How bed composition affects erosion by debris flows - an experimental assessment

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Key Points:

- Small changes in water and clay content of the bed significantly affect debris-flow erosion processes and magnitude.
- Bed-water content increases erosion when the bed is nearly saturated, whereas for clay content an optimum exists for erosion around 3-4%.
- Water and clay content of the bed affect debris-flow erosion by affecting bed pore pressure when the debris flow overrides the bed.

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Abstract

A solid physical understanding of debris-flow erosion is needed for both hazard prediction and understanding landscape evolution. However, the processes and forces involved in erosion by debris flows and especially how the erodible surface itself influences erosion are poorly understood. Here, we experimentally investigate the effects of bed composition on debris-flow erosion, by systematically varying the composition of an erodible bed in a small-scale debris-flow flume. The experiments show that water and clay content of an unconsolidated bed significantly control erosion magnitude by affecting the transfer of pore pressure, loading conditions, and contraction-dilation behaviour of the bed. As the water content increases and the bed comes close to saturation, erosion increases rapidly, whereas for clay content an optimum for erosion exists around a clay content of 3-4 %. Our results show that small variations in bed composition can have large effects on debris-flow erosion, and thus volume growth and hazard potential.

Plain Language Summary

Debris flows are slurries of water, soil and rock that rush down mountainsides. In their path down-slope they erode material and ultimately may build up depositional fans in lower laying areas. These fans are often preferred sites for settlement. This means that new debris flows directly threaten human life and infrastructure. We know from other studies that the bigger the debris flow the larger the number of casualties. And we also know that debris flows rapidly increase in size when rushing down the mountain, by eroding and picking up loose sediment and rock. However, current computer models, used for hazard prediction, are bad at predicting erosion and therefore debris-flow size. We believe that an important factor for debris-flow erosion is overlooked in these models; the composition of the eroded material. Our experiments with small debris flows in the lab show that the amount of clay and water in the soil control how much erosion occurs. More water in the bed increases erosion, and for clay content, an optimum exists for maximum erosion. This eventually implies that the geology of the catchment and the soil moisture conditions should be assessed carefully when making predictions on debris-flow hazard.

1 Introduction

Debris flows are an active geomorphological agent that, on the short term, pose a threat to human life, property and infrastructure (e.g., Rickenmann, 1999, 2005; Beguería et al., 2009; Luna et al., 2012; Dowling & Santi, 2014; Zou et al., 2020). In the long term, debris flows play an important role in landscape evolution by eroding soil and rock, cutting valleys, and depositing sediments in large fan systems (Blair & McPherson, 1994; Stock & Dietrich, 2003, 2006; Cavalli & Marchi, 2008; De Haas et al., 2014; de Haas et al., 2018). Understanding debris-flow erosion is important to explain long-term landscape evolution, but it is also crucial for mitigating risks posed by debris flows. Debris-flow volume has directly been linked to the number of casualties (Dowling & Santi, 2014), and volume growth of the debris flow, due to erosion and sediment entrainment, can be several orders of magnitude larger than the initial flow volume (e.g., Takahashi, 1978; Hungr et al., 2005; Santi et al., 2008; Navratil et al., 2013; Frank et al., 2015; Simoni et al., 2020). In current hazard analyses, volume growth is often predicted based on the availability of loose sediment (e.g., Jakob, 2005; De Haas et al., 2020), on volumes of past debris flows (e.g., Èkes & Friele, 2003; Giraud, 2005; Conway et al., 2010; de Haas et al., 2022), catchment and watershed characteristics (e.g., Takahashi, 1981; Wilford et al., 2004; Wan & Lei, 2009; de Haas & Densmore, 2019; Welsh & Davies, 2011) or on linear regression between peak discharge and volume (e.g., Rickenmann, 1999). These criteria are based on the intrinsic and autogenic settings of the debris-flow systems. However, when boundary conditions change, for example by anthropogenic impacts or climate change, debris-flow hazard will change accordingly (Rebetez et al., 1997; Cannon & DeGraff, 2009; Lugon & Stoffel, 2010; Stoffel & Huggel, 2012; Stoffel et al., 2014) and hazard predictions based on intrinsic settings will not always suffice.

The importance of erosion in debris-flow volume growth has led to an increase in the number of numerical debris-flow models that incorporate erosion (Takahashi, 1978; Hungr et al., 2005; Iverson, 2012; Abancó & Hürlimann, 2014; Frank et al., 2015; Iverson & Ouyang, 2015; Han et al., 2016; Li et al., 2020; Baggio et al., 2021). However, the vast amount of approaches, from empirical to physics-based, and the varying incorporated physical mechanisms, highlight the lack of a unified debris-flow erosion theory (De Haas et al., 2020) and the need for a better physical understanding of the involved processes and parameters. Experiments in large- and small-scale flumes have highlighted the importance of certain parameters on erosion processes. For example, De Haas and Woerkom (2016) and Roelofs et al. (2022) showed that the water, gravel, and clay content of the debris flow itself affect erosion magnitude and patterns by changing the erosional shear and impact forces as well as the pore pressure in the debris flow that is transferred to the top layer of the bed. These studies showed that increasing gravel and water content linearly relates to an increase in erosion (De Haas & Woerkom, 2016; Roelofs et al., 2022), whereas clay content non-linearly interacts with erosion via interstitial fluid viscosity and increased pore pressures (Roelofs et al., 2022). In addition, experiments from large-scale flume studies by Iverson et al. (2011) and Reid et al. (2011) show that higher water content of the bed results in higher bed pore pressures and larger quantities of erosion. This finding is in line with observations from the field (McCoy et al., 2012; de Haas et al., 2022) and the long-standing theory on how increased pore pressures facilitate erosion by debris flows (Bagnold, 1954; Iverson, 1997; Hungr et al., 2005; McCoy et al., 2012; Li et al., 2020).

