DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

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灾害、风险、预测、防治

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При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).

Conference logo is based on a figure from S.M. Fleishman’s book on Debris Flows (Moscow: Geografgiz, 1951, p. 51).

Deciphering the interplay of surface velocity and flow height in natural debris flows: Field observations from the Illgraben, Switzerland

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Abstract. Debris flows are rapid and extremely destructive gravitational mass movements commonly encountered in mountain torrent catchments. Obtaining continuous, highly time-resolved data on the velocities of multiple consecutive debris flow events is challenging but needed for an improved process understanding and constraining simulation models. In this study, we use pulse-Doppler (PD) radar measurements gathered during the 2022 season at Illgraben, Switzerland, to analyze four debris-flow events. The PD radar, operating in a pulsed mode, provides spatially resolved cells known as range gates. Within each range gate, velocities are determined using the Doppler effect, resulting in Doppler spectra with a resolution of approximately 4 Hz per range gate. By plotting time series of these spectra, called Doppler images, we gain detailed insight into the distribution of surface velocities of incoming flows. In addition, we compute median velocity values from the spectra and incorporate independent flow height measurements taken at the same location to explore the relationship between these key debris-flow metrics. Our analysis reveals a moderate to strong positive linear correlation between the median velocities and corresponding flow heights. These findings have significant implications for the debris-flow community, providing valuable insights for refining debris flow models and developing effective mitigation strategies.

Key words: *Pulse-Doppler radar, debris flow monitoring, Illgraben, surface velocity, flow height*

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Установление взаимосвязи между поверхностной скоростью и высотой потока в природных селях: полевые наблюдения в Илльграбене, Швейцария

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Аннотация. Селевые потоки – это быстрые и чрезвычайно разрушительные гравитационные движения масс, часто встречающиеся в горных водосборных бассейнах. Получение непрерывных данных о скоростях нескольких последовательных селевых потоков с высоким временным разрешением является сложной задачей, но необходимой для лучшего понимания процесса и ограничения имитационных моделей. В данном исследовании мы используем данные импульсно-доплеровского (PD) радара, полученные в течение сезона 2022 г. в Илльграбене, Швейцария, для анализа четырех событий селевых потоков. Радар PD, работающий в импульсном режиме, обеспечивает пространственно разрешенные ячейки, называемые воротами диапазона. В пределах каждой зоны скорость определяется с помощью эффекта Доплера, в результате чего получаются доплеровские спектры с разрешением около 4 Гц для каждой зоны. Построив временные ряды этих спектров, называемые доплеровскими изображениями, мы получаем подробное представление о распределении поверхностных скоростей входящих потоков. Кроме того, мы вычисляем медианные значения скорости по спектрам и включаем независимые измерения высоты потока, сделанные в том же месте, чтобы изучить взаимосвязь между этими ключевыми показателями селевых потоков. Наш анализ выявил умеренную или сильную положительную линейную корреляцию между медианными скоростями и соответствующими высотами потоков. Эти результаты имеют важное значение для сообщества специалистов по селевым потокам, предоставляя ценные сведения для уточнения моделей селевых потоков и разработки эффективных стратегий смягчения последствий.

Ключевые слова: *импульсно-доплеровский радар, мониторинг селевых потоков, Илльграбен, поверхностная скорость, высота потока*

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Introduction

Debris flows are one of the most destructive geophysical mass wasting processes in mountainous areas, often triggered by severe convective thunderstorms [Guzzetti et al., 2008]. Consequently, robust risk assessment is imperative for enhancing societal and infrastructural resilience in vulnerable areas. Fundamental components of contemporary debris-flow risk management include numerical modelling [*Mergili et al., 2017; Meyrat et al., 2021*], vulnerability mapping, streamlined mitigation strategies, and the implementation of reliable automated early warning systems. High-resolution field measurements of flow velocity and height are key to advancing the understanding of debris-flow physics and ultimately improving risk management strategies.

