Deciphering seismic and normal-force fluctuation signatures of debris flows: An experimental assessment of effects of flow composition and dynamics

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Abstract
Debris flows are gravity-driven mass movements that are common natural hazards in mountainous regions worldwide. Previous work has shown that measurements of ground vibrations are capable of detecting the timing, speed, and location of debris flows. A remaining question is to what extent additional flow properties, such as grain-size distribution and flow depth can be inferred reliably from seismic data. Here, we experimentally explore the relation of seismic vibrations and normal-force fluctuations with debris-flow composition and dynamics. We use a 5.4 m long and 0.3 m wide channel inclined at 20°, equipped with a geophone plate and force plate. We show that seismic vibrations and normal-force fluctuations induced by debris flows are strongly correlated, and that both are affected by debris-flow composition. We find that the effects of the large-particle distribution on seismic vibrations and normal-force fluctuations are substantially more pronounced than the effects of water fraction, clay fraction, and flow volume, especially when normalized by flow depth. We further show that for flows with similar coarse-particle distributions seismic vibrations and normal-force fluctuations can be reasonably well related to flow depth, even if total flow volume, water fraction, and the size distribution of fines varies. Our experimental results shed light on how changes in large-particle, clay, and water fractions affect the seismic and force-fluctuation signatures of debris flows, and provide important guidelines for their interpretation.

KEYWORDS
composition, debris flow, force fluctuations, force plate, geophone, seismic vibrations

1 | INTRODUCTION

Debris flows are gravity-driven mass movements, consisting of sediment and fluid (Iverson, 1997; McArdell et al., 2007), which are common natural hazards in mountainous regions worldwide (e.g., Dowling & Santi, 2014). At the base of a moving debris flow, individual grains interact with the channel bed through a combination of impact and sliding, causing seismic ground vibrations (e.g., Arattano & Moia, 1999; Zhang et al., 2021) and normal-force fluctuations (e.g., Hsu et al., 2014; McArdell et al., 2007; Yohannes et al., 2012). These forces are increasingly measured and seismology has become a promising tool to obtain quantitative information about debris flows and lahars (e.g., Allstadt et al., 2018; Farin et al., 2019; Kean et al., 2015; Walter et al., 2017; Zhang et al., 2021).

Previous work has shown that measurements of ground vibrations are capable of detecting the timing, speed, and location of debris flows. Nevertheless, the analysis of ground vibrations induced by fluvial processes is a complex task that depends on many factors related to both the source characteristics (flow velocity, sediment concentration, grain size) and other conditions such as distance between sensor and channel and the traversed geological materials (Abanço et al., 2014; Chou et al., 2010; Cole et al., 2009; Coviello et al., 2018;
Gimbert et al., 2019; Huang et al., 2007; Lai et al., 2018; Tsai et al., 2012). This work aims to experimentally explore the potential of using seismic vibrations and normal-force fluctuations to infer flow composition (i.e., particle-size distribution and water content), flow volume, and flow dynamics (i.e., flow depth).

Recent theoretical models suggest that the seismic ground velocity spectrum and basal fluctuating force spectrum induced by debris flows predominantly scale with $u^{1.5}D_e^{1.5}$, where $u$ is flow velocity and $D_e$ is the effective particle diameter of the flow, under the assumption of steady flow, a particle impact velocity similar to the average flow front velocity, and a bed roughness length scale similar to $D_e$ (Farin et al., 2019; Lai et al., 2018). Indeed, for natural debris flows in the Illgraben torrent in the Swiss Alps, Zhang et al. (2021) found that the seismic basal fluctuating force spectrum scales with $D_e^{1.5}$. This non-linear relation between particle diameter and forces exerted at the bed suggests that the relatively large particles dominate the seismic vibrations and force fluctuations (Farin et al., 2019; Hsu et al., 2014; Zhang et al., 2021). For two experiments in the US Geological Survey (USGS) debris-flow flume, Allstadt et al. (2020) found systematic relationships of seismic vibrations and normal-force fluctuations with flow depth, mean basal shear stress, mean normal stress, flow velocity, flow momentum, and bulk density, where the strongest relationships were those with flow depth and mean shear stress. However, for debris flows in the Illgraben torrent Zhang et al. (2021) found no relationship with flow velocity. While these findings thus suggest the presence of links between debris-flow dynamics and composition and seismic vibrations and normal-force fluctuations, there is no consensus on the exact nature of these links.

In reality not only the effective particle diameter, but also other aspects of flow composition, such as clay fraction and water content, may affect debris-flow dynamics and generated forces (e.g., D’Agostino et al., 2010; De Haas et al., 2015; Hsu et al., 2008; Hürlimann et al., 2015; Kaitna et al., 2016; Scheidl & Rickenmann, 2010; Stock & Dietrich, 2006). Debris flows generally contain 20% to 60% water by volume (e.g., Costa, 1988), and their grain-size distribution typically includes sediment particles ranging in size from microns (e.g., clay and silt) to meters (e.g., boulders) (e.g., Blair & McPherson, 1994; Kim & Lowe, 2004). The composition of debris flows can vary substantially ranging from mudflows and lahars with a high fraction of fine particles (clay, silt, sand) to granular flows with a high fraction of coarse particles with diameters that may exceed a meter (e.g., Kaitna et al., 2016). Moreover, their composition may also strongly differ within an event – typically a coarse-grained flow front with a low water content is followed by a finer-grained and more fluidal flow body (e.g., Iverson, 1997; McArdell et al., 2007). The interstitial fluid of a debris flow can be highly viscous because of suspension of clay and silt particles in the interstitial water (e.g., Coussot, 1997), which on the one hand may facilitate excess pore pressures in the flow thereby enhancing flow mobility and the forces exerted on the bed by decreasing the inter-granular friction (Hsu et al., 2014; Iverson, 2003), while on the other hand may dampen collisions in the flow and with the channel bed (Vallance & Savage, 2000). Indeed, Kaitna et al. (2014) experimentally showed that the viscous matrix in a muddy flow slows particle velocities relative to flow velocity, which may dampen particle impacts with the bed and thus seismic vibrations and normal-force fluctuations. Further research is therefore needed to decipher the potential and limits of seismic vibrations and normal-force fluctuations in characterizing debris-flow dynamics and composition. Such understanding will strongly benefit future interpretation of the seismic and normal-force fluctuation signatures of debris flows.

