E3S Web of Conferences 415, 03016 (2023) https://doi.org/10.1051/e3sconf/202341503016
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# Volume, Peak discharges and Froude Number of Debris-Flow Surges: 10 Years of Monitoring on the Réal Torrent (France)

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**Abstract.** This work presents a summary of data on debris-flow monitoring stations focusing on the surge scale rather than full-scale debris-flow event (several fronts and surges with intermediate diluted flows). Surge-scale debris-flow data are not easily accessible for modellers but would be very beneficial for the community. A summary of the data processing protocol is offered, and its application to the monitoring station of the Réal Torrent is described (drainage area: 2 km², SE France). Investigated bulk surge features are volume, front height, peak discharge, and Froude number. This investigation leads to statistical distributions of these parameters on 34 surges gathered from 2011 to 2020. Their volumes are typically a few thousand cubic metres, their peak flow height is 1 to 2 m, their peak discharge is a few dozens of cubicmetres per second and their Froude number is near critical. Results drawn from this work will be a great asset for modellers to better feed their numerical experiments with realistic, field-driven features.

## 1 Introduction

Debris-flow monitoring has attracted increasing attention in the past twenty years [1]. Thanks to debris-flow monitoring efforts, a wide range of torrent catchments are now equipped to record a variety of data. Although these measurements are being recorded, very few data has yet been made available, especially at the surge scale. The most basic features of debris-flow surges remain unclear: worldwide debris-flow volumes can vary from a few hundreds to a few millions of cubic metres; peak discharges, front depth and velocity are poorly known. Discharge, grain sizes, rheological features of the bulk surges and interstitial fluid are also variable and rarely reported in the literature [but see 1, 2, 4]. Some datasets have been shared, like for instance reported volumes of full-scale debris-flow events in the Illgraben catchment [5] and ful hydrographs of debris flow events in the Moscardo catchment [6]. This paves the way to international collaboration for an easy to use database.

Numerical modellers as well as physical modelling initiatives need such data ranges to better design their simulations. Due to this lack of dataset, wide ranges of parameters are explored, for example wide ranges of Froude numbers [7–9 among others]. Exploring such wide ranges requires huge amounts of effort, which could be redirected towards better understanding the physics of debris-flow surges if a narrower range was used. On the contrary, there is a habit of using very simple flow hydrographs, with narrow ranges of discharge, when the variability of real flow hydrographs has shown to have a significant impact on the flow behaviour [4]. Providing a complete database, including multiple sites in different geomorphological contexts would allow modellers to design experiments closer to field reality. Understanding the high variability of Nature is complex, and takes both financial andtemporal resources. Providing a public data set would allow debris-flow research to focus on deeper questions. The present work is a proof of concept. It aims to quickly present a protocol to be implemented in order to build such a complete database and shows preliminary results on the monitoring site of the Réal Torrent[1,10,11]. This database contains data on representative surge volumes, Froude numbers, maximum height and peak discharge of the surges.

## 2 Methods

### 2.1 Overview of an event analysis

Debris-flow monitoring stations have several types of measurement strategies [12,1]. In Figure 1, a conceptual sketch of the essence of the protocol implemented in the Réal is displayed. Overall, several types of sensors are necessary to feed the database regarding velocity, depth and wetted cross-section (Fig. 1a):
(i) flow stage measurements with a frequency that allows catching the peak flow;
(ii) accurate hypothesis on the cross-section at the monitoring station (Fig. 1b), which can include hypotheses on channel erosion / deposition or detailed geometry of the cross-section (e.g. a check dam);