The large influence of water content of the bed on erosion can be explained by the difference between undrained and drained loading conditions. Drained loading occurs when air and fluid are able to drain through the pores without increasing pore pressure. In contrast, under undrained loading conditions, pore fluid in the soil is unable to drain out or into the pores, leading to increased or decreased pore pressure. In the most extreme case, the pore fluid bears the entire unit weight of the saturated debris (Major, 2000). Increased pore pressure decreases intergranular friction between the grains and can enable liquefaction of the sediment, which enhances the erodibility of the bed (Major, 2000; Hungr et al., 2005; Sassa & hui Wang, 2005; Iverson, 2012). The dissipation of excess pore pressure can be described by the hydraulic diffusivity D (Major, 2000; McCoy et al., 2012). Diffusivity is controlled by the water content of the bed but also by the characteristics of the soil, i.e. permeability and matrix compressibility (see Major (2000); McCoy et al. (2012) for mathematical description). These are, themselves defined by the grain-size distribution of the soil and the clay content. In addition, the content of fines in the bed also influences the dynamic viscosity of the interstitial fluid and the fluid compressibility as it penetrates into the bed.

Another physical soil characteristic that influences erosion susceptibility is shear strength θ, which is the ability of soils to resist movement along a slip surface. Shear strength is dependent on the composition of the soil, the level of compaction, and moisture content. Furthermore, it is important to consider how soils react to compaction and shearing, as this directly influences pore pressures in the bed. When soils dilate in response to shear, pore pressures decrease, and when soils contract in response to shearing, pore pressures increase (Iverson, 2012; McCoy et al., 2012; Iverson & Ouyang, 2015). Modelling work by Iverson (2012) shows that if finer sediment is present in a bed, overridden by a debris flow, slight shear displacement can play a dominant role in generating pore fluid pressures. When enough fine sediment is present this makes the soil behave effectively undrained (Iverson, 2012). However, to date, it remains unclear how these balancing forces and processes influence erosion by debris flows for different soil compositions. To advance our understanding of debris-flow erosion, we want to elucidate the effects of bed composition on debris-flow erosion processes. We aim to determine and quantify the effects of clay and water content of the bed on debris-flow erosion processes and magnitude. We also aim at gaining a better understanding of the interaction between different erosion mechanisms and influencing parameters, e.g. liquefaction, drained versus undrained loading, and diffusivity. To this end, we perform experiments in a small-scale debris-flow flume with an erodible bed to systematically test the influence of the bed's clay and water content on erosion processes and magnitude.

2 Materials and methods

2.1 Flume set-up, bed composition and data-analyses

To study and quantify the effects of bed composition on debris-flow erosion magnitude and processes, we combined a series of flume experiments with geotechnical tests to determine the diffusivity and porosity of the soils used in the flume. The flume consisted of a 5.4 m long and 0.3 m wide chute with a depression in the lower 2.5 m, a mixing tank with a forced-action mixer (Baron E120), and a custom-made release gate (See Figure 1) (set-up is similar to de Haas et al. (2021); Roelofs et al. (2022)). In the depression in the lower half of the chute, an erodible, unsaturated, and loosely packed bed was created, of which we systematically varied the composition. Erosion under the different bed compositions was tested at three different flume angles: 28°, 31°, 34°. For all experiments, the debris-flow composition was kept constant (see Supplementary Table A1). To ensure repeatability and account for natural variability, every experimental setting was performed twice. Within the debris flows, frictional forces dominated flow dynamics (see Supplementary Table A1), similar to most debris flows in nature (Zhou & Ng, 2010). For a small number of experiments, conducted under a flume angle of 28°, viscous forces dominated over collisional forces.

The loosely packed bed consisted of sand, clay (kaolin), and water in different ratios. To test the influence of the water content of the bed, we used a sandy bed without clay in which we systematically varied the total mass fraction of water from 0.09 to 0.15 (Supplementary material Table A1). To test the influence of clay content of the bed, we used a total mass fraction of water of 0.11 and varied the dry mass fraction of clay within the sandy bed from 0 to 0.1, while keeping the sand porosity roughly constant (Supplementary material Table A1). For every experiment, the bed was prepared by mixing the sediment and water with a hand-held mortar mixer, after which the mixture was placed in the recess in the lower half of the flume. For the grain-size distribution of the used sediments see Supplementary Material Figure A1.

Two pore pressure sensors were installed underneath the flume, 50 cm downslope of the start of the erodible bed. These sensors were connected to small plastic tubes, with permeable filters, that protruded into the bed at different heights (3 and 4 cm below the surface). The small tubes above the sensors were filled with de-aired water before every experiment and the recorded hydrostatic pressure was used as the reference pressure.

To quantify the net erosion, the bed was scanned using a Vialux z-Snapper 3D scanner. This scanner created a 3D point cloud of sub-mm accuracy of the bed by structured light and imaging before and after the debris flow had passed. The point clouds were denoised and transformed into gridded digital elevation models (DEMs) of 0.3 mm resolution by natural neighbour interpolation.

2.2 Diffusivity and porosity tests

The diffusivity of the bed compositions with varying amounts of clay was determined following the methodology of Major (2000). Tests were conducted for dry bulk