Since the early 2000s, numerous scientific debris flow monitoring sites have been established worldwide. A prevalent method employed at several test sites involves measuring flow height using radar, ultrasonic, or laser sensors positioned above the channel bed [*Arattano and Marchi, 2008; Comiti et al., 2014; Cui et al., 2018; Hürlimann et al., 2014; Kean et al., 2013; McArdell et al., 2007*]. To further assess flow velocity, two or more flow-height sensors, often combined with infrasound- or seismic sensors, are installed at known intervals within a debris flow catchment. The gradient of the resulting time-stamped signals is then correlated to derive a front velocity value using a travel-time-distance method. In addition, for events with multiple significant surges, the entire time series can be cross-correlated to obtain surge-scale velocity estimates [*Coviello et al., 2019; Lapillonne et al., 2023; Marchi et al., 2023; Schimmel et al., 2022; Yan et al., 2023*]. These methods offer widespread applicability and relatively low installation expense but provide only approximate estimates of event velocity. Without continuous velocity information on a temporal microscale, especially for events characterized by multiple successive surges or events that give rise to roll waves [*Arai et al., 2013; Viroulet et al., 2018; Walter et al., 2023*] or erosion-deposition waves [*Edwards and Gray, 2015; Schöffl et al., 2023*], subsequent dynamic analysis remains somehow speculative.

To achieve high-resolution characterization of debris-flow velocities, more sophisticated sensors and techniques such as 3D-LiDAR scanner [*Aaron et al., 2023; Spielmann and Aaron,* *2024*] combined with Particle Image velocimetry [*Theule et al., 2018*] or pulse-Doppler radar [*Schöffl et al., 2023*] have been introduced at debris-flow monitoring sites in recent years. These studies have revealed significant velocity fluctuations within natural debris-flow events.

However, to the authors' knowledge, the relation between the key flow metrics of height and velocity has not been investigated from high temporal resolution measurements of natural debris-flow events. In this study, we undertake a thorough examination of these velocity dynamics using pulse-Doppler radar imaging, complemented by flow height observations during the 2022 debris-flow season, which included four notable events at Illgraben, Switzerland.

Methods and test-site

Illgraben test-site & flow height measurements

The Illgraben debris flow monitoring site is located in south-western Switzerland, near Leuk in the canton of Valais. The catchment area covers 8.9 km^2 from the summit of the Illhorn (2716 m a.s.l.) to the confluence of the Illbach with the Rhone (610 m a.s.l.) [*McArdell et al., 2007*]. The close proximity to the major Alpine tectonic faults [*McArdell and Sartori, 2021*] has produced highly erodible and weathered rocks, as well as the steep north-western dolomite cliffs of the catchment area, regularly cause an exceptionally high number of debris flows during the summer months due to heavy convective rainfall [*Badoux et al., 2009; Hirschberg et al., 2021*].

The monitoring site has been in operation since 2000 by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL [*Hürlimann et al., 2003*], with observations of flow velocity estimated using the travel time of flows between sensors installed along the lower 4 km length of the channel, and flow depth measured at several locations including at check dams 25 (geophone), 27 (geophones and two stage radar sensors) and 29 (geophones, laser, stage radar, and a force plate [*McArdell et al., 2007*]). Bulk density is determined using the vertical force and flow depth information from the force plate, and the discharge and event volume are determined using depth and cross-sectional geometry at the force plate [*McArdell et al., 2023*]. The WSL flow depth measurements are made a few meters upstream of the brink of the check dam because erosion and deposition are generally small due to the presence of the check dam.

Pulse-Doppler (PD) radar

In early 2022, the Institute of Mountain Risk Engineering (IAN) of the BOKU in Vienna, Austria, and the WSL started a cooperation and a joint measurement campaign. As a result, a pulse-Doppler (PD) radar (type SR2000-05-P) manufactured by IBTP Koschuch was set up for the debris-flow seasons of 2022 and 2023.

