Original Article

Field Measurements of Forces in Debris Flows at the Illgraben: Implications for Channel-Bed Erosion

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Using a large force plate as installed in the channel bed at the Illgraben debris-flow observation station, we illustrate flow properties of three typical types of debris flow which occur there, single-surge debris flows, multiple-surge flows, and more complicated surges with many individual roll waves. In all three types of flow, the median value of the normal and shear stresses are largest at the front or fronts of each surge. Additionally, the fluctuations in normal and shear stress are also largest at the flow front, reaching values up to 1.5 times larger than the median value. The presence of large force fluctuations at the front of the surges is in agreement with previously-published results which show that the rate of erosion is largest within the first minute of the arrival of a debris-flow surge.

Key words: force plate measurements, pressure fluctuations, field measurements

1. INTRODUCTION

Observation of debris-flow properties in naturally triggered debris flows provides an opportunity to better understand the flow process. This work is motivated by recent observations that large debris flows at the Illgraben are capable of eroding substantial amounts of sediment in a low-gradient (~10%) channel on the debris-flow fan [*e.g.*, *Schürch et al*., 2011], thereby lowering the elevation of the channel and increasing the volume of the debris flows as they travel down the channel.

Observations of sediment erosion from the channel bed at the Illgraben suggest that debris flows entrain sediment mainly at the head of the flow [*Berger et al*., 2011a] which is in agreement with large-scale laboratory experiments at the USGS debris-flow flume for debris flows entraining wet sediment [*Iverson et al*., 2010] but is contrasted by observations of significant sediment entrainment at the tail of small debris flows both in the field at Chalk Cliffs [*McCoy et al*., 2012] and in laboratory experiments [*Weber*, 2004]. Based on a comparison of pressure fluctuations measured using force plates on a vertical wall aligned parallel to the flow direction, *Berger et al*. [2011a] argued that the sediment entrainment at the head of a debris flow may be related to pressure fluctuations in the flow which are largest at the boulder-rich leading edge of the flow. The results from a large force plate installed flush with the channel bed at the Illgraben [*McArdell et al*., 2007; *Berger et al*., 2011a] also supported the idea that pressure fluctuations can cause significant erosion of channel-bed sediment. However the data logger used on the force plate at that time was only capable of storing the median force value at 1s intervals.

Unfortunately the channel-bed erosion sensors deployed by *Berger et al.* [2011a] are difficult and expensive to install, however we were able to upgrade the large force plate to record force values at a much higher frequency, providing an opportunity to further investigate the presence of pressure fluctuations on the channel bed in debris flows. Measurements of three debris flows in 2013 are described in this paper.

2. FIELD SITE AND INSTRUMENTATION

2.1 Catchment

The Illgraben catchment in southwest Switzerland is among the most active catchments in Europe for mass movements. The active part of the catchment on the north face of the Illhorn mountain has an area of 4.5 km^2 is underlain by sedimentary rocks which weather to produce quartzite and

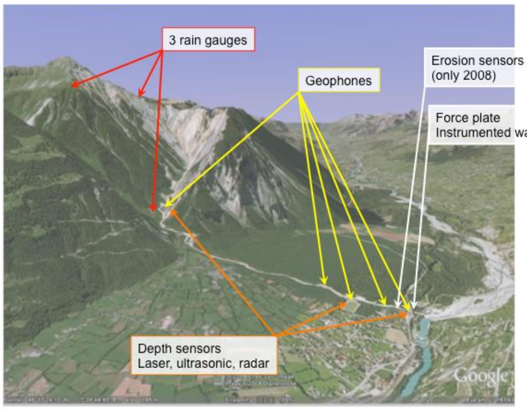

Fig. 1 Oblique view (Google Earth) of the Illgraben catchment showing the active catchment and location of the instrumentation. The radius of the debris-flow fan is about 2 km.

dolomite boulders up to several meters in diameter as well as some clay-size particles.

Sediment produced by large bedrock landslides [*e.g.*, *Caduff et al*., 2014; *Bennett et al*., 2012] and rockfall supplies sediment to gullies and the main channel, which have been identified as initiation zones for debris-flows [*e.g.*, *Berger et al*., 2011b].

