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Stress anisotropy in natural debris flows during impacting a monitoring structure

Abstract The frictional resistance of rock and debris is supposed to induce stress anisotropy in the unsteady, non-uniform flow of gravitational mass flows, including debris flows. Though widely used in analytical models and numerical simulation tools, concurrent measurements of stresses in different directions are not yet available for natural flow events. The present study aims to investigate the relation of longitudinal and bed-normal stress exerted by two natural debris flows impacting a monitoring barrier in the Gadria creek, Italy. For that, a force plate in front of a barrier was used to continuously record forces normal to the channel bed, whereas load cells mounted on the vertical wall of the barrier recorded forces in flow direction. We observed an anisotropic stress state during most of the flow events, with stress ratios ranging between 0.1 and 3.5. Video recordings reveal complex deposition and remobilization patterns in front of the barrier during surges and highlight the unsteady nature of debris flows. These first-time in-situ measurements confirm the assumption of stress anisotropy in natural debris flows for gravitational mass flows, and provide data for model testing.

Keywords Debris flow · Stress anisotropy · Field monitoring · Gadria creek

Introduction

Debris flows are saturated sediment–water mixtures flowing along a channel at high speed that can endanger human life and infrastructure (e.g., Ballesterio-Canovas 2016; Schlögl et al. 2021). The flow behavior is highly unsteady and non-uniform, often characterized by a sequence of surges (Zanuttigh and Lamberti 2007; Arai et al. 2013). Generally, the front contains large boulders, followed by a more liquid body with fewer large particles (Pierson 1986), which is a consequence of dynamic particle segregation (Leonardi et al. 2015; Gray 2017). The combination of high impact forces due to the bouldery front and the high mobility of the more fluid body pushing ahead highlights the particular devastating characteristic of these hazards in mountainous areas.

For the mitigation of debris-flow hazards, predictions of analytical and numerical flow models are needed to assess relevant quantities like run-out length (Hung 1995; Takahashi 2014), super-elevation (Scheidt et al. 2015), run-up heights (Iverson et al. 2016; Faug 2015; Mancarella and Hung 2010), and impact forces (Faug 2021; Jiang and Towhata 2013; Li et al. 2020; Vagnon and Segalini 2016; Tan et al. 2019). A common feature of the above models derived to predict these parameters is that, due to the high solids content, a non-isotropic stress state should be considered, resulting from the frictional properties of the granular matter involved (Hung 2008).

In numerical models simulating the dynamics of mass flows, this stress anisotropy is usually defined as the ratio of longitudinal to normal stress and represented by a pressure coefficient k , inspired by principles from soil mechanics. For soil, Rankine (1856) derived a theory that differentiates between an active state (expansion) and a passive state (compaction) at the condition of plastic equilibrium. For the simple geometry of a horizontal surface slope behind a vertical wall, the earth-pressure coefficients for the active state k_{act} and for the passive state k_{pass} are calculated with

$$k_{pass/act} = \frac{1 \pm \sin \varphi_{int}}{1 \mp \sin \varphi_{int}} \quad (1)$$

where φ_{int} is the internal friction angle of the material (Craig 1995). For granular avalanches, Savage and Hutter (1989) derived an earth-pressure coefficient equation that also considers the bed friction angle φ_{bed} :

$$k_{pass/act} = 2 \frac{(1 \pm (1 - (1 + \tan^2 \varphi_{bed}) \cos^2 \varphi_{int})^{\frac{1}{2}})}{\cos^2 \varphi_{int}} - 1 \quad (2)$$

In case $\varphi_{bed} > \varphi_{int}$, the equation reduces to Rankine's model and isotropic stress conditions results if both φ_{bed} and φ_{int} are zero, as it is the case in fluids (Iverson and Denlinger 2001). For flowing material, basal friction may induce the principle stresses to slightly rotate (i.e., a deviation of bed-normal and parallel direction). A modified version was therefore proposed by Hung (2008) to consider the influence of the basal friction for the case the depth gradient is not small. Since gravitational mass flows are highly unsteady and may undergo several transitions between active and passive stress states during flow, the magnitude of the pressure coefficient is expected to be important for modeling (Pirulli et al. 2007; Pudasaini and Kröner 2008). Assuming plausible values of the friction angles of natural material, the coefficient k roughly varies between 0.2 and 1 for the active state and between 1 and 5 for the passive state, which is the range typically applied in depth-averaged continuum models for debris flows (Hung 1995; Pirulli et al. 2007; Pudasaini and Kröner 2008). For granular flows impacting an obstacle (passive state) Luo and Zhang (2020) back-calculated values between 0.5 and 2, whereas Chung et al. (2019) report values up to 5. Sarno et al. (2013) applied k values between 0.3 and 1.5 for simulating a dam break scenario. The importance of non-isotropic stress conditions is also supported by a study on shock waves in granular flows by Pudasaini and Kröner (2008). On the other side, a constant value $k=1$ was applied for run-up simulations of saturated debris in large-scale experiments (Iverson et al. 2016). Satisfying results were also obtained by back-calculating natural debris-flow events