Measuring the particle-size distribution and water content of a moving debris flow is nearly impossible (e.g., Iverson, 1997). As a result, the bulk of our knowledge on the particle-size distribution of debris flows stems from analyses of their deposits (e.g., Kim & Lowe, 2004; Marchi et al., 2002; Takahashi, 1991). However, obtaining a representative sample size for determining particle-size distributions is problematic because of the wide range of particle sizes in debris-flow deposits. Many published grain-size distributions are therefore biased because they ignore the presence of cobbles and boulders (e.g., Berti et al., 2000; Major & Voight, 1986). Non-invasive measurements for determining the composition of debris flows may increase our understanding of the range of compositions occurring in debris flows, and the relation between flow composition and flow dynamics, but such methods have so far remained limited to the identification of boulders on video imagery (e.g., Okano et al., 2012). The relationship of seismic vibrations and normal-force fluctuations with effective particle diameter in theoretical models (e.g., Farin et al., 2019; Kean et al., 2015; Lai et al., 2018) and field measurements (Zhang et al., 2021), suggests that geophone and load cell measurements may be used to extract information on flow composition – such an exercise requires that we enhance our understanding of the relation of seismic vibrations and normal-force fluctuations with debris-flow composition.

Several authors have previously used laboratory flumes to simulate debris flows (e.g., Allstadt et al., 2020; D’Agostino et al., 2010; De Haas et al., 2015, 2018; Hürlimann et al., 2015; Liu, 1996; Major & Iverson, 1999; Van Steijn & Coutard, 1989). A major advantage of physical-scale experiments is that boundary conditions can be fully controlled, and that the particle-size distribution is fully known. Moreover, experiments on a relatively small scale are useful because they allow experiments to be done in large numbers, thoroughly evaluating the effects of a large range of boundary conditions (e.g., De Haas et al., 2015).

Here we present a large dataset of debris-flow experiments aimed at unraveling the relation of debris-flow composition and dynamics with seismic vibrations and normal-force fluctuations. We tackle the following research questions:

- How do the seismic vibrations and normal-force fluctuations induced by debris flows relate to each other?
- How do debris-flow composition and volume affect seismic vibrations and normal-force fluctuations?
- To what extent can debris-flow dynamics and composition be inferred from the seismic vibrations and normal-force fluctuations of a debris flow?

This article is structured as follows: We first detail layout and boundary conditions of the experimental flume and laboratory experiments, measurement and analysis techniques, and potential scale effects. Then we present the general flow characteristics, seismic and normal-force fluctuation distributions, and their relation to debris-flow composition, volume, and dynamics. Finally, we discuss the potential for estimating debris-flow composition and dynamics from
seismic and normal-force fluctuations, the correspondence of seismic vibrations and normal-force fluctuations, and evaluate the Farin et al. (2019) model for the generation of seismic ground velocity against our measurements.

2 | MATERIALS AND METHODS

To study the potential of seismic vibrations and normal-force fluctuations for quantifying forces at the debris flow to channel-bed interaction, and the effects of debris-flow composition on these forces, we conducted a series of experiments with systematic variations of angular gravel (8–11 mm), clay (kaolin), and water fractions relative to a reference debris flow mixture predominantly consisting of sand. A total of 56 experiments were performed – 14 varying gravel fractions, 14 varying clay fractions, 14 varying water fractions, and 14 varying flow volume (Supporting Information Table S1). To account for the effects of natural variability, each experimental setting was repeated twice.

2.1 | Experimental setup

The experimental flume consists of a straight, rectangular, channel of 5.4 m long and 0.3 m wide (Figure 1). The channel can be inclined at angles ranging between 0° and 35°, but was set at 20° for all experiments presented here. The channel is built from stainless steel, and has a fixed bed covered by sandpaper. Sediment mixing and release into the channel is done with a forced-action mixer (Baron E120), with a custom-made release gate of 0.3 m wide. Sediment and water were typically agitated for ~30 s, and agitation stopped 0.8 s before gate opening, to minimize seismic vibrations in the flume induced by the sediment mixing.

To measure force fluctuations at the bed, two plastic plates of 0.14 wide and 0.06 m long were installed in the flume bed at distances of 2.90 m and 2.98 m downstream of the release gate. A HBM PW6D load cell was mounted on the underside in the middle of the upstream plastic plate and a Geospace GS-20DX geophone, measuring ground velocity, was mounted on the underside in the middle of the downstream plastic plate. For the Geospace GS-20DX geophone the manufacturer specifies a natural frequency of 10 Hz and a flat response to 1000 Hz. The sensor measured seismic movements in both the vertical and horizontal directions. The design of this setup is comparable to the Swiss Geophone Plate previously used for fluvial bedload measurements (e.g., Rickenmann et al., 2012, 2014; Wyss et al., 2016). To minimize seismic vibrations induced by the mixer and seismic resonance, the outside of the flume was covered by anti-drumming material (Vibraflex UF 35 mm). In addition, the measurement plates were largely disconnected from the flume bed, with a gap of 1 mm which was water-sealed by a cling film. This was done to minimize path effects.