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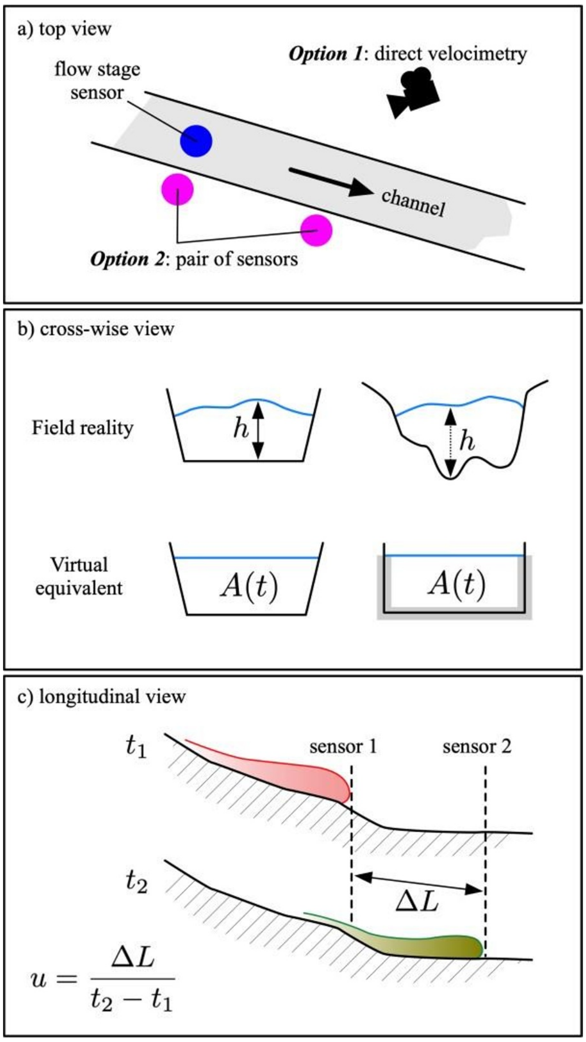


**Fig. 1.** Overview of a debris-flow event analysis: a) typical location and types of sensors, b) cross section approximations: real cross sections are approximated to a virtual equivalent to estimate wetted areas for discharge and volume calculations, c) velocity estimation by travel time analysis

(iii) access to the flow velocity either via direct measurements (LS-PIV or image processing) or using the travel time of the surge between a pair of sensors (Fig. 1c).

These measurements must be available at a location at which it is reasonable to assume that: (i) the measured velocity can be safely assumed to be the velocity of the surge caught by the flow stage sensors; (ii) the surges keep their physical integrity between the two sensors, i.e., the surge does not stop, is not divided into multiple surges or merged with other surges, and the surge shape between the two sensors has not drastically changed.

If these assumptions are valid, it will be possible to access the main properties of interest, i.e., the velocity of the surge $u$, the peak discharge $Qp$, the volume $V$, the peak flow stage $hmax$ and the Froude number $F$. These key parameters describing the surges are then computed using the time series from the sensors where $\Delta t = 1/f$, $f$ is the sampling frequency of the signal and $Q(t)$ is the instantaneous discharge:

$$Q(t) = u \cdot A(t) \quad (1)$$

$$V = \Sigma t\ Q(t) \cdot \Delta t \quad (2)$$

$$F = \frac{u}{\sqrt{g \cdot h_{max}}} \quad (3)$$

## 2.2 Surge identification

Detecting a debris-flow surge is not a trivial task. Monitoring stations record all the continuum of flow types encountered in steep headwaters, and differentiating debris-flow surges from debris flood and runoff with high sediment transport can sometimes be tricky. This is especially true for continuous monitoring stations where the harsh conditions lead to measurement setups focused on being reliable and light in data transfer, meaning camera recordings of the events can be scarce.

Similarly, because debris flows are generally composed of several surges and eventually have liquid diluted flows, defining the end of the surge front and the beginning of the diluted flows is important. Indeed, the surge front is a very complex and the most destructive part of the flows. Focusing data analysis on this front goes hand in hand with the intention for this database to be used for modelling the surge behaviour. This work is thus different from previous initiatives where the full event, sometimes with multiple surges and more diluted flows, was aggregated (as provided in [5]). The applicability of Eq. (2) also relies on high solid concentration, meaning diluted flows cannot be taken into account.

By experience, identifying debris-flow surges using exclusively the flow stage sensor is quite unreliable, especially in catchments where after-flows are very intense. Another criterion may be used and preferably one that can be cross-controlled. Having a rational and precise threshold for differentiation and definition of surges is vital to the rigour of this database project.

