



Brief communication: First field observations of basal slip velocities in natural debris flows

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Abstract.

The internal dynamics of field-scale debris flows are challenging to observe. Constitutive equations for debris flows, often base on simplified shear models that assume a no-slip condition at the bed. However, laboratory experiments suggest that basal slip can occur under fixed bed conditions, influenced by the variable material composition of debris flows, which includes
15 grains and boulders interacting with the basal boundary. This study presents results from a novel monitoring system that has been designed to directly measure basal slip velocities in natural debris flows using paired conductivity sensors. The system, which was installed in the Lattenbach catchment (Tyrol, Austria), captures high-resolution temporal data from debris-flow events. A detailed examination of two events that occurred in June 2025 has revealed the presence of persistent slip velocities, particularly during surge phases and granular flow fronts. Basal sliding was found to be consistently lower in comparison to
20 surface velocities. These findings call into question the no-slip assumption of traditional rheological models and underscore the significance of basal slip in the dynamics of debris flows. Future research will focus on refining the detection depth of the sensors, analysing additional events, and conducting comparative studies across different catchments to further understand the role of basal slip in debris flows.

1 Introduction

25 Due to the challenges in observing the internal structure of field-scale debris flows, their analysis often relies on simplified shear models that assume a no-slip condition at the bed. However, while most rheological models are typically based on this no-slip assumption, laboratory experiments suggest that basal slip can occur in debris flows under fixed bed conditions (e.g. Sanvitale and Bowman, 2017; Taylor-Noonan et al., 2022). The variable composition of debris flows, which includes submerged grains and boulders of various sizes suspended in a mixture of fine particles and water, is expected to result in
30 sliding, colliding, and rolling of grains and boulders along the basal flow boundaries. Unlike the no-slip boundary condition typically observed with fluid flow over a solid surface, the movement of solid particles across a solid surface necessitates a partially slip boundary condition (Du et al., 2021). This is supported by experiments and simulations that have demonstrated



the significant influence of surface roughness on debris-flow motion (e.g., Iverson et al., 2010; Zheng et al., 2021). These conclusions highlight the importance of basal roughness and expose the limitations of assuming no-slip boundary conditions in the field of natural debris flows.

In natural debris flows, the occurrence of basal slip conditions has not yet been directly confirmed; however, there is strong evidence supporting the existence of a sliding at the base, based on investigations of erosion and deposition processes (Berger et al., 2011; Roelofs et al., 2022) as well as measurements of surface velocities (Aaron et al., 2023) or vertical velocity distributions (Nagl et al., 2020). This study introduces a novel technique to measure basal sliding and reports of the first results derived for two natural debris flows. The focus is on the following three research questions:

- 1) Is the proposed method capable to measure basal slip velocities?
- 2) What is the value range of the derived slip velocities?
- 3) Are slip velocities limited to specific phases of the debris flow (e.g., the granular front), or do they occur throughout the entire course of the observed events?

2 Methods

The Lattenbach catchment, located in western Tyrol, Austria, covers an area of approximately 5.3 km² and lies within a tectonic fault zone at the transition between the Silvretta crystalline and the carbone rocks of the Northern Calcerous Alps. This geological setting promotes high sediment production, which in turn favors the frequent occurrence of debris flow processes (Huebl and Kaitna, 2021). The measurement system used to observe slip velocities is part of a monitoring setup situated at an elevation of approximately 1,000 m asl. This system is installed between two force plates within a channel section, which is reinforced by a series of check dams.

The measurement principle is similar to a technique introduced for laboratory experiments to measure vertical velocity profiles in sediment-fluid mixtures in a rotating drum setup (Kaitna et al., 2014) and was transferred to a field monitoring station at the Gatria creek, Italy (Nagl et al., 2020). High-resolution temporal fluctuations in the conductivity of the passing debris are measured at the channel bed using four pairs of electrodes (ED1, ED2, ED3 and ED4) (see Fig. 1b). The conductivity fluctuations from each electrode pair are subjected to a low-pass filter and subsequently cross-correlated. Since the distance between the pairs is known, the time lag can be used to infer basal slip velocities according to the relationship $v = \frac{ds}{t}$.