To compare the force fluctuations at the bed to flow depth we installed two Baumer OADM 20 U2480/S14C distance sensors, capable of measuring flow depth at sub-millimeter accuracy, above the middle of the geophone and force plates. In addition, Baumer FADK14U4470/S14/IO distance sensors, measuring flow depth at 1–2 mm accuracy, were installed at distances of 1.40, 2.81, and 5.36 m from the release gate. Flow velocities were extracted from the difference in arrival time between the distance sensors. In this work we use the average velocity between the mixing tank and distance sensor directly above the load cell for analysis. All measurement devices in the flume were sampling at a frequency of 9500 Hz.
To visually capture the general behavior of the flows three GoPro HERO6 cameras were installed above the flume, at the downstream end of the channel, and above the force and geophone plates. Videos were captured at 1040 dpi and at 60 frames per second.

2.2 | Debris flow composition

The debris flow mixtures were composed of clay (kaolin), sand, and gravel (8–11 mm). Our reference experiment had a total mass of 60 kg (~0.03 m³), with a sediment mixture consisting of 20 vol% of gravel, 75 vol% of sand, and 5 vol% of clay, and had a water to sediment ratio of 40 vol% (Figure 2). In our experimental series we varied gravel in the flow from a fraction of 0.0 to 0.6, with increments of 0.1. Clay fractions were varied between 0.0 and 0.25, volumetric water fractions ranged between 0.25 and 0.57, and total flow mass ranged from 38 to 108 kg (0.018–0.054 m³) (Figure 2; Table S1). The grain-size distributions typically comprised three peaks, related to the gravel around a particle size of 10 mm, the sand around a particle size of 0.33 mm, and the clay (Figure 2). The $D_{50}$ ranged between 0.36 mm and 5.52 mm and $D_{84}$ ranged between 0.92 and 10.25 mm, for gravel fractions ranging from 0 to 0.6, respectively. Increasing the clay fraction from 0 to 0.25 led to a decrease in $D_{50}$ from 0.48 mm to 0.33 mm and a decrease in $D_{84}$ from 6.79 to 2.60 (Figure 2; Table S1).

2.3 | Data analyses

To minimize low-frequency noise in the geophone data, caused by vibrations in the flume resulting from the forced-action mixer, we applied a band-stop filter of 2.5 to 50 Hz (cf. Hsu et al., 2014). This frequency range is well below the inverse of particle impact durations typical for laboratory settings (Farin et al., 2015). We converted the raw geophone signal to mean amplitude by calculating the mean of the absolute value of the raw signal over 0.05 s time windows (cf. Arattano et al., 2014). To obtain the normal force fluctuations we first applied a low-pass filter with a corner frequency of 0.1 Hz, and then subtracted the filtered normal force data from the raw normal force data (Figure 3b). A 2.5–50 Hz band-stop filter was then also applied to the normal-force fluctuation data.

To evaluate the effect of debris-flow composition on the force fluctuations we extracted (1) the 99th percentile force during the passage of the flow and (2) the mean force fluctuation over 0.35 s around the flow peak (Figure 3). Seismic and force-fluctuation energy were calculated as the squared integrated seismic and force-fluctuation amplitudes, respectively (cf. Schimmel et al., 2021).

2.4 | Potential scale effects

It has previously been argued that small-scale experimental debris flows exhibit disproportionately large effects of yield strength, viscous flow resistance, and grain inertia, while exhibiting disproportionately little effect of pore-fluid pressure (Iverson, 1997, 2015; Iverson et al., 2010). The dimensionless numbers denoting flow dynamics of our experimental debris flows, such as shear rate, Savage number, Bagnold number, and Friction number (see Supporting Information Data S1 for equations and explanation) are generally in the range of debris flows in the large-scale USGS flume and natural debris flows (Table 1; Iverson, 1997; Iverson & Denlinger, 2001; Zhou & Ng, 2010).

Previously, De Haas et al. (2015, 2016, 2018) showed that the large-scale flow patterns and deposits of small-scale experimental debris flows mimic those of natural debris flows. Similar to nature, in these small-scale debris flows coarse particles become concentrated near the flow front, ultimately forming coarse-grained lateral levees and snouts (De Haas et al., 2015, 2016). Moreover, De Haas et al. (2015) showed that small-scale experimental debris flows geometrically follow scaling relationships found for natural debris flows (e.g., Griswold & Iverson, 2008; Iverson, 1997; Rickenmann, 1999):
channel width-to-depth ratios, and runout length and area relative to debris-flow volume, are all similar to those of natural debris flows (De Haas et al., 2015). Nevertheless, we emphasize that the experimental small-scale debris flows presented here are not intended as 1:1 scaled analogues of natural debris flows, but rather aim to qualitatively highlight the relation of debris-flow composition and volume with seismic vibrations and normal-force fluctuations.