with a depth-averaged simulation tool assuming isotropic stress conditions (Bartelt et al. 2017; Schraml et al. 2015).

An estimate of the ratio of the normal and longitudinal stress is also used in impact models for the engineering design of mitigation measures against debris flows. The “hydrostatic” approach calculates the impact pressure p_h as

$$p_h = k \times \rho \times g \times h \quad (3)$$

where ρ is the mean bulk density, g is the gravity, and h is the flow height. The coefficient k is either empirically defined or derived from geotechnical considerations (Eqs. 1 and 2). The span of the empirical values for k ranges from 2.5 to 7.5 (Scotton and Deganutti 1997), 7 to 11 (Lichtenhahn 1972), and 9 (Armanini 1997). There are few combined experimental and numerical studies investigating the magnitude and variation of k , directly.

To our knowledge, no combined field measurements of basal normal stress and longitudinal pressure are currently available to quantify the stress ratio that is used in dynamic modeling of the flow and impact behavior of debris flows. Here, we present in situ measurements of longitudinal and normal stress just in front of an obstacle, which are indicative of the variation of stress anisotropy that occurs in natural debris flows. We are interested in the following questions:

- How do the longitudinal and bed-normal stresses as well as their ratio vary during the passage of a natural debris-flow event?
- Is there a relation between stress ratio and bulk flow parameters?
- What is the stress ratio in between surges (at rest)?

In “Methods,” we give an overview of the field site and explain the experimental setup as well as data analysis in detail. Results are presented in “Results and analysis” and discussed in “Conclusion.”

Methods

Field site

The infrastructure is located in the Gadria watershed, Italy. The catchment drains an area of 6.3 km², with an altitude difference from 2,950 m a.s.l. to 1394 m a.s.l. at the fan apex. The Gadria creek and its tributary Strimm creek built up the large alluvial fan of 10.6 km². Steep topography, metamorphic and highly fragmented rock, as well as glacial deposits in the upper catchment, provide the

basis of a high frequency of debris flows in the Gadria creek. Details on the catchment and historic debris-flow events can be found in (Cavalli et al. 2013; Comiti et al. 2014; Nagl et al. 2020). The channel reach observed in this study is located upstream of the fan apex and has an artificial, trapezoidal cross-section with a fixed channel bed inclined at 6° and a rock-riprap channel bank.

Measurement setup

In 2016, a monitoring structure was installed in the centerline of the channel of Gadria creek, close to the fan apex and upstream of a large retention basin. The pylon consists of a concrete element of 3-m height and 1-m width, which is connected to a foundation plate below the channel bed (Fig. 1). In front of the barrier, a disconnected transverse check dam builds up the second element of the system. Here, two 1 × 1 m force plates are installed to measure the forces perpendicular to the channel bed (i.e., normal force). One force plate is installed just in front of the barrier and a second one at a distance of 2 m from the barrier. Each force plate is supported by four load pins (Batarow. MB927-100-S1-A) of nominal load of 100 kN, each; see Fig. 2. The sampling frequency was set to 2.4 kHz. Both force plates are equipped with a fluid pressure sensor (Keller Inc., model PR 25Y, range ± 1.5 bar) to obtain the basal pore-fluid pressure. The configuration is the same as described in Kaitna et al. (2014, 2016) and Nagl et al. (2020). Additionally, an ultra-sonic sensor (Pepperl + Fuchs, type UB4000) above the force plate beside the barrier (channel flow height) and the second sensor (SICK, type UM30) in front of the barrier (barrier flow height) are used to determine the flow height (Fig. 1). Sampling frequency was set to 100 Hz. The combined measurements of flow height and normal force were used to calculate a time and depth-averaged bulk density. At the barrier itself, an array of 14 load cells with a nominal maximum load of 1 and 2 MN (HBM, C6A 1-2MN) were installed at the vertical, upstream front. The diameter of the protection plate above each load cell is 0.2 m. The center of the lowermost load cell is located at 0.25 m above the channel bed; the distance between each load cell is 0.2 m. The arrangement allows determining impact forces over height at more detail. To protect the sensors against intruding mud by debris flows, a thin steel plate with a thickness of 2 mm was mounted above the sensor array (not visible in Fig. 1). The steel plate is directly connected to the sensors and the concrete barrier to ensure no damping effects. The sampling frequency of each load cell is set to 4.8 kHz. The flow velocity upstream of the barrier was estimated manually by particle tracking of video