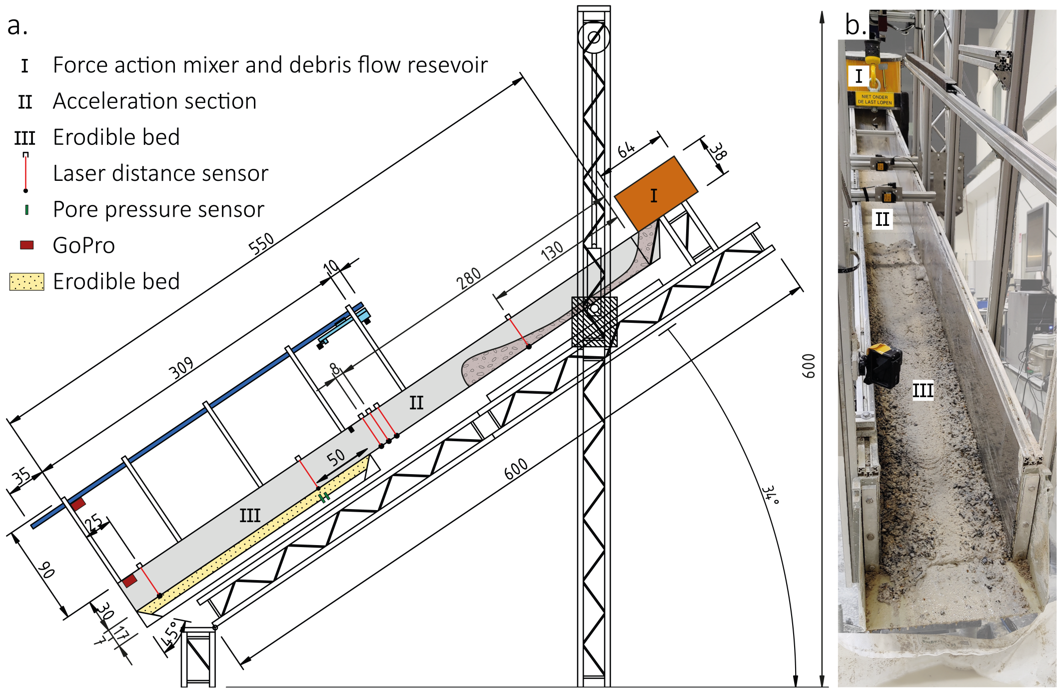

Figure 1. Schematic (a.) and photo (b.) of the flume. Sketch: orange rectangle represents the force action mixer and the dotted yellow trapezoid represents the erodible bed. All dimensions are in centimetres.

clay mass fractions ranging from 0 to 0.1, with a step size of 0.01. A smooth transparent tube with a radius of 6.25 cm was filled with a sand-clay-water mixture up to an approximate height of 55 cm. Fully suspended conditions at the beginning of every test were established by using rotating blades, connected to a drilling machine. Pore-fluid pressures were measured with piezoresistive transmitters (Keller Series) at 5, 15, 25 and 45 cm above the impermeable bottom of the tube at predetermined time intervals, ranging from one measurement per second to one measurement per five seconds depending on the clay content. At the end of each test, the final height H_w of the water column was measured and the pressure conditions were assumed to be hydrostatic. The diffusion coefficient D was determined by iterating between the measured and predicted excess fluid pressure (for details and equations we would like to refer to Major (2000)). The porosity of the beds with varying clay fractions was determined by inserting the different bed mixtures in soil sample rings, saturating the sediment in the rings with water, weighing the saturated samples, and comparing that to the dry weight of the sample.

The porosity of the initial beds in the flume is larger than the porosity of the dry unconsolidated material (random loose packing) and dry consolidated material (random close packing), which are, respectively, 0.34 and 0.27 for beds without clay. In the initial beds, the apparent cohesion caused by water in the unsaturated bed results in a larger porosity. Saturation of our bed mixtures occurs around a water volume fraction equal to the dry porosity, equal to a mass fraction of 14-20% for a bed without clay. In our experiments, a water mass fraction >15% led to saturation and denser packing of the sediment during mixing. The effect of this dense packing is increased intergranular contact and higher resistance against erosion, and caused different behaviour above the saturation threshold. These bed conditions were therefore excluded from the present analysis but are included in the online dataset.

3 Results

3.1 General erosion trends for varying clay and water content of the bed

The net-change patterns for the different experiments clearly show the significant influence of the clay and water content of the bed for debris-flow erosion (Figure 2, Figure A2). When the clay fraction of the bed is increased from 0 to 0.04, erosion increases (Figure 2.a) with increasing scour at the upstream part of the erodible bed. Under a further increase of the clay fraction, from 0.06 to 0.1, erosion slowly ceases and becomes more homogeneous over the length of the bed (Figure 2.a). The above-described trend is valid for all three flume angles under which experiments have been conducted (Figure 2.b). However, under a flume angle of 28°, we observe a muted response in net change and erosion pattern, with less erosion but also less deposition. Under this flume angle, viscous forces dominate within the debris flow, in contrast to the dominance of frictional forces under higher flume angles. We hypothesize that this difference in flow characteristics under a flume angle of 28 ° explains the less pronounced erosion and deposition.

Under an increasing water fraction, up to 0.13, net change stays stable and net deposition occurs (Figure 2.b). A further increase in water fraction results in a dramatic increase in net erosion under flume angles of 31° and 34° (Figure 2.b). The spatial erosion patterns under different bed water contents are comparable, with scour at the top of the erodible bed and deposition on the lower half.

3.2 Diffusivity and porosity for different clay fractions of the bed

To quantify how effectively interstitial fluid and pore pressure travel through the bed under varying clay content, the diffusivity and porosity of those different bed compositions were determined. With an increase in clay fraction, the diffusivity and porosity of the bed decrease exponentially (Figure 2.c-d). The exponential decrease in diffusivity and porosity as a function of the clay fraction shows that clay fills up the pore spaces and decreases the flow of interstitial fluid and the transfer of pore pressure through the bed.

3.3 Pore pressure in the bed under varying bed compositions

To study if and how changing pore pressures in the bed influence erosion during our experiments, we explore the temporal pattern of pore pressure relative to the initial conditions in the bed for six key bed conditions. In most experiments, we observe a decrease in relative pore pressure at initial debris flow impact (Figure 3), followed by an increase of 100 to 400 Pa, depending on the bed composition. This pressure is lower than the maximum normal force (based on flow depth) exerted by the debris flows on the bed, which on average ranges between 500 and 600 Pa, depending on the angle of the flume.

An increase in clay fraction has three notable effects on the pore pressure. First, the lowering of the pressure at flow-front arrival disappears (Figure 3.a-c). Second, from no clay to a clay fraction of 0.04, the maximum pore pressure becomes higher and dissipation of the increased pressure becomes slower (from 7.5 sec to 12 sec at a clay fraction of 0.04, Figure 3.a-b). Third, under the highest clay fraction, the change in pore pressure is significantly smaller, and the response is slow (Figure 3.c).