3 | RESULTS

3.1 | General flow characteristics

The overall flow patterns in the experimental debris flows were similar. After the flows were released from the mixing tank an initial flow front would form which would then be overtaken by a second

TABLE 1  Physical and dimensionless parameters of small-scale, experimental debris flows and large-scale natural debris flows. Values were taken or calculated from the source specified in the header unless denoted otherwise in the footnotes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol (unit)</th>
<th>This study</th>
<th>De Haas et al. (2015)</th>
<th>USGS flume debris flows(a)</th>
<th>Natural debris flows(a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median grain size ($D_{50}$)</td>
<td>$\delta$ (m)</td>
<td>0.0003–0.0005</td>
<td>0.0005–0.0002</td>
<td>0.001</td>
<td>$10^{-5}$–$10^{-1}$</td>
</tr>
<tr>
<td>Maximum flow depth</td>
<td>$H$ (m)</td>
<td>0.02–0.06</td>
<td>0.005–0.02</td>
<td>0.1</td>
<td>0.1–10</td>
</tr>
<tr>
<td>Frontal flow velocity</td>
<td>$u$ (m s$^{-1}$)</td>
<td>0.4–1.9</td>
<td>0.9–2.9</td>
<td>10</td>
<td>0.1–20</td>
</tr>
<tr>
<td>Flow shear rate</td>
<td>$\gamma$ (1/s)</td>
<td>8–91</td>
<td>105–371</td>
<td>100</td>
<td>1–100</td>
</tr>
<tr>
<td>Solid volume fraction</td>
<td>$v_s$ (–)</td>
<td>0.43–0.75</td>
<td>0.35–0.59</td>
<td>0.6</td>
<td>0.4–0.8</td>
</tr>
<tr>
<td>Savage number</td>
<td>$N_S$</td>
<td>0.1–24</td>
<td>0.17–2.25</td>
<td>0.2</td>
<td>$10^{-7}$–$10^{0}$ ab,c</td>
</tr>
<tr>
<td>Bagnold number</td>
<td>$N_B$</td>
<td>12–3,016</td>
<td>37–1,589</td>
<td>400</td>
<td>$10^{2}$–$10^{8}$ ab</td>
</tr>
<tr>
<td>Friction number</td>
<td>$N_F$</td>
<td>3,250–6,760</td>
<td>141–2760</td>
<td>2,000</td>
<td>$10^{2}$–$10^{5}$ ac</td>
</tr>
</tbody>
</table>

(a)Iverson (1997).
(b)Iverson and Denlinger (2001).
(c)Zhou and Ng (2010).
more mobile surge. In general, this second surge would overtake the flow front upstream of the measurement section, and in some cases shortly after the measurement section leading to hydrographs with two flow peaks at the measurement station. In each experimental debris flow a cloud of saltating and rolling gravel outran the main debris-flow front. The size of this cloud increased with overall gravel fraction, and became nil towards the largest clay fractions (experimental movies can be accessed at https://doi.org/10.24416/UU01-83GMFG).

Overall, we observed an increase in coarse-particle accumulation near the flow front with increasing gravel fraction (compare Figure 4a,b), and a decrease in coarse particle accumulation with increasing clay fraction (compare Figure 4c,d), while changes in frontal coarse-particle accumulation were limited with increasing water fraction and volume (Figure 4e–h).

The frontal flow velocity (average velocity between the mixing tank and load cell) of the experimental debris flows strongly depends on the composition of the flows (Figure 5). The frontal flow velocity is maximum for gravel fractions of ~0.3 with a velocity of ~1.8 m s⁻¹, while frontal flow velocity decreases to ~1.6 m s⁻¹ at the smallest and largest gravel fractions (Figure 5a). The maximum flow depth is inversely related to frontal flow velocity, with the smallest maximum flow depth, 0.04–0.05 m, for a gravel fraction of ~0.3, and largest flows depth of around 0.55 m for gravel fractions of 0.0 and 0.6 which have the smallest frontal flow velocities (Figure 5e). Similarly, there is an optimum clay fraction for which frontal flow velocity is maximal.

![Figure 4](image_url) Movie stills of experimental debris flows with varying compositions and volumes. (a) Experimental flow 003 with a low gravel fraction of 0.1. (b) Experimental flow 013 with a high gravel fraction of 0.6. (c) Experimental flow 017 with a low clay fraction of 0.03. (d) Experimental flow 027 with a high clay fraction of 0.25. (e) Experimental flow 030 with a low water fraction of 0.25. (f) Experimental flow 041 with a high water fraction of 0.57. (g) Experimental flow 043 with a small volume of 0.018 m³. (h) Experimental flow 056 with a large volume of 0.056 m³. See Supporting Information Table S1 for experimental details. Experimental movies can be accessed at https://doi.org/10.24416/UU01-83GMFG [Color figure can be viewed at wileyonlinelibrary.com]

![Figure 5](image_url) Frontal flow velocity and maximum flow depth as a function of gravel fraction, clay fraction, water fraction, and flow volume in the experimental debris flows, with all other parameters held constant.
Maximum frontal flow velocity coincides with a clay fraction of 0.1, and decreases to frontal flow velocities of ~1.3 and ~1.2 m s\(^{-1}\) for clay fractions of 0.0 and 0.25, respectively (Figure 5b). Maximum flow depths for clay fractions ranging between 0.05 and 0.20 are in the range 0.04–0.05 m, while the flow depths at clay fractions smaller than 0.05 m are ~0.02 m and at clay fractions > 0.2 approximately 0.03 m (Figure 5f). These low maximum flow depths are the result of the absence of a clear frontal flow peak in these experimental debris flows. An increase in water fraction in the experimental debris flows leads to a strong increase in frontal flow velocity toward a water fraction of 0.3 (Figure 5c). For water fractions larger than 0.3 frontal flow velocities are approximately 1.8 m s\(^{-1}\). Maximum flow depths decrease with increasing water fraction, from ~0.05 m at a water fraction of 0.25 to ~0.035 m at a water fraction of 0.57 (Figure 5g). An increase in flow volume leads to a strong increase in maximum flow depth (Figure 5d), while it has a negligible effect on frontal flow velocity (Figure 5h). Comparable relations of debris-flow composition and volume with flow velocity and flow depth were previously reported for small-scale experimental debris flows by De Haas et al. (2015) and De Haas and van Woerkom (2016).