Fig. 1 a Sketch of the monitoring barrier and installations relevant for this study, and b photo of monitoring barrier from August 2017

Fig. 2 **a** Schematic illustration of the force plates used to determine the basal normal force with an implemented pore fluid transducer. **b** Four load pins are used inside with a load capacity of 40 kN

recordings of the event of 2018 by a (Mobotix M15, variable frame rate) and at the event 2019 with a (Dahua, IPC-HFW5231E-Z12E, 25 frames per second) and arranged perpendicular to the channel (S1 and S2 in the supplement material).

Filtering and data analysis

The data sets of the longitudinal and normal force were processed as follows:

- To eliminate random noise, we denoised the data with a wavelet filter (db4 level 8) (e.g. Hu et al. 2011; Cui et al. 2015). Subsequently, we used a band-stop filter to exclude the resonance frequency of the basal force plates, which was determined to be in the range of 130–161 Hz. For the load cells attached to the front of the barrier, we found no measureable resonance frequency.
- The impact force of debris flows can be separated into two different types of impacts, referring to the duration of exposure. Impacts by individual boulders exhibit a high contact force in short time, whereas the bulk pressure of the mixture shows a more steady force acting over a longer time period onto the obstacle (Zhang 1993). Since we are only interested in the bulk impact pressure, we excluded force peaks by single boulders by computing a binned median over 1 s (e.g. Schneider et al. 2011). An example of the results of this data processing routine is shown in Fig. 3.
- The binned impact force of the load cells of the first meter above ground (see sketch in Figs. 3 and 4) was converted to pressure by dividing each time series through the respective plate area of 0.0314 m². The ratio of longitudinal pressure σ_3 and normal pressure σ_1 was calculated for each sensor height individually. For this, σ_1 was reduced to account for the height above the force plate of respective load cell assuming a linear normal pressure distribution in vertical direction. Finally, we averaged the derived stress ratio of each level that was exposed to the debris flow to obtain a single value.

Results and analysis

The two debris flows we present here occurred in the years 2018 and 2019. Despite significant variations of visual appearance, both flows were triggered by intensive rainstorm events and displayed several individual surges. Stage hydrographs recorded directly in front of the barrier (sensor 2) and next to the barrier (sensor 1) illustrate

not only the interesting flow dynamics of individual events but also reflect the interaction of the barrier with the flow and the complex erosion–deposition pattern during the events (Fig. 5(a–d)). For the readers’ convenience, we refer to video footage provided in Supplementary Material S1 (event 2018) and S2 (event 2019).

Bulk flow behavior

For the debris flow on 21st July 2018, a precursory debris flood was observed at 03:21:50 UTC, followed by a period of limited discharge (Fig. 5(a)). At this stage, the diameters of sporadically transported boulders were larger than the observed flow depth (see video in the Supplementary Material S1). At $t = 390$ s after starting the measurements (corresponding to 03:20:37 UTC), a distinct front of a still relatively fluid mixture ensued, which then gradually evolved into a mixture of high sediment concentration, which we interpreted as a fully developed debris flow (Fig. 5(c)). The debris flow exhibited eight surges with a maximum flow height of 2.3 m and velocities up to 5.6 m/s. The first part of the debris flows was close to Froude number 1 and often contained coarse material building up a wedge of deposition at the base of the barrier. This “dead zone” was regularly eroded during subsequent surges and rebuilt by material of

Fig. 3 Example of impact forces at the lowermost load cell (marked in red color in the inset sketch) of the 2018 debris flow. Black lines are binned data over 1 s, and the red lines show the original signal time series with a sampling rate of 4.8 kHz

Fig. 4 Concept of earth-pressure coefficient measurements during impact with the monitoring barrier

the incoming flow. We observed standing waves at the barrier when the mixture had a more liquid appearance and Froude numbers were higher than 1. Between the surges, velocities and flow height decreased and a small amount of deposited material was visible on the force plates. The bulk density calculated from the normal force and flow height measurements measured at plate 1 (beside the barrier) ranged from 2200 kg/m³ at the very front to 1800 kg/m³ at the tail of the flow.