Increasing the water content of the bed from 0.1 to 0.13 leads to an increase in the maximum pore pressure and a decrease in the initial pressure draw-down (Figure 3.d,e). Under these conditions, we also observe the establishment of a new pressure equilibrium (Figure 3.e, flattening of the blue line after 5 sec.). Under high water fractions of the bed (0.14), the increase in pore pressure is more rapid after flow-front arrival (Figure 3.f),

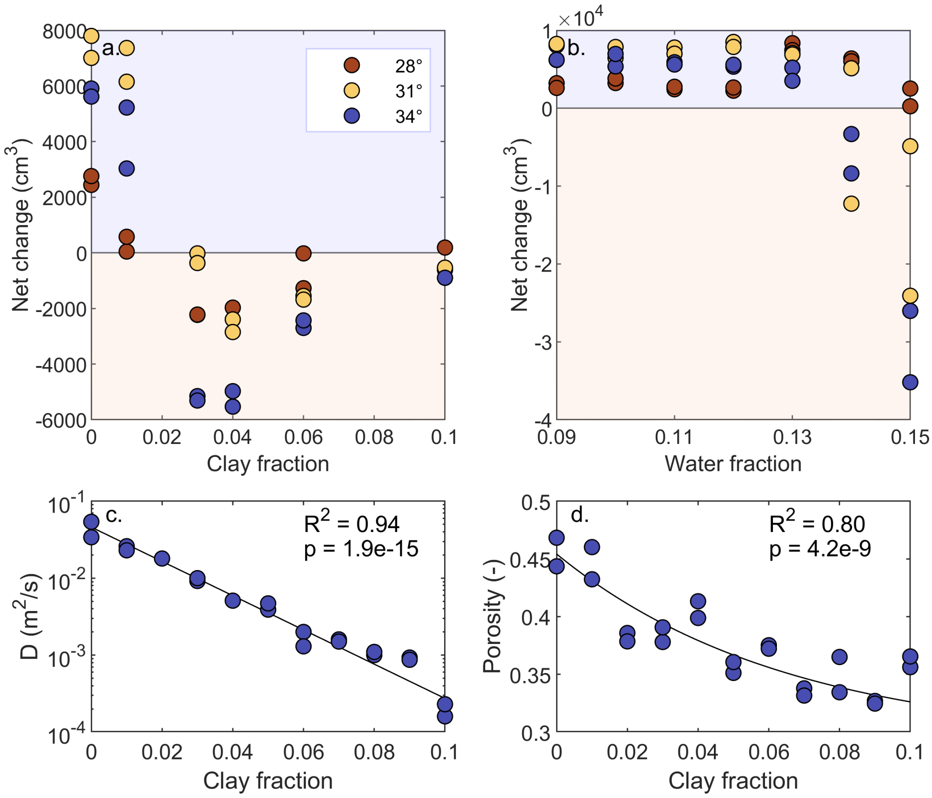

Figure 2. Overview of net change (cm^3) under different (a.) clay fractions (dry bulk mass fraction) and different (b.) water fractions (fraction of total mass) in the erodible bed, as well as results of the diffusivity (c.) and porosity (d.) tests for varying clay fractions (fraction of dry weight) with exponential trend lines. For the first two panels (a.-b.), the different colors of the data points indicate the flume angle under which the experiment was conducted. Note that a negative net change means more sediment was eroded in the flume than was deposited, and vice versa for a positive net change.

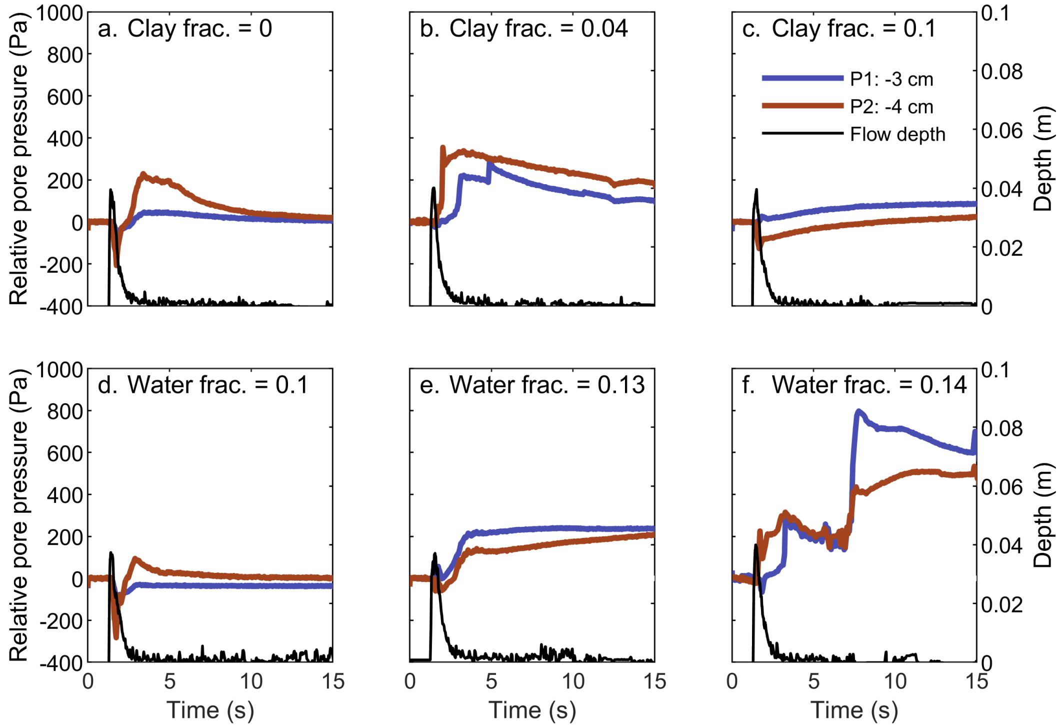

Figure 3. Relative pore-fluid pressure in the erodible bed measured by two pressure sensors (P1 and P2) installed at different depths during six representative experiments conducted at a flume angle of 34°. Flow depth of the debris flow overriding the bed is plotted in black. Panels a.-c. show results from experiments with increasing clay fractions (experiment 181, 153 and 157 respectively). Panels d.-f. show results from experiments with increasing water fractions (experiment 180, 201 and 187 respectively). Note that the pore pressure displayed is relative to the initial pressure created by the water in the protruding tubes. For pore pressures uncorrected for initial conditions see Figure A3. P2 records a higher pressure, explained by its lower position in the bed and thus the larger water column that can exist above it. Other differences between the data from the sensors can be explained by small heterogeneities in the bed, caused by either non-perfect mixing of the sediment, slight differences in packing during bed insertion, or other simple stochastics.

and the response in pore pressure is more chaotic. The latter could be explained by severe erosion around the sensors.