The hydrographs of the experimental debris flows typically had an asymmetric shape with a rapid increase in flow depth behind the flow front and a gradual tapering flow depth towards the tail of the flow (Figures 3 and 6). The flows with clay fractions smaller than 0.05 form an exception, because these did not form a distinct flow front.
3.2 | Seismic and normal-force fluctuation distributions

The dominant seismic and normal-force fluctuation frequency of the experimental debris flows is approximately 250 Hz (Figure 6). Most force fluctuations occur in the frequency range 50–500 Hz. In general, there is a subtle increase in power as the debris flows approach the geophone and force plate, followed by maximum power values coinciding with the flow front, after which the power slowly tapers. At the start of the measurements, coinciding with the release of the debris flows from the mixing tank, a peak in power can often be observed in frequencies < 50 Hz which is the result of vibrations and resonance induced by the mixing tank.

There is great similarity in the spectrograms of the seismic vibrations and the normal-force fluctuations (Figure 6). Both have a similar power distribution, with roughly similar frequency distributions, maximum values coinciding with the flow front, and gradual tapering power values behind the flow peak. The spectrograms of the debris flows vary strongly with the composition of the flows. Figure 6 shows examples of a gravel-rich debris flow (gravel fraction 0.6), clay-rich debris flow (clay fraction 0.2), and water-rich debris flow (water fraction 0.54). The spectrogram of the gravel-rich debris flow is characterized by relatively large powers throughout the flow. In contrast, the clay-rich debris flow has a restricted power peak near the flow front and peak. The spectrogram of the water-rich debris flow shows limited power at the flow front and similar power peaks throughout the passage of the bulk of the flow.

To quantify the comparability of the vertical and horizontal seismic vibrations and the normal-force fluctuations, we compare the 99th percentile force during the passage of the flow and the mean force in a 0.35 s window around the flow peak (Figure 7) for all experimental flows (Figure 7). This analysis reveals a very strong correlation between the vertical and horizontal ground velocity, with an \( R^2 \) of 0.89 when considering the mean values around the flow peak and an \( R^2 \) of 0.88 when considering the 99th percentile force during the passage of the flow (Figure 7a). Similarly, there is a very strong correlation between vertical ground velocity and the normal-force fluctuations, with \( R^2 \) of 0.91 and 0.80 for the mean values around the flow peak and the 99th percentile force during the passage of the flow, respectively (Figure 7b). Because of the strong comparability between seismic vibrations and normal-force fluctuations, from here on we show trends between debris-flow properties and vertical ground velocity.

3.3 | Effects of flow composition on seismic vibrations and energy

There is an increase in vertical ground velocity with increasing gravel fraction in the flows (Figure 8a). The 99th percentile force during the passage of the flow and the mean force in a 0.35 s window around the flow peak show similar trends, although the former has vertical ground velocities that are approximately an order of magnitude larger than those of the latter. The increase in seismic vibrations with increasing gravel fraction is in sharp contrast with the relation of gravel fraction with frontal flow velocity and peak flow depth (Figure 5a,e). Vertical ground velocity is largely unrelated to clay fraction (Figure 8b), with similar values of 99th percentile force during the passage of the flow and the mean in a 0.35 s window around the flow peak for the full range of clay fractions of 0.00 to 0.25. Vertical ground velocity decreases with increasing water fraction (Figure 8c). This relation follows the decrease in peak flow depth with increasing water fraction (Figure 5g), while it is in contrast with the increase in frontal flow velocity with increasing water fraction (Figure 5c). An increase in

![Figure 7](image-url) Comparison between seismic and normal-force fluctuations in the experimental debris flows, expressed as the 99th percentile force during the passage of the flow and the mean force fluctuation over 0.35 s around the flow peak. (a) Vertical ground velocity versus horizontal ground velocity. (b) Vertical ground velocity versus normal-force fluctuation.
flow volume causes an increase in vertical ground velocity (Figure 8d), seemingly in line with the increase in maximum flow depth with increasing flow volume (Figure 5h).

We find strong positive relations of gravel fraction and flow volume with vertical seismic energy, as integrated over the full flow duration (Figure 8e,h). In particular, the relation between flow volume and seismic energy is very clean with very limited scatter. There is no consistent trend in the relation between clay fraction and vertical seismic energy (Figure 8f). The low seismic energy for flows with a clay fraction of 0.25 are the result of the low flow velocity of these flows that caused these flows to deposit and not reach the end of the channel. We further find a marginal decrease in vertical seismic energy with increasing clay fraction.

**Figure 8** Mean (around the 0.35 s around the flow peak) and 99th percentile vertical ground velocity and vertical seismic energy, as functions of gravel fraction, clay fraction, water fraction, and flow volume.

**Figure 9** (a–d) Ratio between peak vertical ground velocity ($G_v$) and peak flow depth ($H$) as a function of gravel fraction, clay fraction, water fraction, and flow volume. (e–h) Ratio between peak and mean vertical ground velocity and mean vertical ground velocity as a function of gravel fraction, clay fraction, water fraction, and flow volume. (i–l) Time lag between (1) the peak vertical ground velocity and the peak flow depth and (2) time lag between the flow arrival and peak flow depth, as a function of gravel fraction, clay fraction, water fraction, and flow volume.
energy with increasing water fraction (Figure 8g). The earlier-described relations seem to partly follow the relations of flow composition and volume with maximum flow depth (Figure 5).