The event on 26th July 2019 triggered the measurements at 12:11:46 UTC. Again, a precursory flow conveyed coarse sediment through the monitored channel reach and deposited sediment at the barrier (Fig. 5(b) and Supplementary Material S2). At $t \sim 800$ s after the start of data recording, the front of a debris flow hits the barrier with a front velocity of about 2.5 m/s. The peak flow height was around 2.6 m. In contrast to 2018, the well-defined granular

front contained a large number of boulders with diameters about the same dimension as the flow height. Subsequently, sixteen surges could be identified with velocities up to 3.5 m/s (Fig. 5(d)). These surges had a muddier appearance without large boulders. The flow velocity in between surges strongly decreased and eventually came to a halt. The deposited material with heights larger than 1 m was subsequently re-mobilized and pushed forward by the following surges, similar to erosion–deposition waves described in granular literature (Edwards and Gray 2015). During the final stages of the event, the mixture became more and more dilute and eventually eroded the sediment deposited on force plate. The bulk density ranged from 2300 kg/m³ at the very front to 2000 kg/m³ during the event. It is important to note that, after the transit of the first peak, the flow mostly concentrated on the left side of the channel cross-section, between the barrier and the embankment. At the right

Fig. 5 Stage hydrographs of the two debris flows in 2018 (a, c) and 2019 (b, d) at the Gadria creek. The black and gray lines display flow height measurements in front of the barrier and next to the barrier (above force plate 1 and 2, respectively)

Fig. 6 Time series of derived bed-normal stress (orange line), longitudinal stress (blue line), and corresponding earth-pressure coefficient (black line) of the debris flow 2018

side of the channel, cross-section coarse material of the front was deposited and eventually was re-mobilized by subsequent surges.

Stress measurements

Our results show a significant variation of the stress ratio during both debris-flow events. The wide grain size distribution of the flows hinders our ability to determine a representative internal friction angle. When using a plausible range of 25 to 45° for the internal friction angle (e.g., Major 1997; Iverson 1997), Eq. 1 yields k -values from 0.17 to 5.8. Based on combined measurements of basal shear and normal stress, McArdell et al. (2007) derived a basal friction angle of 20° for natural debris flows at the Illgraben creek. When applying this value to our site, Eq. 2 yields k -values from 0.36 to 5.6.

For the debris flow in 2018, the first surge impact occurred at 430 s, where both flow height measurements increased, with a second peak shortly after. At this point, the magnitude of the ratio of the longitudinal and normal stress reached values up to 2 (Fig. 6). Subsequent impacts at 483 s and at 495 s showed values between 2 and 3. At $t \sim 500$ s, we register the highest value of k , which coincides with a boulder impacting and temporary depositing next to

the barrier, which was not excluded by our 1-s filter algorithm. For most of the remaining flow duration, the pressure coefficient varied around or below unity. The following surge of 1-m flow height had a velocity of 3.5 m/s and interestingly reached a stress ratio close to unity. The following surges had flow heights below 1 m with minimum values of 0.5 m between surges. Here, the stress ratio values mostly varied between 0.5 and 1.5 and decreased in some parts to 0.1 when flow heights were low. The normal pressure (orange line in Fig. 6) remained relatively high compared to the longitudinal pressure due to material depositing between surges.

For the debris flow in 2019, the highest value of the stress ratio coefficient of 3.5 corresponds with the main peak of the longitudinal pressure, measured a short time after the first impact when material was building up in front of the barrier (Fig. 7). During the subsequent flow, the stress ratio mostly varied between 1 and 2. During this stage, measurements may be affected by the already mentioned shift of the main flow to the left side of the channel cross-section. The short peak at $t \sim 990$ s could be attributed to a boulder that hit the barrier and re-mobilized after some seconds.

To visualize whether different sections of the surge hydrographs are connected to variations of the pressure coefficient, we marked

Fig. 7 Time series of derived bed-normal stress (orange line), longitudinal stress (blue line), and corresponding earth-pressure coefficient (black line) of the debris flow 2019

the ascending sections (i.e., surges impacting the barrier) and the descending sections of the stage hydrographs with blue respectively orange colors in Figs. 8 and 9. The expectation is that, during the main impact (ascending section), the mass will compress, which corresponds to a passive state with k -values > 1 . When flow height decreases, the compressive stress state relaxes and k -values should decrease.

