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Effects of debris-flow and bed composition on erosion and entrainment

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Abstract. Erosion and entrainment of material by debris flows determine debris-flow volume growth and therefore hazard potential. Recent advances in field, laboratory, and modelling studies have distilled two driving forces behind debris-flow erosion; impact and shear forces. A third factor influencing the (relative) importance of these forces is the viscosity and abundance of the interstitial fluid in the debris flow and the bed. However, how erosion and these forces depend on the composition of the debris flow itself and the composition of the bed remains unclear. Here, we present results of small-scale flume experiments with a loosely packed erodible bed that highlight the far-reaching effects of debris-flow and bed composition on erosion processes and magnitude. We quantify the effects of gravel, clay, and solid fraction in the debris flow on bed erosion. In addition, we quantify the effects of water and clay content of the unconsolidated bed on erosion by a debris flow. We show that debris flow erosion increases linearly when the gravel fraction of a debris flow is increased, which is linked to an increase in both impact and shear forces. We find that debris flow erosion, and the related forces, are non-linearly impacted by the clay and water content of the debris flow and those of the bed. For both the clay content of the debris flow and the bed, an optimum in erosion exists around a specific clay percentage that does not directly relate to an optimum in either shear or impact forces. When the water content of the bed and/or the debris flow is increased, erosion becomes largest when supersaturated conditions occur. These conditions are unrelated to the magnitude of the two erodible forces. This shows that both clay and water content affect erosion by affecting the transfer of pore pressures from the debris flow to the bed. We can therefore conclude that impact and shear forces dictate debris flow erosion in most cases but that their (relative) importance is significantly altered by the means and effectivity of pore pressure transfer from the debris flow to the bed. The latter is highly influenced by the viscosity and abundance of the interstitial fluid of the debris flow and the composition of the bed.

1 Introduction

Debris flows can grow in volume due to the entrainment of bed material by eroding the underlying bed, either of the bedrock and/or unconsolidated substrate. At locations with an abundance of loose substrate volume growth can be up to several orders of magnitude [e.g. 1-2]. If debris flows grow in size their destructive power increases and so does their hazard to mountain communities [3-4]. The erodible power of debris flows, combined with consecutive flow activity, is further suggested to be a primary process in cutting valleys in steep landscapes [5]. On a shorter timescale, the erosion, reworking, and deposition of sediment by debris flows is a main driver in the evolution of alluvial and debris-flow fans [6]. To minimize debris-flow hazards on Earth and decipher their ability to change landscapes we aim to gain a better understanding of the mechanisms of debris-flow erosion and the parameters that affect it.

In current hazard prediction, volume growth is often predicted based on catchment characteristics [e.g. 1,7], past debris flows [e.g. 8], or on linear regression between peak discharge and volume [3]. In other words, intrinsic and autogenic settings are used for predictions. However, when boundary conditions, such as precipitation intensity and weathering rates, change due to a changing climate, these predictions will not always suffice. Therefore, a solid physical understanding of debris flow erosion and entrainment is required.

Despite the importance of erosion and entrainment of material by debris flows, a unified theory for this process does not yet exist. Multiple numerical models have been developed describing erosion based on a variety of approaches, from empirical to physics-based, using a variety of key concepts and erosional forces.

Observations from field and experimental studies suggest two driving forces behind debris-flow erosion; 1) basal shear forces [1,2,9] and 2) impact forces [10,11]. A third factor influencing the (relative) importance of these forces is the abundance and viscosity of the interstitial fluid [e.g. 10,12]. The composition of the interstitial fluid could potentially affect the forces acting on the bed and/or influence the transfer of pore pressure from the flow to the bed.

Experiments on debris flow erosion have shown that the composition of a debris flow and the erodible bed affects erosion magnitude. Questions remain on how exactly different debris flow constituents (gravel, clay, and water) and bed constituents (clay and water) affect erosion magnitude and processes. The objective of our

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study is therefore to unravel the effects of debris-flow composition and bed composition on debris-flow erosion and erosional mechanisms. We aim at understanding the mechanisms of debris-flow erosion and aim to assess the erosion potential as a function of debris flow and bed composition.

This abstract combines the work by Roelofs et al. (2022) [13] and work in progress by the same authors.