The PD radar enables non-contact measurement of surface velocity using the Doppler effect. At Illgraben, the PD radar was positioned on the orographic right side of the channel, directed towards check dam 27 (Fig. 1). The radar beam (beamwidth ~ 6°) covered an upstream distance of about 120 m before the signal was obstructed by a bend in the torrent channel. For our measurement campaign at the Illgraben we selected a spatial resolution of so-called range gates (RG) with a length (r_{RG}) of about 20 m, corresponding to a pulse length (τ) of 137 ns as defined by the formula $r_{RG} = (c\tau)/2$ [*Skolnik, 2008*], whereas c is the speed of light. The pulses are transmitted at a pulse repetition frequency (PRF) of 60 kHz. The echo signal is time-sampled and processed by a complex Fast Fourier Transform (FFT), resulting in Doppler spectra with a time step of $\Delta t \sim 0.272$ s for each range gate. A single Doppler spectrum has a resolution of 0.0527 m/s per class, for a total of 1024 classes, with a maximum unambiguously detectable velocity of 27 m/s. Within each class, the amplitude of the echo intensity (power signal) indicates which velocity classes correspond to moving parts on the surface of an incoming flow. To determine median values, we truncate the spectra above a certain multiple of the noise level to obtain a maximum velocity value as described in [*Schöffl et al., 2023;*

Schreiber et al., 2001]. In this study, we focus solely on the data from RG2, as this is where the sensor for the flow height is located.

Fig. 1. PD radar installed at Illgraben. Check dam (CD) 27 can be seen in the background, where the stage sensor and range gate 2 are located

Doppler imaging

The information that Doppler spectra provide about an observed flux becomes visible when the spectra are plotted as a time series, such as Velocity Time Intensity (VTI) or Doppler images, as shown in Fig. 2. The echo intensity, displayed on a color scale, provides an indication of the reflected cross-sectional area and thus the size of a moving object [*Gauer et al., 2007; Schöffl et al., 2023; Schreiber et al., 2001*]. The purple to reddish areas in Fig. 2 indicate a strong backscattered signal, especially when an object with a relatively large cross-section, such as a debris-flow front or a surge, passes through a range gate.

Data & analysis

For the convenience of the reader, we abbreviate the recorded debris flow events in this study as #DF, followed by the year, month, and day on which they occurred. The precise measurement capability is exploited in the use of PD radar as an automated early warning system by the company IBTP Koschuch. Although the radar at Illgraben was installed solely for scientific purposes, it is noteworthy that the system was able to automatically detect and record all debris-flow events during the two measurement seasons. We note that for the first three events, the radar signal amplifier was defective, so the absolute echo intensity values were degraded by a factor of ~10, but still sufficiently sensitive to fully image the events. We fixed the amplifier before the last event (#DF20220908) of 2022.

#DF20220605

The first event we encountered (#DF20220605) was characterized by an initially en-bloc moving, distinct granular debris flow front, resulting in a relatively narrow band of affected Doppler velocity classes and peak flow heights exceeding 2 m. This phenomenon is vividly illustrated in Fig. 2*a*, where a boulder-laden front with plug flow-like behavior as indicated in Iverson, (1997) and measured in the field by Nagl et al. (2020), arrives at ~100 s and moves coherently through the channel. This en-bloc motion initially corresponds to a narrow band of affected Doppler velocities between ~2 and ~5 m s^{-1} with median velocities close to 4 m s^{-1} However, the flux then exhibits a velocity jump at ~190 s, similar to an event observed by Aaron et al. (2023) at Illgraben on September 19, 2021. Thus, the velocity range suddenly increases positively to between ~3.5 m s^{-1} and nearly 8 m s^{-1} with median velocities jumping from ~2.6 m s^{-1} to ~4.6 m s^{-1}. The flow then begins to fluctuate in height and velocity as it breaks up into a series of over 60 roll waves that slowly decay over time until the end of the event.

#DF20220630

The second event (#DF20220630) was preceded by a flood-like surge, visible in the Doppler image from 72 s to 121 s, exhibiting a broad velocity spectrum with median velocities fluctuating around 1.5 m s^{-1} (Fig. 2*b*). The debris flow itself then emerged, consisting of 5 distinct debris flow surges (Fig. 2*b*), 4 of which were recorded by the flow height measurements from 121 s to 1672 s. Interestingly, the first and second surge displayed similar but attenuated oscilliating flow behavior as #DF20220605, with lower overall median velocities ~2 m s^{-1} and flow heights ~1 m, which subsided over time.