4 Discussion

4.1 Effects of water and clay in the bed on erosion

Our experiments show that bed composition strongly controls the magnitude of erosion by debris flows. The results of our experiments with varying bed water content are in agreement with earlier experimental results (Iverson et al., 2011; Reid et al., 2011) and field studies (McCoy et al., 2012; de Haas et al., 2022) that show that an increase in bed water content enhances erosion by debris flows. The studies by Iverson et al. (2011); Reid et al. (2011); McCoy et al. (2012); de Haas et al. (2022) show a linear response in erosion magnitude to bed water content, whereas, in our experiments, erosion exponentially increases between a water fraction of 0.13 and 0.15. The difference between our and previous studies already hints at the possible importance of fines in the bed. In our water content experiments, fines were absent in the bed mixture, whereas fines were present in the bed in the experiments by Iverson et al. (2011) and Reid et al. (2011), similar to natural settings. Due to the lack of fines in some of our experiments, drainage of water in the bed is unhindered (up to a water content of 0.13) and the increase in pore pressure is limited when a debris flow overrides the bed (see Figures 3.d and 4.a). In addition, the unhindered draining of fluid from a debris flow into the bed decreases the momentum and velocity of the debris flow (as shown by Iverson et al. (2011); Reid et al. (2011); Roelofs et al. (2022)), further limiting the amount of erosion (see Figure 2.b,c). Above a water content of 0.13 en-masse failure occurs (Figure A2.c,d) as the bed becomes saturated when overridden by the debris flow.

Our experiments with varying bed clay fractions further illustrate the significant effects of fines in the substrate for debris-flow erosion magnitude and processes (see Figure 2.a). A small increase in the bed clay fraction (up to a dry weight fraction of 0.04) increases erosion. The clay in the bed decreases its diffusivity exponentially (Figures 2.c and 4.b), which decreases the ease at which fluids drain through the bed and increases the pore pressure in the bed directly underneath the debris flow (conceptualized in Figure 4.b). This causes local undrained loading conditions, enhanced bed pore pressures, and erosion aided by liquefaction of the top of the bed related to an increase in water fraction of the bed (also discussed by e.g. Major (2000); Sassa and hui Wang (2005); Berger et al. (2011); Iverson et al. (2011); Iverson (2012); McCoy et al. (2012)). In this case, the debris flow loses little momentum, which further enhances erosion (Iverson et al., 2011; Roelofs et al., 2022). The increased pore pressure decreases intergranular friction (Iverson, 1997), promoting erosion of the bed sediments by shear and impact forces. We hypothesize that the clay-related effects on erosion described above will be amplified under higher bed water content, in line with the findings of Iverson et al. (2011); Reid et al. (2011).

A further increase of the bed clay fraction, beyond a fraction of 0.04, results in very limited erosion (conceptualized in Figure 4.c). Under these conditions, we hypothesize that undrained loading still occurs, but that the infilling of the pore spaces by clay particles alters the response of the bed to shear, which becomes more dominated by dilation. This should result in decreasing pore pressure at debris-flow arrival, which we observe in one of the pore pressure sensors but not in both (Figure 3.c). We expect that a small amount of compression still occurs as a result of the normal force exerted on the bed by the debris flow, which mutes the dilation response. Furthermore, the severe decrease in diffusivity under high bed clay fractions (see Figure A2.c) will hamper the transfer of water from the debris flow into the bed.

Our results thus show that a small increase in clay fraction (0-4%) of the bed, while keeping the sand porosity roughly similar, can have a dramatic impact on erosion magnitude and thus volume growth and hazard potential. We do want to highlight that under different clay fractions in our experiments the total porosity decreased. We, therefore, cannot draw conclusions on the erodibility of bed mixtures of similar porosities with varying amounts of clay. It is of interest to note that the observed fines content in natural debris flows is consistent with our tested parameter space. Bulk fraction of fines in real-life debris flows and their deposits ranging from 2-20 % have been reported (Phillips & Davies, 1991; Remaître et al., 2005; Ni et al., 2011; Yong et al., 2013). These deposits also form the unconsolidated beds in debris-flow gullies and variations in clay content may therefore help explain the widely contrasting erosion rates and magnitudes we observe in the field (e.g., Hungr et al., 2005; Santi et al., 2008; de Haas et al., 2022).

