Seismic Measurements of Roll Waves in Debris Flows

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Abstract. Accurate debris-flow modelling depends on the ability to simulate surging and pulsing behaviour. However, our understanding of these phenomena is starved of observational constraints. Here we propose the use of seismic measurements, which resolve the arrival of coarse-grained roll wave fronts in debris flows at Illgraben, Switzerland. Roll waves likely play a key role in flow pulses but are typically only observed with point measurements like depth gauges. We compare in-torrent force plate measurements with near-torrent seismic records and discuss how these data can test existing roll wave theories.

1 Debris flows and roll wave formation

Details of debris-flow dynamics are difficult to constrain and model. The underlying rheology is still debated and even the flow behaviour of selected events is far from understood [1]. Debris flows tend to develop surges with individual flow pulses moving at different speeds and potentially overtaking each other to influence the overall mass transport and velocity [2, 3].

Channel geometry and roughness, sorting phenomena and friction likely play a crucial role in debris flow surging behaviour [4]. A related mechanism is the accumulation of a boulder-rich debris-flow front, which forms as a result of particle segregation and provides flow resistance for the trailing material leading to a bulging of the longitudinal surface profile [2].

Non-steady and surging debris-flow dynamics may also result from instabilities, which are characteristic for shallow, open-channel flows [5]. Perturbations of specific wavelengths theoretically grow in an unstable manner to move downstream at speeds different from the particle velocities [4, 6]. As such “roll waves” overtake each other, they may affect or even control debris-flow surges. Roll waves are observed as peaks in flow depth within the debris-flow tail. However, point measurements cannot constrain roll wave dispersion and the conditions for roll wave formation. Thus, it remains unclear to what extent roll waves influence debris-flow dynamics and surging behavior.

Here we present roll wave measurements at Illgraben, Switzerland, one of Europe’s most active debris-flow channels. In addition to conventional flow depth measurements, we present records of impact forces between debris-flow particles and the underlying bed. We observe these impacts with geophones and a force plate and with a near-torrent seismometer. We discuss the benefit of these impact measurements for our understanding of roll waves within debris flows and explore future research directions.

2 Debris flows at Illgraben, Switzerland

2.1 Site

Illgraben’s catchment in Southwestern Switzerland reaches from its highest point at Mount Illhorn (2717 m) down to 600 m at the estuary with the Rhône River (Fig. 1). Frequent slope failures in the upper catchment deposit in the channel and re-mobilize as debris flows during heavy summer precipitation 3-5 times a year [7].

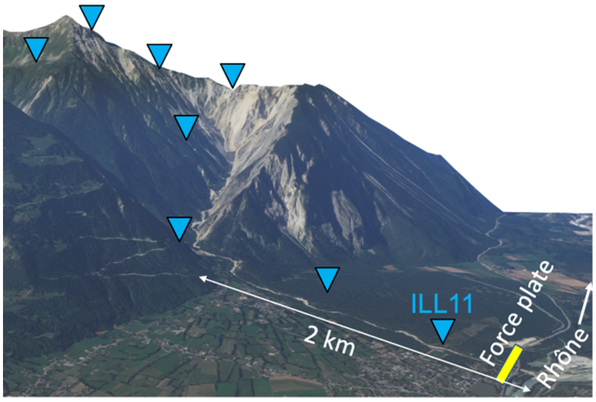

Fig. 1: Illgraben catchment with locations of seismometers (blue triangles) and force plate (yellow bar).

2.2 Measurements

A seasonal seismometer network has been operational since 2017 monitoring debris flow and slope failure activity [8]. This supplements in-torrent

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instrumentation in the lower catchment of Illgraben, consisting of flow depth gauges, Swiss geophone plates and a force plate (Figure 1) measuring shear and normal forces between debris flows and the channel bed [9].

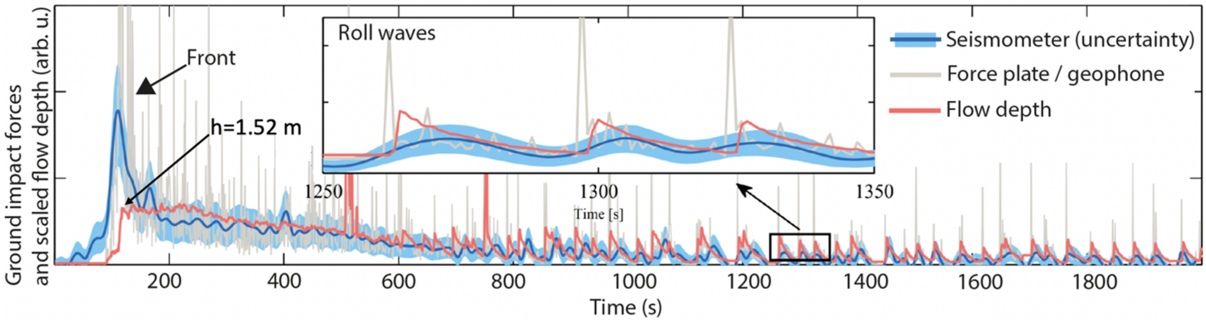

Fig. 2: Seismic and flow-depth measurements of roll waves at Illgraben. Modified from [8].