The ratio between the peak vertical ground velocity and the peak flow depth increases linearly with gravel fraction (Figure 9a). For flow volumes 0.02–0.03 m³ there appears to be a slight decrease in this ratio, while it increases strongly with larger flow volumes (Figure 9d). In contrast, the ratio between the peak vertical ground velocity and the peak flow depth is largely unaffected by clay and water fraction (Figure 9b,c). Despite a reasonable amount of scatter, the ratio between the peak and the mean vertical ground velocity is roughly constant and around a value of 2 for most flows (Figure 9e–h). The time lag between the peak vertical ground velocity and the peak flow depth is very close to the time lag between the flow arrival and the flow peak (Figure 9i–l). This shows that the maximum vertical ground velocity occurs directly behind the flow front for all flows.

3.4 | Relation between flow depth and vertical ground velocity

We find a positive, non-linear, relation between maximum flow depth and vertical ground velocity in the 0.35 s around the maximum flow depth (Figure 10). Most of the flows of different compositions and volume seem to follow a similar trend, although considerable scatter is present. However, the four flows with the lowest gravel content in our series (gravel fraction ≤ 0.1) strongly deviate from the observed trend, and yield very low force fluctuations despite having a relatively large flow depth (Figure 5e), suggesting that large particles dominate the seismic vibrations and normal-force fluctuations and that an absence of large particles leads to a strong decrease in force fluctuations.

3.5 | Relation between grain size and vertical ground velocity

For the experimental runs in which we systematically increased the gravel fractions from 0.0 to 0.6 (experimental debris flows 001–014 in Table S1), there is an increase in median grain size from 0.36 to 5.52 mm, an increase in \( D_{50} \) from 0.75 to 9.89 mm, and an increase in \( D_{90} \) from 2.27 to 14.15 mm (Figure 11). For \( D_{50} \) and \( D_{90} \) there is a strong increase in vertical ground velocity for grain sizes smaller than 3 mm, above which the increase flattens out (Figure 11a,b). For \( D_{70} \) and \( D_{80} \), there is also a relatively strong initial increase in vertical ground velocity for grain sizes smaller than 3 mm (Figure 11c,d). For larger grain sizes the increase in vertical ground velocity becomes increasingly strong. For \( D_{50} \) and \( D_{90} \) there is an initially relatively subtle increase in vertical ground velocity with grain size, but above grain sizes larger than \( \sim 8 \) mm vertical ground velocity increases very strongly (Figure 11e,f). For grain sizes larger than \( D_{70} \) the relations have a distinct break in slope – typically around grain sizes of 5 to 8 mm.

4 | DISCUSSION

4.1 | Estimating debris-flow characteristics and composition from seismic vibrations and normal-force fluctuations

Our results show that vertical and horizontal ground velocity and normal-force fluctuations are both strongly controlled by the composition of a debris flow (Figure 8). We find that (1) the large-particle distribution dominates the seismic vibrations and normal-force fluctuations (Figures 8a,e and 11). (2) An increase in large particles (gravel in our experiments) leads to a strong increase in the magnitude

![Figure 10](https://wileyonlinelibrary.com) Relation between maximum flow depth and vertical ground velocity in a 0.35 s window around the maximum flow depth [Color figure can be viewed at wileyonlinelibrary.com]
of ground velocities and normal-force fluctuations (Figure 8a,e), (3) an increase in water fraction (i.e., decrease in sediment concentration) leads to a subtle decrease in the magnitude of ground velocities and normal-force fluctuations (Figure 8c,g), and (4) clay fraction does not substantially affect ground velocities and normal-force fluctuations (Figure 8b,f). (5) An increase in flow volume leads to an increase in the magnitude of ground velocities and normal-force fluctuations (Figure 8d,h). (6) For flows with similar large-particle distributions seismic vibrations and normal-force fluctuations may be reasonably-well related to flow depth, even if total flow volume, water fraction, and the size-distribution of fines varies (Figure 10). (7) There is a strong non-linear relationship between flow volume and seismic energy for flows of similar composition (Figure 8h). These findings suggest that, within certain limits of flow composition, it may be possible to extract large-particle distribution, water fraction, flow depth, and flow volume from seismic or normal-force measurements, as long as one can constrain n – 1 of these variables. These findings mostly agree with findings from previous theoretical models, physical scale experiments, and field measurements, as detailed later.

An increase in gravel fraction caused both an overall increase in grain size as well as an increase in the coarse-particle accumulation near the flow front in our experiments. This increase in the accumulation of large particles near the flow front explains why the peak maximum ground velocity and normal-force fluctuations occur near the flow front rather than at the flow peak (Figure 9i–l). Accordingly, multiple authors have identified boulder-rich fronts as the dominant seismic source of debris flows and lahars (e.g., Arattano & Moia, 1999; Vázquez et al., 2016; Coviello et al., 2018, 2019; Lai et al., 2018; Farin et al., 2019). In addition, Michel et al. (2019) show that times at which large debris was transported within debris flows from Van Tassel, California, USA, and Chalk Cliffs, Colorado, USA, stand out in time-series signals and spectrograms of ground vibration, especially when occurring during periods of relatively low sediment concentration. Similarly, Berger et al. (2011) found that fluctuating forces are higher at coarser, erosive flow fronts than finer-grained wetter tails in debris flows in the Ilgraben torrent in the Swiss Alps.

The experimental flows generally follow a similar non-linear increase in seismic vibrations and normal-force fluctuations with increasing flow depth, for those flows with approximately similar large-particle concentrations (Figure 10). These findings suggest that it may be possible to extract flow depth from seismic or normal-force fluctuation measurements, as long as the large-particle distribution does not vary substantially within a flow or between flows. These findings agree with multiple previous case studies which have shown that within narrow grain size limits and under similar flow conditions, the amplitude of the seismic signal relates closely to flow depth (e.g., Allstadt et al., 2020; Doyle et al., 2010; Lavigne et al., 2000; Marchi et al., 2002). In addition, McCoy et al. (2013) and Hsu et al. (2014) found a positive correlation between mean normal stress – which is proportional to flow depth in steady uniform flows – and fluctuating stress in force plate measurements in small debris flows.