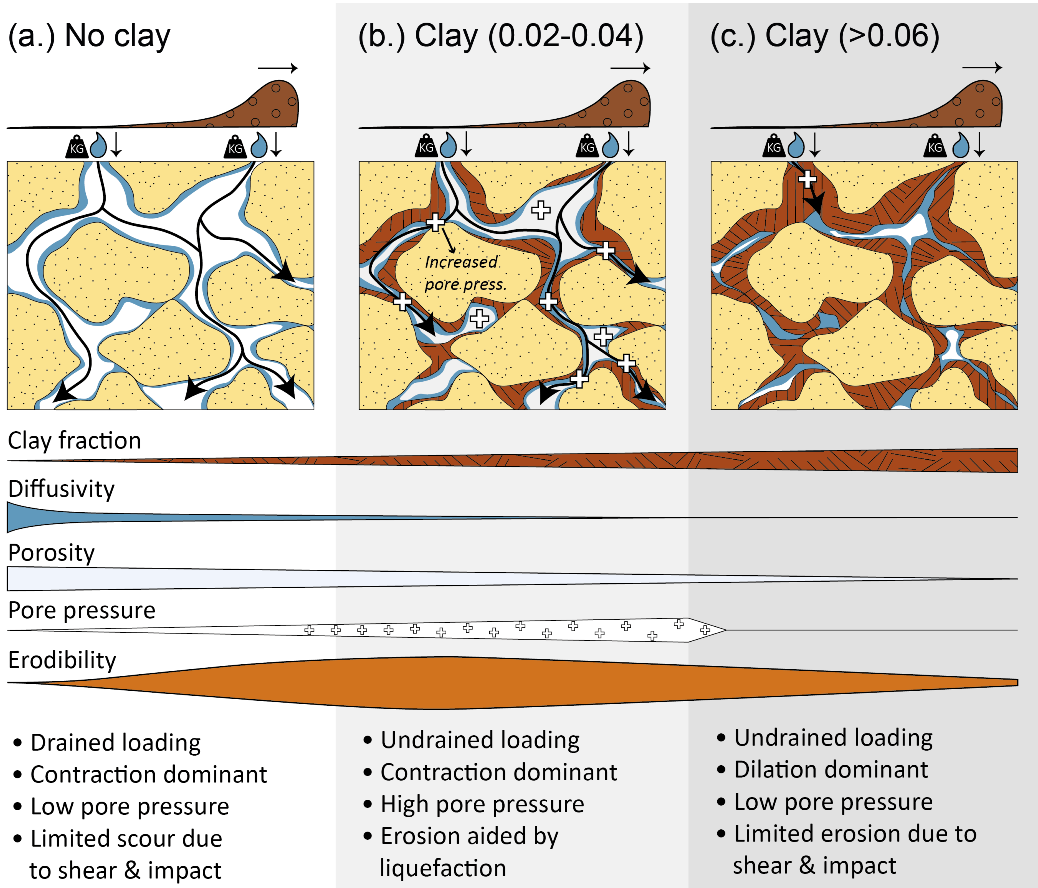

Figure 4. Schematic representation of the non-linear effects of bed clay content on erosion by debris flows. Without clay (a.), interstitial fluid from the debris flow can drain unhindered through the bed and erosion occurs as limited scour due to shear and impact forces imposed on the bed. With the optimal amount of clay (b.), in our experiments 2-4% of the dry bulk mass of the bed, transfer of pore pressure in the bed occurs but is hindered by clay particles decreasing the diffusivity of the bed. Therefore, undrained loading occurs, and erosion is increased due to liquefaction of the top layer of the bed. With very high clay fractions in the bed (c.), the soil is relatively more compacted due to the clay particles filling up the pore space and the behavior of the soil becomes more dominated by dilation. Therefore, erosion is limited.

4.2 The bed, the flow, or both?

Our results show that the composition of the bed can have a significant impact on both the amount of erosion caused by an overriding debris flow and the relative importance of contrasting processes. Previous experimental work has also shown that the composition of the debris flow affects erosion magnitude and processes (Egashira et al., 2001; Hungr et al., 2005; Fagents & Baloga, 2006; De Haas & Woerkom, 2016; Roelofs et al., 2022). Combining these results, we can state that debris-flow erosion is significantly affected by the abundance of water and clay in both the debris flow and the erodible bed. The importance of shear and impact forces on debris-flow erosion has long been recognized (Takahashi, 1978, 1981; Hungr et al., 2005; Stock & Dietrich, 2006; Mangeney et al., 2007; Hsu et al., 2008; Berger et al., 2011; Frank et al., 2015; Roelofs et al., 2022; de Haas et al., 2022), as well as the importance of pore pressures for debris-flow dynamics (e.g., Costa, 1984; Iverson, 1997; Major & Iverson, 1999; McCoy et al., 2010). However, the influence that clay has on the relative importance of different erosion forces has been overlooked. This study and Roelofs et al. (2022) show that the effects of bed and debris flow composition, and especially clay and water content of both the unconsolidated bed and the debris flow itself, should be accounted for. The presence of water and fines directly affects the mobility and momentum of the debris flow (Iverson et al., 2011; De Haas & Woerkom, 2016; Roelofs et al., 2022), draining conditions (as also discussed by Roelofs et al., 2022), the effectiveness of pore pressure transfer, and the occurrence of liquefaction. Whereby the presence of clay can also influence bed porosity (as in this study) as well as the contractive or dilative behaviour of the sediment.

Our results show that the composition of the soil can have a large but complex effect on debris-flow erosion and thus highlight the importance of incorporating bed composition effects in debris-flow erosion models. In current debris-flow erosion models, erosion is predicted based on the forces exerted on the bed by the debris flow (e.g., Iverson, 2012; Chen & Zhang, 2015; Iverson & Ouyang, 2015; Frank et al., 2017; Pudasaini & Fischer, 2020). Soil composition is at best incorporated as an erodibility factor (Chen & Zhang, 2015; Frank et al., 2015, 2017; Gregoretti et al., 2019; Baggio et al., 2021). We advocate that for accurate erosion prediction among different catchments, where calibration is not always possible, an erosion model in which the erodibility of the soil is described in a physics-based manner is needed.

4.3 How the small particles matter - lab vs field

Many studies have shown that small-scale debris flows in laboratory flumes can be used to study natural debris-flow behaviour, and depositional and erosional mechanisms (Egashira et al., 2001; Iverson et al., 2011; De Haas et al., 2015; De Haas & Woerkom, 2016; Zheng et al., 2021; Roelofs et al., 2022). In our specific case, the erosion trends observed in our experiments clearly link to physical processes and parameters that affect debris-flow erosion in the field, i.e. diffusivity of the bed, pore pressures, (un)drained loading conditions, contractive or dilative behaviour of the sediment, and bed shear strength. Therefore, we believe that the trends in our data related to clay and water content of the bed are of relevance to the field.

However, scale effects cannot be fully neglected. In our study, special attention should be given to the reduced effects of fluid pore pressure in lab-scale debris flows (Iverson, 1997; Iverson & Denlinger, 2001; Iverson et al., 2010). The ability of a flow to retain excess fluid pressure increases quadratically over increasing flow depth, which significantly affects debris flow dynamics (Iverson & Denlinger, 2001) and possibly erosion. In our experiments, the recorded pore pressures in the bed did not rise above the normal force exerted by the debris flows, opposing observations from the field (McArdell et al., 2007; McCoy et al., 2012), larger-scale debris-flow experiments (Iverson et al., 2011), and debris-flow experiments in centrifuges (Bowman et al., 2010). Despite this discrepancy, the bed pore pressures are clearly influenced by changes in the water and clay content of the bed in our experiments, and there is no physical argument for why this would be different on a larger scale. However, it is likely that the trends we observe related to clay and water content of the bed might shift slightly in response to larger debris flows.