#DF20220704

Unlike the other three events, #DF20220704 had a wide range of velocities involved, from 0 to 12 m/s, indicating a more fluidized vortical surface flow with multiple velocities occurring simultaneously (Fig. 2*c*). Although this was a large-scale event featuring peak velocities of ~12 m s^{-1} and flow heights of ~3 m of the season, it is debatable whether it can be classified as a debris flow. As reported in Bolliger et al. (2024) the mean bulk density measured at the lower station at Illgraben amounts to 1189 kg m^{-3}, which would imply a more flash flood-like event in the nature of a debris flood as classified in Church and Jakob (2020) or the possibility of a hyperconcentrated flow as defined by Brenna et al. (2020).

#DF20220908

The last event of the season (#DF20220908) commenced with a flash flood-like surge that was detected by the PD radar at ~1407 s (Fig. 2*d*) with median velocites peaking at ~3.5 m s^{-1}. However, at that time there was no significant corresponding increase in the flow stage. Consequently, the flow height sensor measurement cycle was triggered when a pronounced front arrived at ~1477 s, characterized by median velocities of ~4 m s^{-1} and peak flow heights approaching 2 m. Subsequently, the flow underwent minor oscillations before experiencing a major surge at ~1650 s, with median velocities reaching ~6 m s^{-1} and maximum velocities peaking at ~9 m s^{-1}, accompanied by corresponding peak flow heights exceeding 2 m. This behavior mirrors observations by Aaron et al. (2023) and Hübl and Kaitna (2021) indicating that post-frontal surge or flow velocities can significantly exceed those of the front itself.

Relationship of flow height and suface velocity

We observe statistically significant correlations between flow height and median surface velocity for all four events. Interestingly, the data set of #DF20220605, which is characterized by a complex pulse-like flow pattern with more than 60 consecutive roll waves, shows the strongest correlation (R^2 = 0.85) over the entire event duration (75 s to 1380 s) (Fig. 3*a*). This is described by the function "Y = 2.28 * X – 0.36", indicating a positive linear relation.