Slip velocities were derived by cross-correlating the filtered sensor data using a floating data window with a duration of 0.5 seconds and an overlap of 50 % of the window length. Only correlation values with an autocorrelation coefficient (ACF) of at least 0.5 and velocities within the range of 0 to 10 m s⁻¹ were considered, as illustrated in Fig. 2. This parameter configuration has proven to be well-suited for providing an overview analysis and is further supported by insights gained from evaluations of vertical velocity distributions at the Gatria Creek (Nagl et al., 2020). Regarding sensor combinations, only adjacent electrode pairs (ED1 and ED2 with a spacing of 6.0 cm, ED2 and ED3 with a spacing of 7.7 cm, ED3 and ED4 with a spacing of 6.0 cm) were cross-correlated. For more distant pairs (e.g., ED1 and ED4), the results were found to be significantly less



robust. Surface velocity was independently measured by a Pulse Doppler Radar at a sampling frequency of 2 Hz (cf. (Schöffl et al., 2023)). To remove the scatter all the velocity data in this first evaluation is binned to a running median of 60 seconds, in order to obtain a clear overview over the entire events.

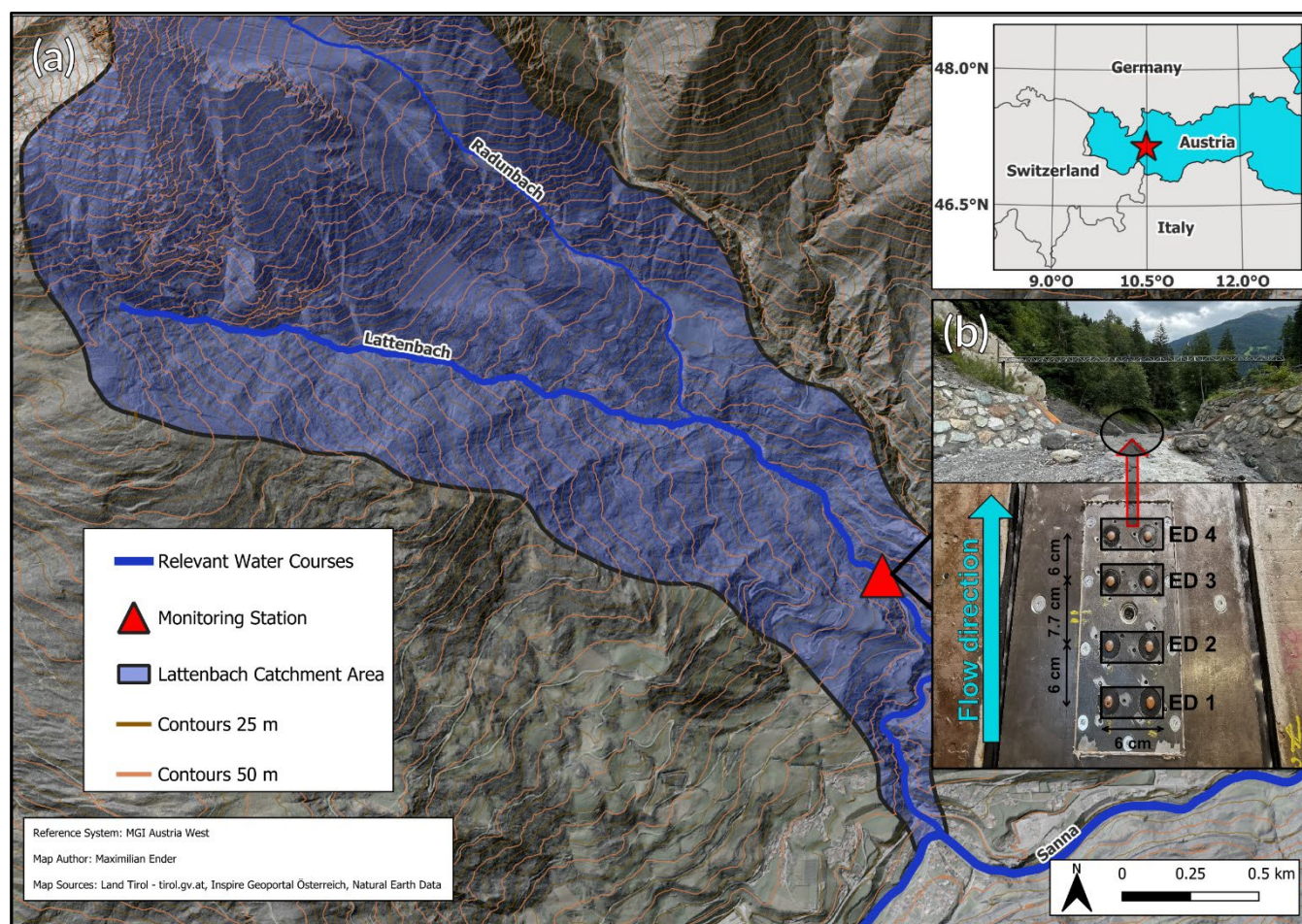


Figure 1: Visualization of (a) the catchment overview map with presentation of location of the monitoring station and (b) the slip velocity measurement system setup.