For the debris-flow event in 2018, we find that the pressure ratio mostly increases with flow height and decreases in line with flow height (Fig. 8). This observation is repeated for subsequent surges, however, less pronounced. There might be partly a transition from an active to a passive stress state in between surges. We assume that this is connected to the deposition of sediment in front of the barrier on the force plate, creating a stationary wedge of material and diverting the flow around the barrier, which leads to an increase of internal strength as the sediment deposits and to dampening the measurement of longitudinal stress. The arrival of a subsequent surge eventually re-mobilizes the material again.

For the debris-flow event of 2019, we find a similar pattern as for the 2018 event. There is an increase of stress ratio when the flow impacts the barrier and mostly a decrease when flow height decreases (Fig. 9). During most of the flow the stress ratio plots above $k = 1$. We conjecture that this may be connected to the observation that the flow is concentrated at the left side of the channel cross-section and the deposited material, which was built-up on the right side, pushes against the barrier (Supplementary Material S2). Even when the flow stops between surges, the pressure onto the barrier remains high. During the second half of the event, the pressure ratio varies slightly above unity, even though several waves hit

the structure. Similar to the debris flow in 2018, the variation of the pressure ratio is reduced towards the end of the event. This may be explained by a more fluid consistency, with a high amount of fine material. For this reason, we analyze the relation of the pressures, and the ratio with flow parameters like the Froude number, liquefaction ratio (ratio of pore-fluid pressure to total normal pressure), surface velocity, and the flow heights.

Stress measurements and flow characteristics

In Fig. 10, we plot the longitudinal stress, normal stress, and the stress ratio k in dependence of the flow velocity, flow height (in front of barrier and in the channel), the liquefaction ratio, and the Froude number. For the velocity, we use the surface velocity estimated by particle tracking from video analysis. We expect a positive correlation of the stress ratio with flow velocity. The velocity of the event in 2018 ranged between 0.8 and 5.5 m/s, while the 2019 debris flow showed surface velocities between 0 and 3.5 m/s. For both events, the surface velocity exhibits a linear relationship with the longitudinal stress, normal stress, and the stress ratio. The most robust relationship is observed for the normal stress (event 2018: $R^2 = 0.31$; event 2019: $R^2 = 0.53$) (Fig. 10(a)), whereas the longitudinal stress displayed higher variations (Fig. 10(f)). For the event in 2019, the first part of the flow contained a high number of boulders (see video in the Supplementary Material S2), which results in a strong variation of stress measurements in longitudinal direction (Fig. 7, 800–825 s). If we exclude the first 25 s of the bouldery front, the r^2 value would reach 0.51. Due to the positive correlations of stress measurements with flow velocity, the stress ratio displays a

Fig. 8 Time history of the stress ratio (k -value) of event 2018 and the flow heights in front of the barrier (gray line) and beside the barrier (black line). Thick blue line indicates the ascending part of each surge, and the thick orange line is the descending part of the surge

Fig. 9 Time history of the stress ratio (k -value) of event 2019 and the flow heights in front of the barrier (grey line) and beside the barrier (black line). Thick blue line indicates the ascending part of each surge and the thick orange line the descending part of the surge

Fig. 10 Relation of normal stress, longitudinal stress, and stress ratio (k -value) against flow characteristics of the event 2018 and 2019 as surface velocity (a, f, k), and flow height in the channel (sensor 1) (b,

g, l), flow height in front of barrier (sensor 2) (c, h, m), liquefaction ratio (d, i, n) and Froude number (e, j, o)

weaker correlation with velocity and is also less robust (event 2018: $R^2 = 0.048$; event 2019: $R^2 = 0.072$). For the event in 2019, their material came to a halt in between surges, a situation which approaches a passive stress state. The respective stress ratio varied between 0.6 and 1.5, with a mean value of 1.2 (Fig. 10(k)).

To test the relation between stress measurements and flow heights, we use the flow height recordings directly in front of the barrier and the one next to the barrier (in the channel), which we consider less affected by the structure (Fig. 1). The flow height in the channel shows a linear relationship with the normal pressure with only minor variations (event 2018: $R^2 = 0.73$; event 2019: $R^2 = 0.90$) (Fig. 10(b)). This is indicative of a relative constant density during both events. Likewise, the relation of flow height in the channel and longitudinal pressure measured at the barrier shows a robust relation (event 2018: $R^2 = 0.6$; event 2019: $R^2 = 0.52$) with higher variations due to the bouldery front in 2019 during the first seconds of the flow (Fig. 10(g)). However, we can find only a weak relation of the stress ratio for event 2018 with R^2 of 0.24 and none for the 2019 event ($R^2 = 0.0009$) (Fig. 10(l)). When excluding the bouldery front, we derive only a slightly better linear correlation with $R^2 = 0.05$.