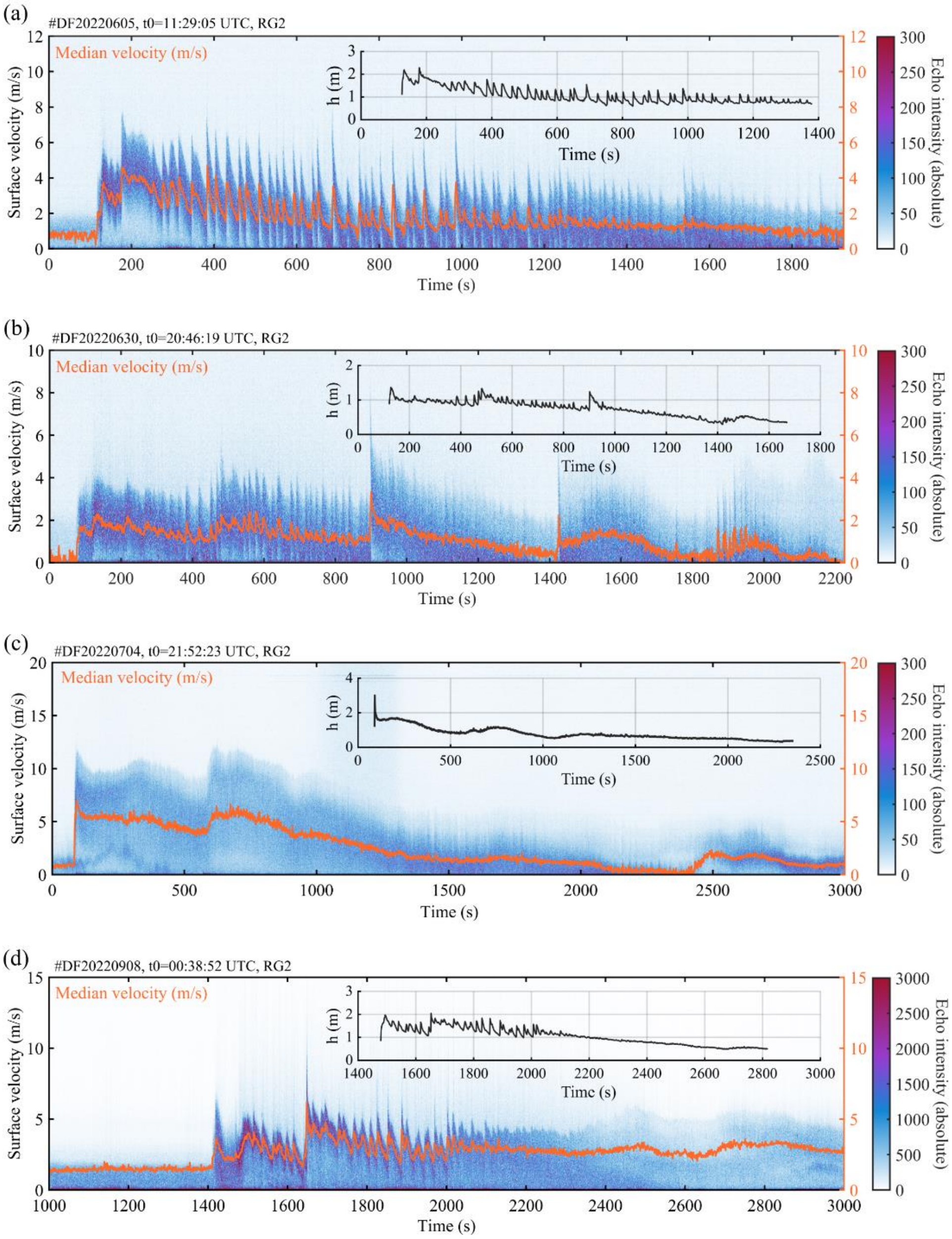

Fig. 11. Event catalogue of the debris flows that occurred in 2022 at Illgraben in chronological order. Doppler images and corresponding median velocities derived from range gate 2 and the respective evolution of flow height measurements

For #DF20200630 (Fig. 3*b*), we observe a moderate correlation (R^2 = 0.59; Y = 1.36 * X + 0.275) for the entire event duration (121 s to 1672 s). However, when analyzed on a surge scale, we find statistically strong relationships: R^2 = 0.73 (Y = 2.70 * X – 1.22), R^2 = 0.74 (Y = 2.36 * X – 0.69), and R^2 = 0.88 (Y = 2.96 * X – 0.73) for surges 1 to 3, respectively (121 s to 466 s; 467 s to 899 s; 900 s to 1416 s). No relation (R^2 = 0.14) is apparent for the last surge (1417 s to 1672 s). We attribute this finding to a transition from a dense, granular debris-flow phase to a more water-saturated flow (watery tail), where flow velocities increase while flow heights seem to stabilize around 0.4–0.5 m before slowly ceasing.

As mentioned above, #DF20220704 stands out in appearance. Although characterized by the highest velocities and flow heights, no oscillations, and thus no significant occurrence of multiple intra-event surges or waves, can be observed, except for the interval from approximately 600 s to approximately 630 s, where a velocity jump from median velocities of about 4 m s^{-1} rises to over 6 m s^{-1} (Fig. 2*c*). Interestingly, we find that the initial frontal surge (89–105 s) shows no relationship, as peak velocities seem to occur three seconds after peak flow heights. From 1060 s to 1210 s, a negative linear correlation is evident: as flow height increases, velocity decreases (Fig. 3*c*). We hypothesize that this again represents a transition phase where the sediment-water composition is prone to change. However, we find a statistically strong correlation for the entire event duration (89 to 2352 s) with an R^2 value of 0.72 and a corresponding function of Y = 4.46 * X – 0.60.