3 Results

To provide a first insight into the measurement system, the results of two debris-flow events from June 2025 are presented below. Webcam videos of both events are provided in the supplementary material.

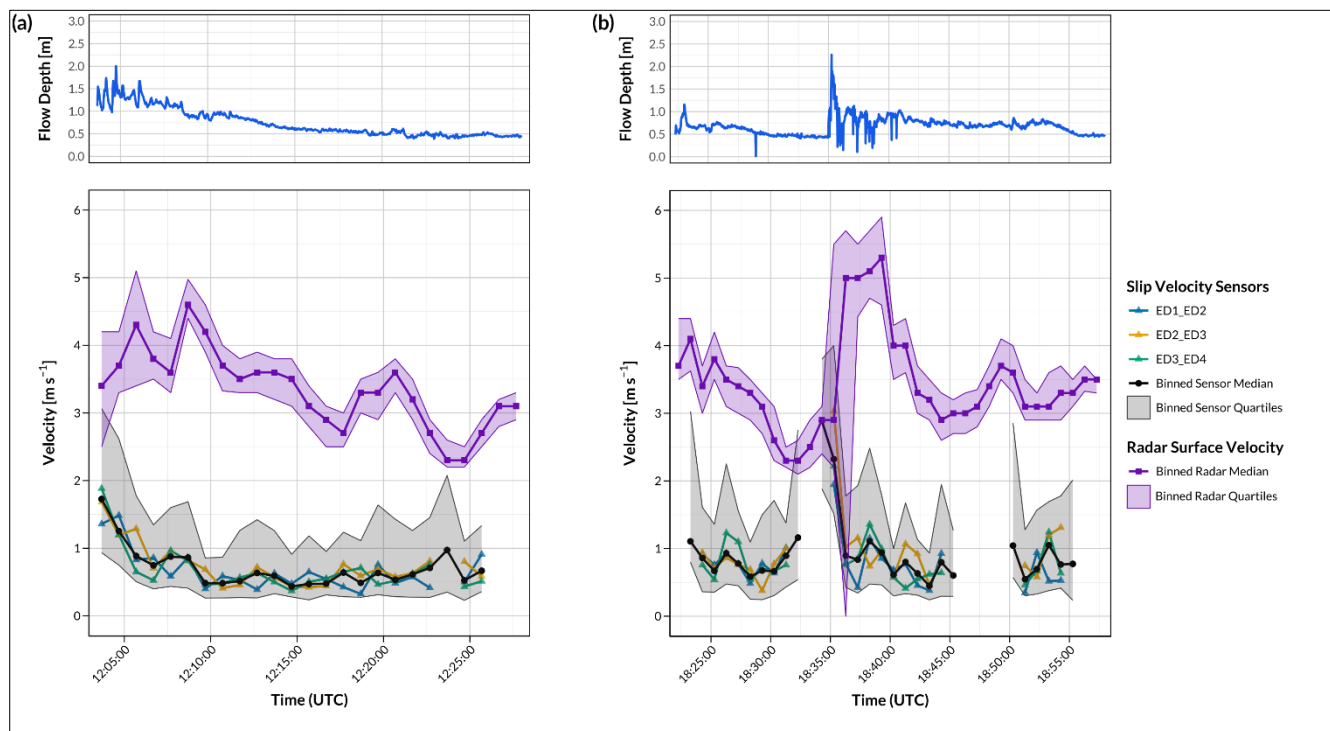


Figure 2: Slip velocity measurements for two debris-flow events at Lattenbach: (a) 15 June 2025 and (b) 30 June 2025. Shown are cross-correlated velocities from three sensor pair combinations. Colored lines represent the aggregated velocities values over 60-second intervals. The black line shows the running median of all velocity points over the same 60-second windows. The grey area represents the corresponding interquartile range. For reference, the surface velocity of the debris flows, derived from Puls Doppler radar data (purple points and line), including a shaded purple area indicating the interquartile range, as well as flow depth measurements from a laser gauge (blue line) are included.

The first event, on 15 June, had a duration of 25 minutes and consisted of a single main surge (Fig 2a). Qualitative analysis of the video recordings reveal a coarse-grained front, followed by finer material with a homogeneous grain-size distribution. Within the surge, several roll waves occurred. Toward the end, the flow behavior becomes more turbulent and gradually transitions into a debris flood.