5 Conclusions

We studied the effects of bed composition on debris-flow erosion magnitude and processes by performing experiments in a flume with an erodible, unconsolidated bed. We tested the effects of the water and the clay content of the bed, while keeping the composition and volume of the debris flow constant. With data from DEMs, we quantified net change, and with data from pore pressure sensors and additional diffusivity and porosity tests, we identified the forces and processes working on and in the bed.

The results from our experiments show that the water and clay content of the bed influence erosion magnitude by affecting pore pressures in the bed, loading conditions, and dilative/contractive behaviour. In our experiments, an optimum exists for maximum erosion under a specific clay content (4% of the dry bulk mass). Under this optimum clay fraction, drainage in the bed is partly hindered, resulting in undrained loading, elevated bed pore pressures, and possibly liquefaction of the top of the bed. Together, these reduce inter-particle friction and promote erosion. An increase in bed water content increases debris-flow erosion in our experiments by filling up pore space with water, resulting in elevated bed pore pressures when the debris flow overrides the bed. When the bed is close to saturation, this causes en-masse failure.

From our results, we can infer that small changes in hydrological and geological settings of a catchment may significantly impact debris-flow erosion, as small changes in soil moisture and the grain-size distribution of the sediment can lead to significant changes in final debris-flow volume and hazard potential. In addition, a changing climate and resulting environmental change, such as altered precipitation intensity, retreating glaciers, melting permafrost, and changing wildfire occurrence, influence the hydrological settings of the catchment as well as the availability and grain-size distribution of sediments. Therefore, understanding and incorporating bed effects in a more physics-based manner in debris-flow erosion modeling is important for current and future hazard prediction as well as for anticipating longer-term morphological change. Despite the importance of incorporating these effects for accurate predictions, we acknowledge that the data necessary to do so are difficult to obtain and not available for the vast majority of catchments. Therefore, effort should be made to test the relevance of our results in the field and assess if relatively easily obtainable predictors can be used to estimate bed erodiblity (e.g. catchment lithology).

6 Open Research

DEM's and raw data from the pore pressure sensors are available via Yoda (online repository of Utrecht University). The data and an instruction on how we processed the raw data can be found under this link:
`https://public.yoda.uu.nl/geo/UU01/Y0RH2E.html`
DOI: 10.24416/UU01-Y0RH2E

7 Author contributions

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Appendix A Supplementary material

Table A1. Key characteristics of the experimental settings of the flume experiments, including the varied parameters (flume angle, bed composition) and the debris flow composition and characteristics. For the extended list of all experiments, including experiment numbers, see online data supplement (DOI: 10.24416/UU01-Y0RH2E).

Debris flow components	**Unit**	**Values**
Clay	weight fraction (of dry weight)	0.05
	kg	2.4
Sand	weight fraction (of dry weight)	0.75
	kg	36
Gravel	weight fraction (of dry weight)	0.2
	kg	9.6
Water	weight fraction (of total weight)	0.2
	kg	12

Debris flow characteristics	**Unit**	**Values**
Bagnold number	-	200-260
Savage number	-	0.018-0.035
Friction number	-	7500-12000

Flume settings	**Unit**	**Tested angles**
Flume angle	°	28, 31, 34

Bed components	**Unit**	**Tested range**
Sand	weight fraction (of dry weight)	1-0.9
Clay	weight fraction (of dry weight)	0-0.1
Water	weight fraction (of total weight)	0.09-0.15

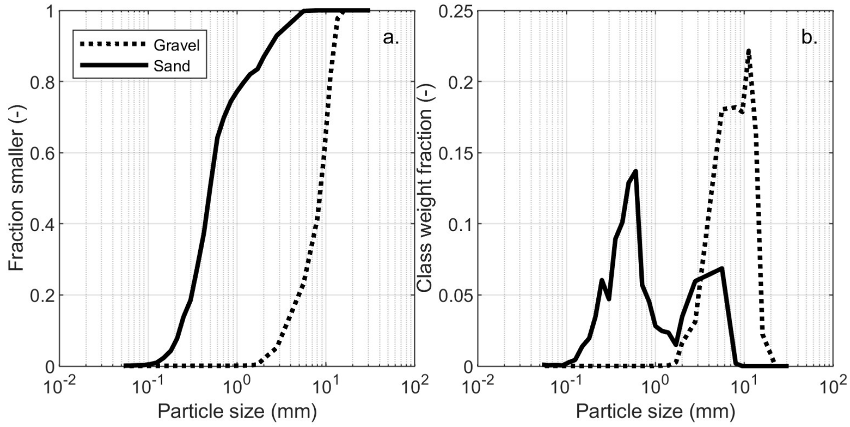

Figure A1. Grain-size distribution of the sand and gravel used for the bed sediment and debris-flow mixtures: a) cumulative particle-size distribution, b) frequency distribution.