The radar measurement cycle of #DF20220908 was triggered by small flash floods, which we do not include in this paper. However, the radar time series (t0) is defined by these minor preceeding floods. The debris-flow phase lasted from 1477 s to 2100 s, during which median velocities showed a moderate correlation with flow height, having an R^2 value of 0.57 and the corresponding function: Y = 2.38 * X – 0.20 (Fig. 3*d*). After this period, we did not observe any correlation, possibly due to the changing composition of the flow and the potential measurement of slowly eroding deposits by the flow height sensor.

Considering that the mean bulk densities of #DF20220630, #DF20220630, and #DF20220908 are in the same range, 1690 kg m^{-3}, 1700 kg m^{-3}, and 1592 kg m^{-3}, respectively [*Bolliger et al., 2024*], if we examine the flow quantities of flow height and surface velocity of the three events neglecting the tail sections discussed above, we find a distinct correlation with an R^2 value of 0.84. This holds when excluding #DF20220704, which seems to follow a different flow regime with a mean bulk density of 1189 kg m^{-3}. The corresponding function that correlates the median velocity values with the observed flow heights is given by Y = 2.54 * X – 0.61.

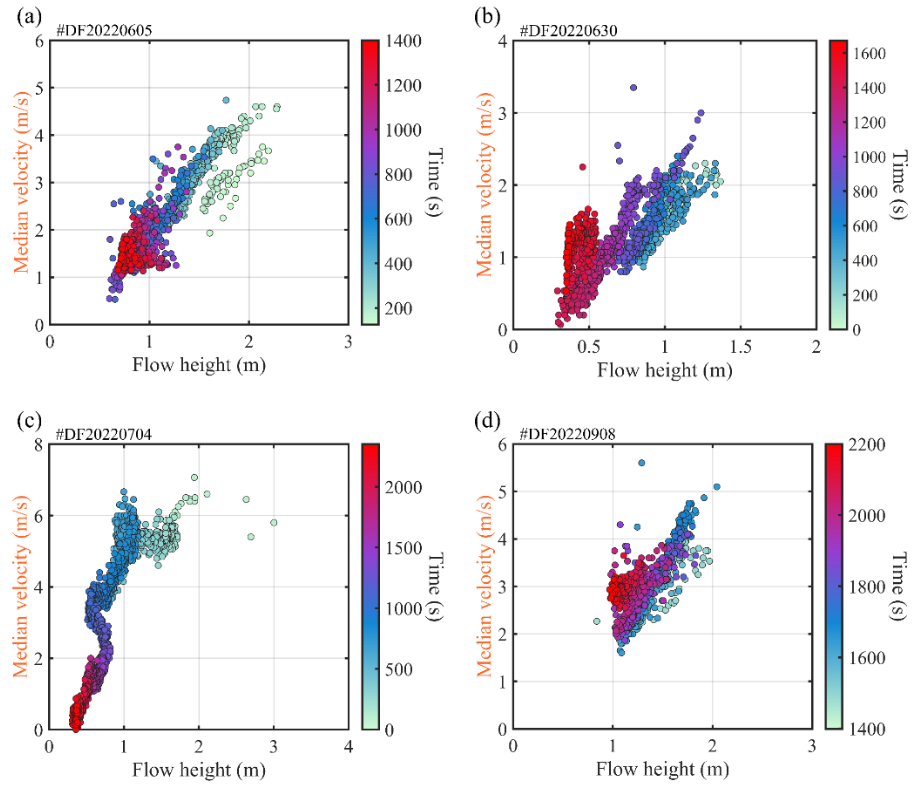

Fig. 12. Scatter plots of flow height and median surface velocities from the observed events. The time scale is highlighted as a color gradient

Conclusions

In this paper, we conducted measurements of four debris-flow events at Illgraben in Switzerland. Our monitoring efforts confirm findings from other research that the velocities of natural debris flows exhibit significant intra-event variability. However, despite the complex flow behavior, we found a moderate to strong linear relationship between flow height and velocity. It appears that variations in the function of these quantities can be attributed to changes in bulk density and hence to fluctuations in the material composition of the flows.

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