## 2.3 Application to the Réal Torrent (France)

For the purpose of illustration of the protocol, data from the Réal Torrent monitoring stations are used [10,11,13,14]. This catchment is monitored by three stations, one on a check dam and two on natural cross-sections further downstream (drainage areas of 1.3 km², 1.7 km² and 2.0 km², respectively). Each station is equipped with a rain gauge, a flow stage sensor and several geophone sensors. The geophone sensors record seismic activity near the flow stage sensor location, as well as upstream and downstream of this location. Distance between the sensors makes the physical integrity hypothesis to be sensible. Stations are also equipped with cameras that allow both to confirm hypotheses on debris-flow surge identification and differentiation from debris floods, and to have access to a cross-control of the velocity measurement by image analysis.

The identification of debris flow is done using the seismic sensors by visual interpretation. Indeed, they provide a data-driven criterion for debris-flow detection because they capture the sediment transport activity. It has been shown that mature debris flows have a characteristic seismic signature where (*i*) the seismic signal shows a sudden increase when the front passes at the level of the sensor, and (*ii*) the seismic activity is high and does not drop to zero for the whole duration of the surge [15]. On the contrary, immature debris flows, debris floods and bedload-laden flows may trigger seismic activity which are instantaneously high, but which do drop to zero, appearing as a very strong and noisy signal, characterized by a low signal-to-noise ratio. The characteristic seismic signal of a debris-flow surge is, in essence, a prolonged and consistent seismic activity. A more thorough description of this method, including discussion on aggregated signals for volume estimation is available in [16].

The delay between the geophone sensors catching the debris-flow signature signal is computed through cross-correlation. Velocity of the front surge is then computed from that delay (Fig. 1c).

For natural cross-sections, different hypotheses are used to assume a relationship between *hmax* and the wetted area, using both the expertise on local geometry from [15] and hypotheses on the erosion / deposition profiles, including results from [17] (Fig. 1b).

The gathered data come from 10 years of recording (2011 - 2020). For this paper only surges with *hmax* > 1 m have been kept, considering them as maturesurges. If multiple surges happen on the same event butdo have seismic signatures clearly separated by a diluted phase, the two surges are considered separately.Conversely, if two surges appear to be almost continuous regarding the characteristic seismic signature but keep their two-peaks shape on all sensors,they are taken as a single surge. This case remains marginal (one surge). These criteria sum to have 34 surges for the Réal Torrent, 26 of which are from the upstream station, located on a 8 m-wide check-dam; four at the intermediate station (7 m-wide natural channel) and two at the lowest station (12 m-wide natural channel).

## 3 Results

### 3.1 Database structure

Results from processing the surges are gathered into a database in HDF5 format and stored by surges. Froude numbers, maximal flow stage, peak discharge, flow volume and front velocity are stored, as well as raw data from the monitoring (rainfall measurements, seismic signals, flow height, location of the sensors and version of the data logger). For each computed property, uncertainties on the measurements and error estimation from the hypotheses are also saved. This is especially critical for natural cross-sections where the hypotheses on wetted areas is a major component of the global uncertainty.

### 3.2 Ranges of hydraulic properties of debris flow surges

Such data points allow us to study ranges of the different properties. In Figure 2, the cumulative distribution functions are plotted for Froude numbers, maximal flow stage, peak discharge and volumes.