2.3 Debris flow seismology

High-frequency (> 1 Hz) seismic signals of granular materials like debris flows are typically modelled as superimposed particle impacts onto the channel bed [10]. Assuming instantaneous momentum exchange during the impact, the frequency signature is characterized by the seismic path between impact location and recording seismometer [11]. This, however, is difficult to constrain as a result of highly heterogeneous subsurface structure near debris-flow channels. In contrast, the force plate measures more closely the impact force histories, although some response of the structural characteristics of the force plate likely affects the signals, as well.

At Illgraben, station ILL11 (sensor model: Trillium Compact 120 s) locates within a few meters of the torrent in the Rhône valley (Fig. 1), some 450 m upstream of the force plate. The close torrent proximity minimizes the role of the path effect. Comparisons between seismic measurements and video footage show that seismic amplitudes are dominated by the effect of particle sizes and flow depth [8]. Consequently, the boulder-rich debris-flow front is seismically the “loudest” flow portion.

Fig. 2 shows a comparison between force plate data and nearby flow depth measurements as well as seismic data from ILL11. The force plate time series are the lower quantile (25%) of the maximum-to-median force differences in non-overlapping bins of 1 s duration. The seismic data are basal fluctuating forces for each time window of 10 s calculated using a damped least squares inversion and the power spectral density (PSD) of seismic signals between 1 and 30 Hz in discrete time windows [8]. Throughout the debris flow, the impact forces measured with seismometer and force plate correlate with flow depth. Towards the beginning of the flow, the particle size effect amplifies seismic and force plate measurements compared to flow depth. Note that whereas flow depth and force plate measurements were nearly co-located, synchronization with the seismometer time series recorded 450 m downstream is subject to large uncertainties. In the flow tail, each time series exhibits regular roll waves. Flow depth steepens at the roll wave arrival and gently drops until the arrival of the next one.

3 Discussion

The records in Figure 2 show clear evidence for roll waves. Higher impact forces at the roll wave front can be explained with theory predicting transient densification of coarse-grained material [6]. However, part of the impact force peak ahead of the flow depth peak likely results from the rapidly changing weight on the force plate: the quasi-static increase in normal force changes rapidly enough to influence the maximum-to-minimum force differences. This adds to any increases in impact forces caused by concentration of coarse particles.

Seismometer chains along a torrent could be used to track roll waves within debris flows. Benchmarked with point measurements of flow depth as in Figure 2, seismic measurements could thus provide observations of roll wave dynamics, which thus far to our knowledge only exist in the laboratory. This would constrain propagation velocities of roll waves, independent of speeds of their hosting debris flows. Similarly, distributed seismic sensors would elucidate under which conditions roll waves are formed and destroyed allowing to test theoretical dependencies on Froude number and channel depth [12, 13]. Importantly, the tracking of roll waves would show if the theoretical limit for merging and amplification behaviour is reached within typical runout distances of a natural debris flow [14].

There exist specific technical challenges, which may limit the potential of seismometer arrays distributed along a torrent channel. First, seismic point measurements are sensitive to a range of locations along a channel, which must be accounted for when allocating impact force generation to channel sections [15]. The non-local generation of impact force signals is evident in Figure 2 showing that in-torrent force plate measurements resolve the arrival of the roll wave front better than near-torrent seismometers. In the latter case, the impact force increase is smeared out to produce a regular seemingly sinusoidal fluctuation. The magnitude of this effect depends on channel-sensor distances, ground properties and grain sizes within the roll waves, and it may or may not mask the seismic signature of roll waves at certain channel portions. As an alternative, tilt measurements may be able to resolve the added weight of roll waves, similar to what has been observed for the arrival of debris flow fronts [16]. However, it remains to be shown if this effect can be captured with instrumentation that is affordable enough to allow for extended sensor chains needed to track the propagation of roll waves along significant portions of a debris flow channel.

4 Conclusions

Relatively easy deployments of seismic sensors could provide sufficient measuring points along a channel to clarify under which conditions roll waves tend to form. First comparisons between flow depth, force plates and geophone measurements are encouraging and suggest the suitability of this method for longer torrent sections. Nevertheless, the required number of sensors and digitizers calls out for low-cost and highly portable instrumentation, whose suitability has yet to be evaluated. If successful, our distributed seismic measurements would have important consequences for numerical models indicating the need to capture flow instabilities to describe pulsing and surging behaviour of debris flows.

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