2.2 Instrumentation

The Illgraben debris-flow observation station [*Hürlimann et al*., 2003] was installed in 2001 to monitor debris flow activity and it has since been expanded to include more instrumentation (**Fig. 1**) including rain gauges and additional depth sensors and geophones [*Badoux et al*., 2009] as well as a large force plate [*McArdell et al*., 2007].

The force plate consists of a 2 m long, 4 m wide, three ton steel structure, installed flush in the base of a concrete check dam, which has a trapezoidal cross-sectional shape (**Fig. 2**). A normal force transducer is installed under each corner and the forces are summed and recorded at 2 kHz on a computer. Each side of the upstream end of the force plate is connected to horizontal force sensors, which are also summed and recorded at 2 kHz. The normal and shear stresses are expressed per unit bed area and correspond to normal pressure and shear stress on the channel bed. The forces were discretized into bins with a 1 s duration, and the median, maximum, and minimum forces were calculated for each bin.

A laser sensor mounted on the road bridge above the force plate measures the distance to the top of the flow. The force plate is also instrumented with a geophone, sampled at 2 kHz, measuring the velocity of the force plate in the vertical direction. Herein, the geophone signal has been reduced to the

Fig. 2 Installation of the force plate.

Table 1 Summary of debris-flow events.

Date (Year 2013)	Front Velocity (m/s)	Front Discharge (m^3/s]
29 July	4.4	27
8 August	3.8	10
24 August	4.4	6

number of impulses per second, with an impulse recorded when the signal passes above a small positive voltage threshold.

The front speed of the debris flows was calculated as the travel time of the flow front between a geophone (installed on a check dam located 460 m upstream of the force plate) and the geophone on the force plate. The front discharge was calculated as the product of the front velocity and the cross-sectional area, assuming a horizontal flow surface in the lateral direction.

3. RESULTS

Three debris flows, typical of those observed at the Illgraben, were selected. All three were triggered by intense rainfall.

3.1 The 29 July 2013 debris flow

The 29 July debris flow is considered to be typical of debris flows with a relatively coarse-grained granular snout. The flow (**Fig 3**) had a relatively long duration precursory surge, where the flow depth increased from near zero (a nearly dry bed) to about 0.25 m over a 5 min. period. The bulk density of the flow increased to about 1700

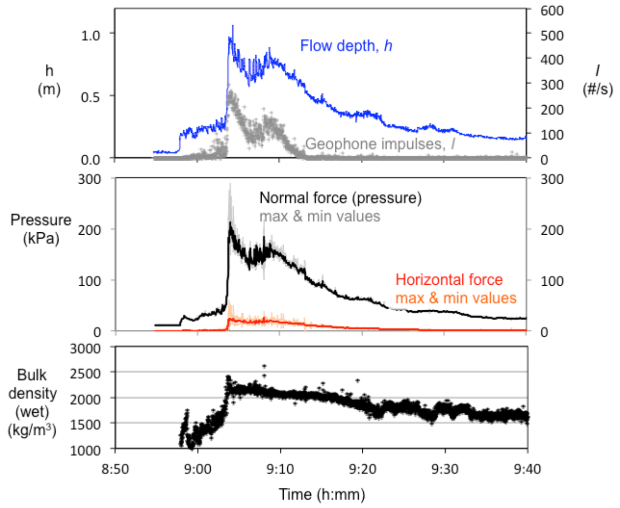

Fig. 3 Measurements of the 29 July 2013 debris flow showing the temporal development of flow depth, geophone impulses (top panel), normal and shear forces and the maximum and minum values (middle panel) and the bulk mass density determined from the normal force and flow depth (bottom panel) during the passage of the debris flow.

