of 0.6. The excessive pore-fluid pressure was accompanied by high fluctuations of normal stress and a concave shape of the velocity profile. Only at the front was some en-block movement observed. In some parts of the flow we found lower shear rates in the basal layer than in the upper layers, indicating the onset of deposition starting at the base. Towards the tail, the fluctuations of the normal stress and pore-fluid pressure decreased.

The 2018 flow was visually more fluid, transformed from a flash flood into a debris flow, and displayed periodic deposition and remobilization. The liquefaction ratio decreased from 0.6 to 0.3 through time as the flow passed over the sensor. A standing wave formed at the barrier and might have affected the measurement of basal stresses. After the peak flow, velocity profiles transformed from concave to convex, indicating the onset of deposition in the lower layers of the flow.

Our results demonstrate that natural debris-flow events undergo different flow regimes and do not show a constant velocity profile or basal stress relations along the flow and between events. We think that this is related to variations in grain size distribution and is highly relevant for run-out as well as deposition and remobilization processes. Increasing shear rates with depth point to shear rate-dependent flow resistance in parts of the flow. We do not find evidence that excess fluid pressure is related to shear rate or normal stress fluctuations. The development of more physically based modelling approaches will benefit from the results presented in this study. Additionally, the data may serve as a benchmark for model testing.

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Data availability
The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Conflict of interest
No conflict of interest has been declared by the authors.

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