75 The second event, on 30 June, had a duration of 35 minutes and comprised three surges (Fig. 2b). The first surge had a viscous appearance and displayed turbulent flow behavior, with a coarse-grained front. The second surge overtops the waning first surge with significantly higher velocity and flow depth, again exhibiting turbulent flow behavior. The third surge is difficult to distinguish from the second; it exhibits a relatively similar velocity to the waning second surge, with a visually slight change to a more fluid material composition. Toward the end of the event, the flow transitions also into a debris flood.



80 A nearly continuous presence of slip can be observed in both events, particularly for the first debris-flow event of 15 June. The 60-second binned medians, slip velocities remain almost consistently below 2 m s^{-1} . In this event, the front is especially well captured, showing the highest slip velocity values, which then decrease to relatively stable values of 0.5 to 1 m s^{-1} with only minor fluctuations. The median basal slip velocity is also markedly lower than the surface velocity, with a mean ratio $v_{\text{slip}}/v_{\text{surf}}$ about 0.3 relative to the surface velocity over the entire course of the event.

85 For the event of 30 June, the continuity is less pronounced; however, three distinct surge-like sections can be identified, separated by intervals with only few slip-velocity correlations (18:32:00 to 18:35:00 UTC and 18:46:00 to 18:50:00 UTC). The middle surge is characterized by a notably high slip velocity of almost 3 m s^{-1} in the beginning, which in this case matches the surface velocity. In the other parts of this event, slip velocities also remain predominantly $< 2 \text{ m s}^{-1}$ in the median, though characterized by stronger fluctuations, yet still consistently lower than the surface velocity. In this event, the ratio $v_{\text{slip}}/v_{\text{surf}}$ is

90 about 0.5 over the entire duration and is thus higher than in the first event.

Differentiating based on the strength of the correlation reveals no visually discernible patterns for either event. Individual correlations are widely scattered, and no clear trend can be identified indicating that lower slip velocity values are associated with higher correlation coefficients, or vice versa. Also, no clear pattern could be observed regarding the sensor combinations employed, neither in the individual correlation values nor in the binned sensor combination medians. The proportion of valid

95 correlations relative to the total possible correlations in the first events was 17.8% for the combination ED1 and ED2, 18.3% for the combination ED2 and ED3, and 18.2% for the combination ED3 and ED4. For the second event, this proportion was significantly lower due to the data gaps between the surges; however, differences between the individual sensor-pair combinations were again minor, with 13.5% for the combination ED1 und ED2, 12.6% for the combination ED2 and ED3, and 12.1% for the combination ED3 and ED4. Interestingly, the correlated slip velocity values of the central sensor

100 combination are markedly higher in the median for both events compared to the two outer sensor-pair combinations. For the event on 15 June, the medians were 0.89 m s^{-1} for the combination ED1 und ED2, 1.11 m s^{-1} for the combination ED2 and ED3, and 0.94 m s^{-1} for the combination ED3 and ED4. In the second event of 30 June, this difference was even more pronounced, with values of 1.27 m s^{-1} for the combination ED1 and ED2, 1.72 m s^{-1} for the combination ED2 and ED3, and 1.45 m s^{-1} for the combination ED3 and ED4. In this event, a slightly higher standard deviation of velocity values is also

105 observed in the central sensor combination, whereas in the first event the central and the rear sensor combinations exhibit higher standard deviations. However, these differences remain relatively small, within a range of $\pm 0.2 \text{ m s}^{-1}$.

4 Discussion

Based on two debris-flow events, we demonstrate that a continuous derivation of slip velocities is feasible. The debris-flow fronts in both events are clearly captured, exhibiting a high basal sliding, potentielle due to their coarser, more granular

110 sediment composition. This behavior has previously been demonstrated in laboratory studies by Sanvitale and Bowman, 2017. The subsequent, persistent occurrence of slip velocities during the surge and viscous phases of the debris flows is noteworthy



and adds missing dynamics to rheological models for debris flows with no-slip boundary conditions (e.g., (Berzi and Jenkins, 2008; Garres-Díaz et al., 2020; Luna et al., 2012; Pastor et al., 2021; Pudasaini, 2012).