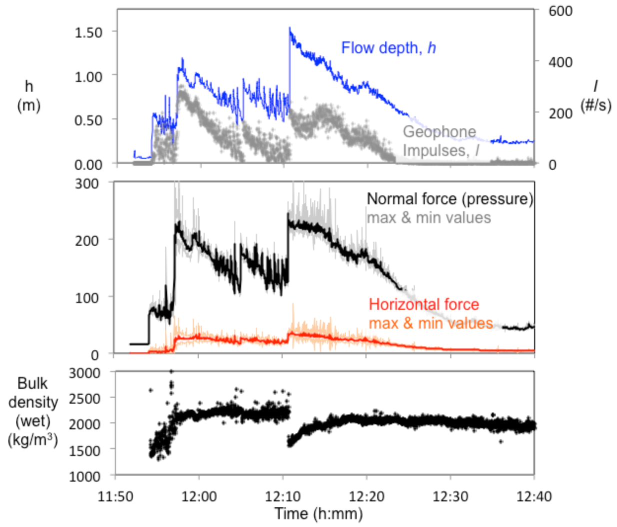

Fig. 4 Measurements of the 8 Aug. 2013 debris flow.

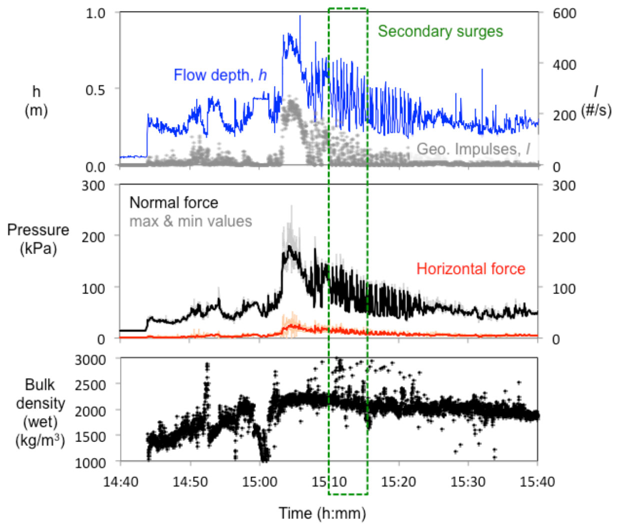

Fig. 5 Measurements of the 24 Aug. 2013 debris flow.

kg/m^3, indicating a significant amount of sediment in transport, which is also apparent in the geophone impulse data. With the arrival of the main surge, the flow depth rapidly increased to nearly 1 m over just a few seconds, which is interpreted as the granular front of the flow. Afterwards, the flow depth fluctuated between 0.7 and 1 m for the next 10 minutes, which is interpreted as the main body of the debris flow. The bulk density of the granular front and body of the flow is about 2200 kg/m^3. Within the main body, the geophone signal remained relatively large, indicating significant agitation within the flow. After the passage of the main body of the flow, the number of geophone impulses rapidly decreased and the flow depth gradually decreased over the subsequent 20 min., which is interpreted as the tail of the debris flow.

The normal and shear stress data show similar trends to the flow depth, however the largest fluctuations in the measured forces (**Fig. 3**, middle panel) are largest only for about a minute after the arrival of the flow front at the force plate.

3.2 The 8 August 2013 debris flow

The 8 Aug. 2013 debris flow is typical of events which consist of one or a few surges of approximately equal size (**Fig. 4**). The general trends are similar to the 29 July event, but in this case the arrival of the first surge was around 11:55 and the second surge at 12:10. The abrupt change of bulk density, from 2200 kg/m^3 to only 1500 kg/m^3 with the arrival of the second surge could be interpreted as a second independent debris flow which may have originated in a sub-catchment different from that of the first surge. We have observed that sometimes several sub-catchments have apparently produced debris flows during the same rain storm event, however conditions do not always permit a field visit after every debris flow.

Similar to the 29 July debris flow, the fluctuations are largest when the flow depth is largest at the start of each surge, however the fluctuations in both normal and shear force remain elevated for about 5 min. of the second surge, indicating significant agitation of the flow.

3.3 The 24 August 2013 debris flow

The 24 August 2014 debris flow had a relatively long-duration flood-like or debris-flood-like snout followed by a body with multiple roll waves (**Fig. 5**). This type of event occurs only once every few years.