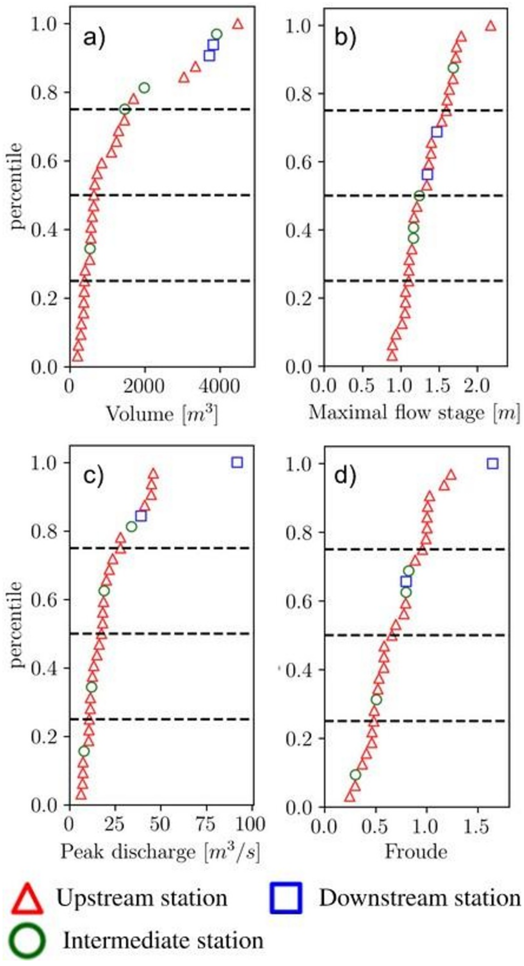


**Fig. 2.** Cumulative density functions of four hydraulic properties of debris-flow surges of the Réal Torrent: a) volume, b) maximal flow stage, c) peak discharge and d) Froude number.

Surge volumes range from 200 to 4500 m³ (Fig. 2a - quantiles 25%, 50%, 75%: 390 m³, 640 m³, 1460 m³). Surges are relatively small, typically from 300 to 2000 m³/km² (recall that this is surge scale and an event may comprise several of them and some after-flows). Maximal flow stage is most of the time lower than 2 m (Fig. 2b - quantiles 25%, 50%, 75%: 1.1 m, 1.25 m, 1.6 m). The peak discharge range between 6 and 92 m³/s (Fig. 2c - quantiles 25%, 50%, 75%: 11 m³/s, 18 m³/s, 28 m³/s). Comparison of these features to features of other debris flow prone catchments can be found in [16]. The unit peak discharge is thus typically 1 to 8 m³/s.m. Finally, Froude numbers range from 0.25 and 1.6 (Fig. 2d - quantiles 25%, 50%, 75%: 0.48, 0.65, 0.95), i.e. are typically near critical, i.e. between 0.5 and 1.5. Interestingly, this is consistent with laboratory observations on debris flood processes [18].

Froude numbers used in the literature for debris-flow modelling are usually much higher than these values. A wider dataset could help to confirm if the measurements made on the Réal Torrent are consistent with other sites or if this trend is site-specific. We should then find features that can be cross-compared between different sites as for instance specific sediment yield (m³/km²), unit discharge (m³/s.m) and Froude numbers. This permits modellers to have a first idea of the ranges of hydraulic properties of debris flows. If more monitoring stations were to get associated with this project, not only would more statistically representative data be available, but also new relationships between these properties could be explored. The interpretation of the current content of the database might not be exploitable as is - 34 events on one site is too specific to be able to retrieve global behaviours - but a rich dataset would allow to explore deeper scientific questions, and benefit the community.

## 4 Discussion

Choosing to segment the event at surge scale is serving the purpose of surge scale modelling but does present drawbacks concerning the study of morphological changes associated to whole events. Complete sediment balance as well as temporal and upstream-downstream transfers are not described. Indeed, bed-load, wash-load and small debris flood events are not included in the database, meaning that the full catchment sediment export is not described.

Several hypotheses would be unreasonable if applied to non-debris flow processes: *(i)* Eq. (1) assumes that the surge velocity is a relevant proxy of the flow velocity. This surge velocity if applied to hydrographs would not be relevant. *(ii)* Eq. (2) is only applicable if the solid concentration is very high. For diluted flows, the solid phase and the liquid phase should be considered separately which is difficult, as the solid concentration cannot be directly measured easily.

## 5 Conclusion

This work is a proof of concept for data processing of debris-flow surges from monitoring stations. Bulk surge features are investigated including volume, front height, peak discharge and Froude number. This investigation leads to statistical distributions of these parameters on 34 surges gathered from 2011 to 2020 on the Réal Torrent. Their volumes are typically a few thousands cubic metres, their peak flow height is 1 to 2 m, their peak discharge is a few dozens of cubic metres per second and their Froude number is near critical.

These results show the potential of an international, collaborative database. We believe debris-flow monitoring has reached sufficient maturity to make representative hydraulic properties available for the modelling community. We clearly intend to complete this database using collaborative approaches and we are looking for monitoring sites and experts willing to share either their raw or pre-processed data to feed the database. The database will be made available and will come with a descriptive note for each monitoring site.

This project is funded by the LabEx Tec21 Investissements d'avenir - agreement n°ANR-11-LABX-0030.

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