115 The ratios between the median slip velocities and the surface velocities observed during the two events are similar to the values shown by Sanvitale and Bowman, 2017, particularly in the first event ($v_{\text{slip}}/v_{\text{surf}} = 0.3$). In the second event, this ratio is higher ($v_{\text{slip}}/v_{\text{surf}} = 0.5$), which can be attributed to the visually greater turbulence of the flow behavior in this event, especially during the second surge. This turbulent flow behavior results in a higher scatter in both, the cross-correlated slip velocity values and the Doppler radar-measured surface velocity values. Basal sliding also occurs in other geomorphological contexts, such as in snow avalanches (e.g., Kern et al., 2009) or temperate glaciers (cf. Bierman and Montgomery, 2020), where the $v_{\text{slip}}/v_{\text{surf}}$ ratio
120 is largely dependent on ice thickness and can reach high values exceeding 0.5 (Pieczonka et al., 2018). Such findings can also be applied to studies of basal slip velocities in natural debris flows; however, more events need to be analysed in a first step in order to draw more conclusions regarding the ratio $v_{\text{slip}}/v_{\text{surf}}$.

Further investigations are also required to evaluate the depth of the conductivity sensors penetrating the passing debris. If the detection depth is found to be high, the measured velocities may not accurately represent the slip velocity at the channel bed
125 but could instead reflect the flow velocity of the lowermost layers of the debris-flow mass. To gain a clearer understanding of the detection depth of the installed conductivity sensors, laboratory tests are planned.

The generally higher correlated velocities observed within the central sensor-pair combination ED2 and ED3 may be attributed to the larger spacing between these two electrode pairs (7.7 cm). The larger the distance between two sensor pairs, the lower the quality of the cross-correlation is expected to be, as it takes more time for the debris to traverse the spacing in-between.
130 However, this cannot be attributed to the ACF values, as they are not significantly lower for the central sensor-pair combination compared to the other combinations. It is therefore likely that the longer travel distance allows acceleration effects to influence the measurements, potentially leading to higher velocity estimates. An additional factor may be that the location of the slip velocity sensor setup directly above a check dam, which could further affect such basal acceleration effects.

The cross-correlation-based velocity derivation is additionally subject to a lower-bound velocity v_{low} , which primarily depends
135 on the sensor-pair spacing Δs and the length of the floating data window t_{WINDOW} : $v_{\text{low}} = \frac{\Delta s}{t_{\text{WINDOW}}}$. Due to the larger spacing between ED2 and ED3, v_{low} is higher when using an equally long floating window (0.5 s), potentially causing an upward shift in the median. Such aspects are the focus of an ongoing cross-correlation parameter sensitivity analysis using data from the vertical velocimeter at the Gatria monitoring station, whose findings will also be included in the derivation of slip velocities.

5 Conclusion & Outlook

140 In this study, we present a method to measure basal slip velocities in natural debris flows at the Lattenbach monitoring station, based on the analysis of two debris-flow events. First results indicate a persistent presence of slip velocity throughout the first event and during surge phases in the second. Both laboratory experiments and monitoring results from natural debris flows suggest the presence of a slip condition at certain parts of a debris flow along the channel bed (e.g., Aaron et al., 2023; Du et



al., 2021; Iverson et al., 2010; Kaitna et al., 2014; Nagl et al., 2020; Roelofs et al., 2022; Sanvitale and Bowman, 2017), despite
145 this phenomenon often being simplified or neglected in most rheological models. Initial evaluation results from a conductivity-
based measurement system, applied to two debris-flow events in the Lattenbach catchment, Tyrol, Austria, provide additional
evidence. The first event exhibited a continuous slip velocity, whereas the second event revealed three distinct surge phases.
In both cases, the surge fronts were consistently associated with high slip velocity values, which subsequently decreased in the
trailing portions of the flow.
150 Furthermore, the slip velocities observed in both events were almost always lower than the surface velocities measured using
a pulse Doppler radar, adding credibility to the derived value. The median ratios of $v_{\text{slip}}/v_{\text{surf}}$ were thereby 0.3 for the first event
and 0.5 for the second event. Future research will focus on analysing additional debris-flow events and evaluating the
penetration depth of the electrodes into the flowing debris mass. A similar sensor system has also been installed at Illgraben,
Switzerland, where a complementary study is planned to provide further insights into the occurrence of slip velocities across
155 different catchments.

6 Code availability

The analyses were performed using R. In the supplementary material included: <https://doi.org/10.5281/zenodo.17249344>.

7 Data availability

In the supplementary material included: <https://doi.org/10.5281/zenodo.17249344>.

160 8 Video supplement

In the supplementary material included: <https://doi.org/10.5281/zenodo.17249344>.

9 Author contribution

GN and ME contributed equally to data preparation, data analysis, result visualization and interpretation, and manuscript
writing. FK, BM, JA, JH, and RK were primarily involved in data analysis. SB and FZ played an important role in the design,
165 construction, and installation of the sensor.

10 Competing interests

The authors declare that they have no conflict of interest.



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