This event began with a complicated flash-flood

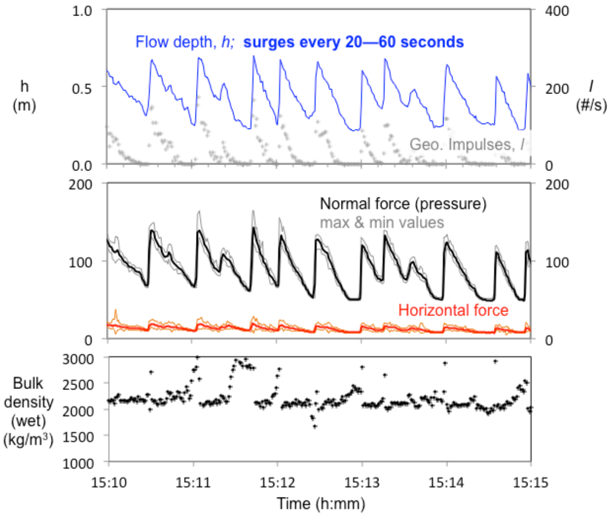

Fig. 6 A five-minute interval of the 24 Aug. 2013 debris flow.

like front at 14:44, which increased in depth in an undular manner until the arrival of the main debris-flow surge at about 15:04. Starting at about 15:05, the flow started showing a pulsing behavior indicative of roll waves, however the amplitude of the waves is quite large, with depths typically varying from 0.3 to 0.7 m (**Fig. 6**), and the flow even comes to a complete stop, which is indicated by flat segments of the lines for flow depth and forces after 15:14 in **Fig. 6**.

The individual roll waves, even though they have a duration of only 20 to 60 s, show pressure and stress fluctuations which mimic the larger surges, i.e. the fluctuations in normal and shear stress are largest at the front of each individual roll wave, even though the individual roll waves do not have granular snouts.

4. DISCUSSION

The debris flows described here share some common features, especially the presence of large fluctuations in normal and shear stress with the arrival of the main surge or smaller surges within the flow. Median normal stress values typically approach 200 kPa, with the largest fluctuations during any interval approaching 300 kPa, or roughly up to 1.5 times larger than the median pressure. Later in the flow, the size of the fluctuations becomes much smaller (typically an order of magnitude smaller) in comparison with the median pressure. Shear stress values show a similar pattern, with the median value about an order of magnitude smaller than the normal force measurements, which indicates a shear to normal force ratio of about 0.1, which is approximately the same as the slope of the channel.

The presence of very large pressure or force fluctuations at the main front of the flow correlates with observations at the Illgraben which suggested that channel-bed erosion occurs within the first minute of the arrival of the debris flow surge. Erosion at the flow front was also reported during large-scale experiments at the USGS debris-flow flume [*Iverson et al*., 2010].

However other field observations of debris flow erosion at Chalk Cliffs [*McCoy et al*., 2012], using the same type of erosion sensor used at the Illgraben, indicate that erosion occurs later in the flow. Some laboratory experiments [*Weber*, 2004] also report erosion after the passage of the main front of the flow. Both of these observations were relatively close to the initiation zone [*McCoy et al*, 2012], whereas the typical debris flow at the Illgraben travels 4 to 5 km before passing the zone where the erosion sensors were installed and the nearby force plate described herein.

One possibility is that the long travel distance of flows at the Illgraben allows the of development more complete longitudinal segregation of coarse particles, permitting the development of very well-defined granular fronts (with associated larger fluctuations in normal and shear stress) followed by the body of the flow which no longer carries as many large particles.

Another explanation is that the ratio of boulder size to flow depth may be larger at the Illgraben, than at Chalk Cliffs. If the stress fluctuations on the channel bed scale with the volume of the boulders carried by the flow, then it is likely that the pressure fluctuations at the Illgraben may be proportionally larger than those at Chalk Cliffs.

5. CONCLUSIONS

Using results from an 8 m^2 force plate installed in the bed of the Illgraben torrent channel, we illustrated the flow properties of three typical types of debris flow which have been observed at the Illgraben, single-surge flows with a clear granular flow front, multiple-surge flows, and more complicated surges with many individual roll waves. In all three types of flow, the median value of the normal and shear stresses are largest at the front of each surge. The fluctuations in normal and shear stress are also largest at the flow front, reaching values up to 1.5 times larger than the median value and decreasing to an order of magnitude smaller than the size of the median stresses in the tail of the flow. The presence of large force fluctuations at the front of the surges is in agreement with previously-published results which show that the rate of erosion is largest within the first minute of the arrival of a debris-flow surge.

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