Allstadt et al. (2020) explain the positive relation between flow depth and seismic vibrations and normal-force fluctuations by arguing that faster particle fluctuations and larger average particle diameters would result in higher fluctuating forces. Because larger, faster flows, have a higher capacity to transport large particles, we can assume that large particle fluctuations are also more likely to occur in larger flows as long as the source material contains sufficiently large particles. This could also explain the relation between flow depth and seismic vibrations and normal-force fluctuations in the experimental debris flows.
presented here, as we observed that the flows with many large particles concentrated near the flow front had the largest flow depths as well (compare Figure 5e with Figure 5f,g).

Kaitna et al. (2014) and Vallance and Savage (2000) have shown that a viscous, clay-rich, matrix slows particle velocities relative to flow velocity in debris flows. This would suggest that an increase in clay content would reduce seismic vibrations and normal-force fluctuations. However, this has not been observed in our set of experiments. Michel et al. (2019) qualitatively show that flow periods with higher sediment concentrations have greater seismic vibrations than flows with lower sediment concentrations. Similarly, we find a decrease in seismic vibrations with decreasing sediment concentration (Figure 8c,g). However, our results further show that this may, at least in part, be attributed to a decreasing flow depth with decreasing sediment concentration in our flows (Figure 5g).

The strong relation between flow volume and seismic energy, defined as the integral of the squared seismic amplitude (Figure 8h), suggests that seismic energy can be used to provide an estimate of event volume where event volume cannot be estimated otherwise. The strong relation we find with seismic energy, may be explained by the fact that this is the only metric in this work taking into consideration flow duration. A strong relation between seismic energy and flow volume was recently also found by Schimmel et al. (2021) for debris flows originating from the Lattenbach, Gradía, and Cancía catchments in the European Alps. These authors, however, suggest a linear relation between flow volume and seismic energy, while we find a non-linear relationship. Given the restricted number of data points presented in Schimmel et al. (2021) and their distribution, such a non-linear fit may also be appropriate for their field data.

4.2 Translating in-channel to outside channel measurements

There are different seismic path effects between experimental environments and natural debris-flow torrents. Our setup with a geophone plate and force plate in the channel facilitates measurements directly beneath the debris flows. However, in natural debris-flow torrents seismic sensors are often installed outside the channel, such that there is a larger source-to-station distance and thus larger seismic path effects. Although the general trends presented here will likely also apply to such measurements outside of the channel, it is important to realize that both the amplitude and peak frequency of the basal fluctuating force spectrum decrease with increasing source-to-station distance (e.g., Farin et al., 2019; Lai et al., 2018; Zhang et al., 2021).

Seismic path effects are also likely the prime explanation for the high dominant frequency domain in our experiments of 200 to 300 Hz compared to frequency bands measured for natural systems. For a range of debris flows and lahars Lähninen (1998) described the typical peak frequency range to fall between 30 and 80 Hz and Huang et al. (2007) at 10 to 100 Hz. For the Rebaixadener torrent in Spain, Aratiano et al. (2014) report a frequency range of 10 to 60 Hz. Michel et al. (2019) showed that debris flows in the bare bedrock channel at Chalk Cliffs, Colorado, USA, produced a seismic signal with a broad frequency range of 5 to 400 Hz, while in the sediment-covered channel at Van Tassel, California, USA, much lower frequencies of 5 to 100 Hz were observed. This difference in frequency is related to the dampening effect of a sediment cover (Michel et al., 2019). Possibly, the absence of a dampening layer of sediment and the stainless steel construction of our flume may therefore also partly explain the relatively high frequency range observed in our experimental debris flows.

4.3 Testing the Farin et al. model for a range of effective particle sizes

Farin et al. (2019) propose a physical model for the high-frequency (> 1 Hz) seismic power spectrum generated by debris flows (their equation 24), building on the work of Tsai et al. (2012), Kean et al. (2015), and Lai et al. (2018). In their formulation the integrated ground velocity spectrum (\textit{iGVS}) (in m s^{-1}) is proportional to the square root of the integrated power spectral density, and can be expressed as:

\begin{equation}
\text{iGVS} \propto u^{1.5} D_e^{1.5} W^{0.5} (1 + e_b) u^{0.5} g(r_0)^{0.5}
\end{equation}

where \( u \) is flow velocity (in m s^{-1}), \( D_e \) is effective particle size (in meters), \( W \) is channel width (in meters), \( e_b \) = basal coefficient of restitution, being 0 for a fully inelastic impact and 1 for a fully elastic impact, \( \phi \) is the solid fraction, and \( g(r_0) \) is a distance dependence caused by wave propagation, depending on the source to station distance \( r_0 \) and the elastic characteristics of the ground (in m^{-5} s^{-1}).

To evaluate the performance of this model, we compare the ground velocity predicted by Equation 1 with the experimental runs wherein we systematically varied gravel fraction. In this exercise it is important to note that it remains unsure to what extent the model assumptions in Farin et al. (2019) apply to small scale experimental debris flows.

The parameters \( u, D_e, W, \) and \( \phi \), follow from our measurements, and we use the range \( e_b = 0.1 - 0.5 \) (realistic range for debris flows, cf. Iverson, 1997). Because we use a geophone plate directly underneath the flow, wave path effects are limited and we assume a range in potential path lengths of 0.01 to 0.06 m based on the along-channel dimensions of the geophone plate, corresponding to \( g(r_0) = 20.6 \text{ m}^{-5} \text{ s}^{-1} \) and \( g(r_0) = 0.083 \text{ m}^{-5} \text{ s}^{-1} \), following the calculations and assumption in Farin et al. (2019). Note that we did not use the closest possible distance, corresponding to flow directly riding over the sensor, because of the challenges associated to working with such near field conditions. The effective diameter depends on the grain-size distribution, and is estimated by Farin et al. (2019) to correspond to \( D_{90} \). The \( D_{23} \) dependence would, however, be different if the standard deviation of the grain size distribution were different although it would always exceed \( D_{90} \).