The flow height in front of the barrier showed a robust relation with normal stress for both events (event 2018: $R^2 = 0.54$; event 2019: $R^2 = 0.93$). Interestingly, the inclination of the linear fit diverges, with the 2019 event having the same inclination as for the undisturbed measurements within the channel, while the 2018 event shows a less steep correlation, indicating a lower bulk density (Fig. 10(c)). We attribute this to the observation that the 2018 was faster and more liquid, which resulted in a standing wave with occasional splashes in front of the barrier structure, leading to an overestimation of flow height (see video in the Supplementary Material S1). Again, a higher variation and a less robust correlation with flow height can be observed for the stress at the barrier in flow direction, and no correlation of the stress ratio and flow height (event 2018: $R^2 = 0.065$; event 2019: $R^2 = 0.758E-5$; Fig. 10(m)).

The liquefaction ratio was estimated as the ratio of pore-fluid pressure and normal stress measured at the force plate in front of the barrier. We find the liquefaction ratio mostly ranging between 0.5 and 0.8 for both events, with the 2019 event having slightly higher values than the 2018 event (Fig. 10(d)). Assuming full saturation of the debris and an average bulk density of 2200 kg/m^3 , the liquefaction ratio for hydrostatic pore-fluid pressure would be 0.45. Hence, for both flows, we measure fluid pressure in excess of hydrostatic. The fact that the liquefaction ratio stays well below unity indicates that some frictional resistance of the grains always contributes to the total flow resistances. Comparing stress measurements with the liquefaction ratio, we find a weak positive correlation for the normal stress and a somehow stronger positive relationship for the longitudinal stress and the stress ratio (Fig. 10(d, i, n)). However, correlation coefficients are rather low.

The Froude number is defined as the ratio between flow inertia and gravity and was calculated with $Fr = v / \sqrt{gh}$. Since we have no continuous measurement of mean flow velocity v , we again used the surface velocity derived from particle tracking. To avoid the disturbance of the flow caused by the barrier, we used flow height measured in the channel next to the barrier. We see no robust linear relation of our stress measurements and the Froude number. Instead, the data shows the highest stress measurements in the lower Froude

number range ($Fr < 1$), which is mainly attributed to the event in 2019, and lower stresses for high Froude numbers (Fig. 10(e, j)). This pattern is somehow akin for the stress ratio, however, less pronounced (Fig. 10(o)). These first results support studies focusing on the impact force of debris flows on engineering mitigation measures that found significant differences between the impact process at low Froude numbers (Armanini et al. 2020; Song et al. 2021), where the inertial part of the flow is less important, and the impact at high Froude numbers, which is mainly controlled by inertia of the flowing mass (Hübl et al. 2009; Ashwood and Hungr 2016).

Conclusion

We present in situ measurements of longitudinal (in flow direction) and bed-normal stress and their evolution over time for two natural debris flows impacting an engineering barrier structure. Together with additional measurements of flow characteristics like flow height, surface velocity, and basal fluid pressure, we analyze the variation of stress measurements. We conclude with the following statements:

- Our monitoring efforts indicate a significant stress anisotropy in natural debris flows. The values of the stress ratio of longitudinal and normal stress mostly vary from 0.1 to 3.5, supporting the range proposed by Hungr (2008). Our results do not support the assumption of a constant pressure ratio ($k = 1$). High stresses and stress ratios are mainly observed in the low Froude number range.
- The pressure ratio mostly increased when surges impacted the barrier and decreased between surges. Synchronized video footage shows that the strongest variations of the stresses and stress ratios above 2 are associated with the presence of large boulders, reflecting the influence of intergranular friction (Savage and Hutter 1989; Hungr 2008) and related divergence of the flow (Faug 2015). For both events, the strongest variation of the stress ratio can be found during the first part of the flow, while during later stages, the pressure ratio showed minor variations slightly above or below unity.
- In between surges, during periods of zero flow velocity, the stress ratio drops to values between 0.6 and 1.5, with a mean value of 1.2.

Material deposition and re-mobilization cannot be controlled in these field measurements but are expected to play an important role during the dynamic interaction between the flow and the barrier and must be considered when interpreting the results. Nevertheless, our monitoring efforts provide unprecedented insights into the impact dynamics of natural debris flows without any scaling limitations.

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