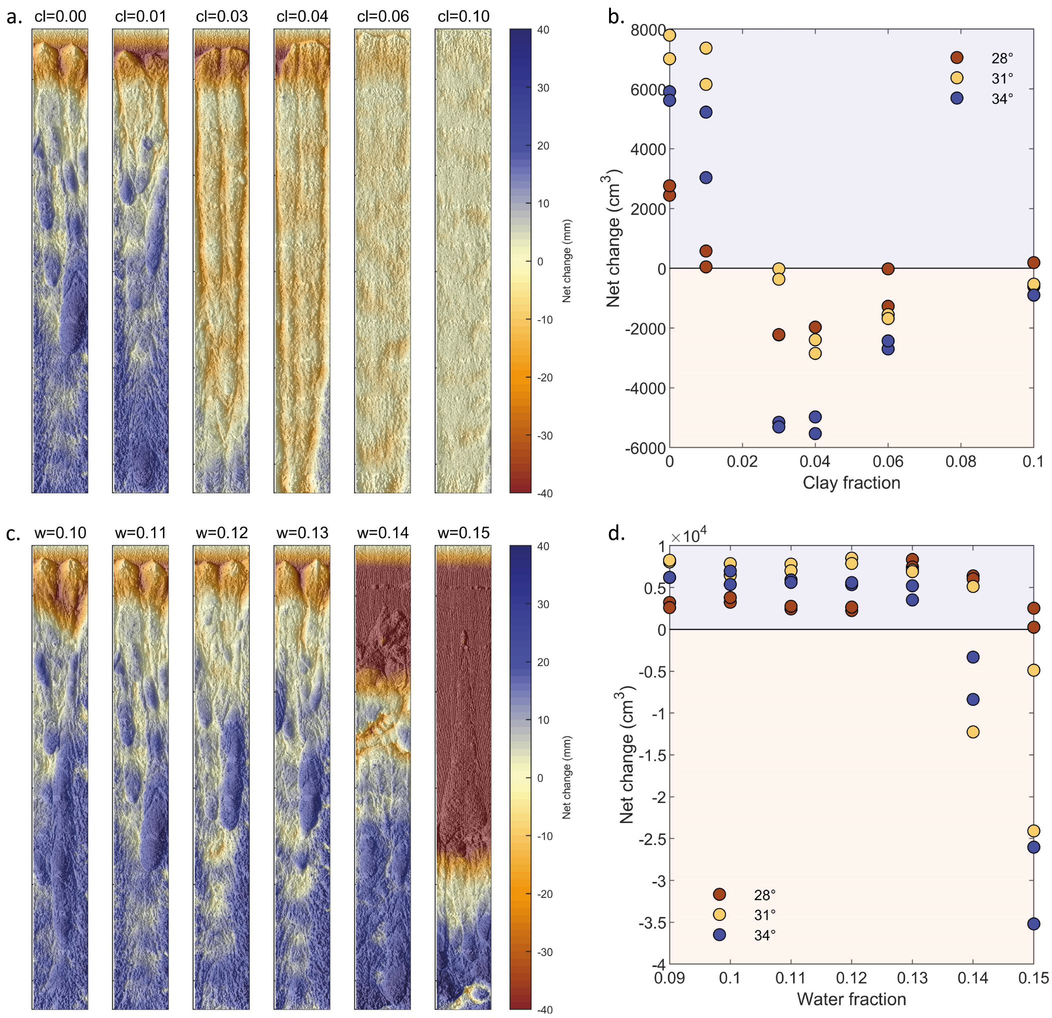

Figure A2. Overview of erosion patterns and magnitude under different clay fractions (fraction of dry weight) and different water fractions (fraction of total weight) in the erodible bed. Panel a. shows six DEMs of difference of experiments with key clay fractions conducted under a flume angle of 34°. Panel b. depicts the net change in cm^3 for all experiments with varying clay fractions conducted under three flume angles. Panel c. shows six DEMs of difference of experiments with key water fractions. Panel c. depicts the net change in cm^3 for all experiments with varying water fractions, conducted under three different flume angles. Note that the width of the DEMs is 30 cm, height is 250 cm

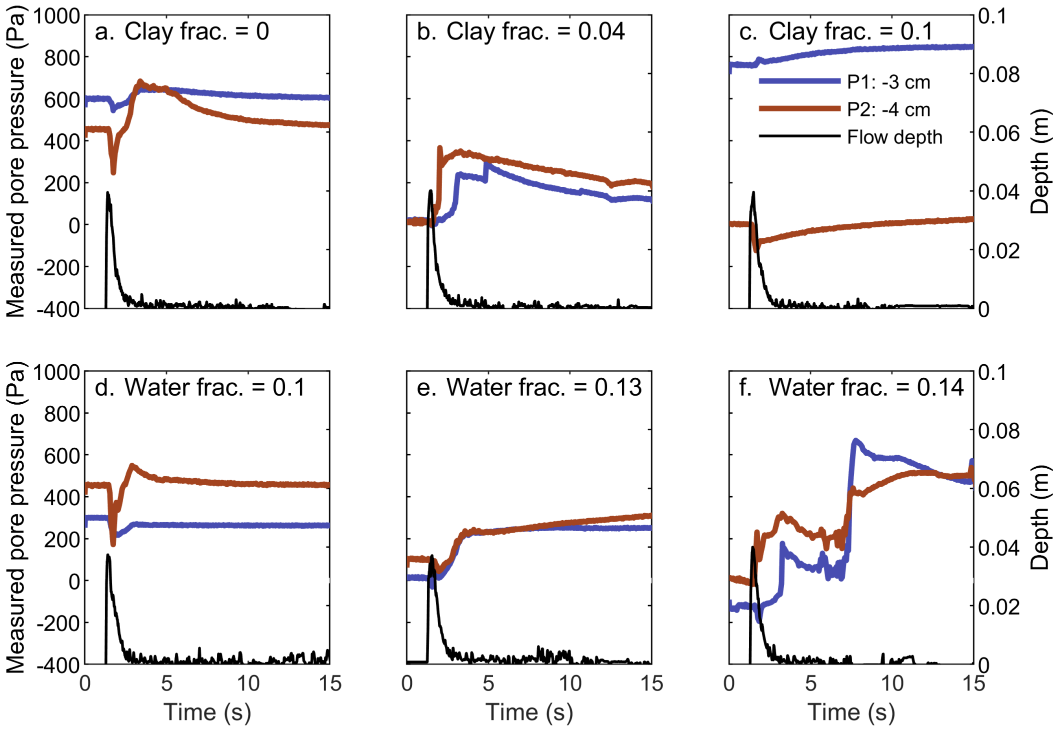

Figure A3. Pore-fluid pressure in the erodible bed measured by two pressure sensors (P1 and P2) installed at different depths during six representative experiments conducted at a flume angle of 34°. Flow depth of the debris flow overriding the bed is plotted in black. Panels a.-c. show results from experiments with increasing clay fractions (experiment 181, 153, and 157 respectively). Panels d.-f. show results from experiments with increasing water fractions (experiment 180, 201, and 187 respectively).

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