In Figure 12, we test the performance of the model by Farin et al. (2019) for a range of potential effective particle diameters. The two parameters in our experiments that are not fixed between experiments are particle size and flow velocity, and overall, the measured ground velocity roughly scales with \( u^{1.5} D_e^{1.5} \) as predicted by Farin et al. (2019). The model most accurately predicts the ground velocity for an effective particle diameter of \( D_{90} \) while the range \( D_{23} - D_{90} \) also yields reasonable results. These observations agree well with previous theoretical estimates from the literature, suggesting that the effective particle size for the wide grain-size distributions of debris flows.
exceeds the median particle size, and is somewhere around the 73rd–90th percentile of the grain-size distribution (e.g., Farin et al., 2019; Lai et al., 2018; Schneider et al., 2011; Yohannes et al., 2012). In general, the predicted integrated ground velocity spectrum is relatively low compared to our measurements for the fine grained, gravel-poor, debris flows in our dataset, while the predicted integrated ground velocity is relatively large for the coarser-grained debris flows in our dataset. This may be attributed to the trimodal grain size distribution used in our experiments, with a gravel, sand, and clay peak (Figure 2).

4.4 | Correspondence of seismic vibrations and normal-force fluctuations

Our results show that seismic vibrations and normal-force fluctuations induced by debris flows are strongly correlated (Figure 7), confirming the theoretical work of Farin et al. (2019). As such, both sensors could be employed to quantify particle-bed interactions in debris flows. There are many active debris-flow torrents in which seismic sensors are installed [see Hürlimann et al. (2019) for an overview], in the form of geophones (e.g., Hürlimann et al., 2014; Marchi & Tecca, 2013; McArvell et al., 2007), seismometers (Lai et al., 2018; Walter et al., 2017) and infrasound sensors (e.g., Kogelnig et al., 2014; Schimmel et al., 2018) – all of which may be used for early warning (e.g., Arattano, 1999; Chmiel et al., 2021; Walter et al., 2017) or for measuring mean frontal flow velocity (e.g., Arattano & Marchi, 2005; McArvell et al., 2007). In addition, some debris-flow monitoring stations are equipped with a force plate, thus measuring normal-force fluctuations (e.g., McArvell et al., 2007; McCoy et al., 2011, 2013; Nagl et al., 2020; Osaka et al., 2014). Our experimental results shed light on how changes in large-particle, clay, and water fractions affect the seismic and force-fluctuation signatures of debris flows, and provide important guidelines for their interpretation in such instrumented torrents.

The key difference between geophone and force plate is that the former is only sensitive to high frequencies (larger than a few to a few tens of Hertz) while the force plate is broadband. After extracting the high frequency fluctuations from the force plate (cf. Figure 3) both devices are able to quantify particle-bed interactions. Our results show that by placing a geophone directly in the torrent bed or connecting it to a ground plate (e.g., Wyss et al., 2016), thereby minimizing seismic path effects, seismic measurements agree with force plate fluctuations in the high-frequency domain. A key implication of this is that for measuring particle-impact signals through force fluctuations one could install the cheaper Swiss geophone plate or a similar device (e.g., Rickenmann et al., 2012, 2014) instead of a more expensive force plate.

5 | CONCLUSIONS

We experimentally explored the relation of debris-flow composition and volume with seismic vibrations and normal-force fluctuations. We did this by releasing small-scale debris flows with volumes of 0.02 to 0.05 m$^3$ (36–108 kg), fluid volume fractions of 0.25 to 0.57, and varying clay, sand, and gravel fractions, through a 5.5 m long and 0.3 m wide flume channel equipped with a geophone plate and force plate to measure seismic vibrations and normal-force fluctuations, respectively.
We find that seismic vibrations and normal-force fluctuations induced by debris flows are strongly correlated, showing that their high-frequency signals both capture the same source processes, in this case ground impacts of saltating and sliding particles. We show that debris-flow composition strongly controls vertical and horizontal ground velocity and normal-force fluctuations, where in particular the large-particle contribution dominates the seismic vibrations and normal-force fluctuations. An increase in large particles leads to a strong increase in the magnitude of ground velocities and normal-force fluctuations; an increase in water fraction leads to a subtle decrease in the magnitude of ground velocities and normal-force fluctuations. An increase in flow volume leads to an increase in the magnitude of ground velocities and normal-force fluctuations. There is a strong non-linear relationship between flow volume and seismic energy, defined as the integral of the squared force fluctuations. There is a strong non-linear relationship between flow volume and seismic energy, defined as the integral of the squared force fluctuations. There is a strong non-linear relationship between flow volume and seismic energy, defined as the integral of the squared force fluctuations. An increase in clay fraction does not systematically affect ground velocities and normal-force fluctuations. An increase in large particles leads to a large-particle contribution dominates the seismic vibrations and ground velocity and normal-force fluctuations, where in particular the debris-flow composition strongly controls vertical and horizontal high-frequency signals both capture the same source processes, in this case ground impacts of saltating and sliding particles. We show that debris-flow composition strongly controls vertical and horizontal ground velocity and normal-force fluctuations, where in particular the large-particle contribution dominates the seismic vibrations and normal-force fluctuations.


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