2 Methods

To study the effects of debris-flow and bed composition on debris-flow erosion and erosional mechanisms, we conducted a series of experiments in a small-scale flume with an erodible, unsaturated, and loosely packed, unconsolidated bed (see [13]). Most experiments were conducted under a flume angle of 34 degrees, but extra tests were performed under flume angles of 32 and 30 degrees. Experiments were done with varying debris-flow compositions and with varying bed compositions. To account for the effects of natural variability, each experimental setting was repeated twice.

2.1 Flume setup and experimental procedures

The flume consists of a straight, rectangular channel of 0.3 m wide and 5.4 m long, a mixing tank with a forced-action mixer, and a custom-made release gate (Fig. 1). The flume was tilted at the beginning of every experiment and mixing of the debris flow mixture happened during the lifting procedure. When the flume reached the desired angle the debris flow was released into the flume by opening the custom-made release gate.

In the lower half of the flume, the bottom was lowered by 7 cm to create space for an erodible bed with a length of 2.5 m. The floor of the flume was covered with sandpaper to simulate natural channel roughness.

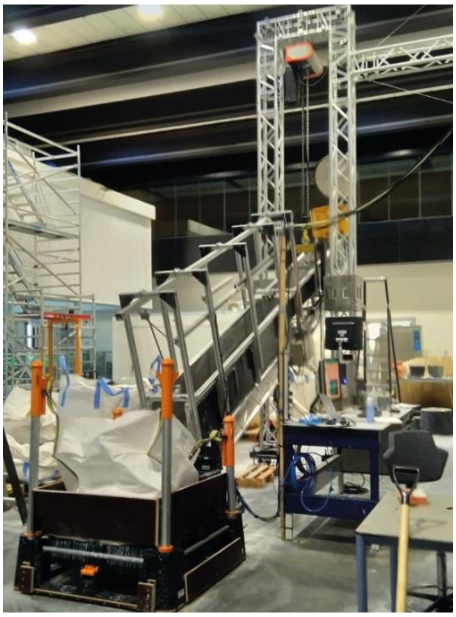

Fig 1 Flume set-up. The yellow cylinder in the top right is the sediment-mixing tank. In the lower half of the flume, beneath the metal frame, the erodible bed is present.

Along the length of the flume, five distance sensors were installed that recorded flow depth during the experiments. From these measurements, we also inferred flow velocities and shear stresses (see [13] for results). In the middle of the flume, just upstream of the erodible bed, a force plate and geophone plate were installed to measure normal forces and seismic ground vibrations, respectively (see [13] for results).

To quantify erosion magnitude and patterns, DoDs (DEMs-of-difference) were created by capturing pre- and post-flow channel-bed elevation with a Vialux z-Snapper 3-D scanner. Strictly speaking, we only capture the change in bed elevation and not erosion as sediment deposition might also occur.

2.2 Debris-flow and bed composition

For studying the effects of debris flow composition we conducted experiments in which we systematically varied the composition of the debris flow while keeping the composition of the bed constant. The debris-flow mixture consisted of four components in varying fractions; gravel, sand, clay (kaolinite), and water. The erodible bed in these experiments consisted of sand (98% of solid weight fraction), clay (2% of solid weight fraction), and water (11% of total weight).

For studying the effects of bed composition we systematically varied the composition of the bed while keeping the composition of the debris flow constant. The debris flow running over the erodible bed of different compositions consisted of 36 kg of sand, 9.6 kg of gravel, 2.4 kg of clay, and 12 kg of water. The loosely packed bed consisted again of sand, clay (kaolin), and water, but this time in different ratios. When clay content was varied, water content was kept constant at 11% of the total weight. When water content was varied the clay fraction of the bed was set to 0%.

3 Results

3.1 Debris-flow composition and erosion

Under increasing gravel fraction debris flow erosion increases linearly, whereas increasing the total solid fraction results in a decrease in erosion (Fig 2.a,c). When the fraction of clay is varied the pattern in erosion magnitude becomes more complex. With the volumetric clay fraction increasing from 0 to 0.075, erosion increases. However, erosion diminishes when increasing the clay fraction from 0.1 to 0.2 (Fig 2.b). These erosion trends are reflected in the magnitude of the forces working on the bed (not presented here, see [13]). Increasing gravel fraction correlates linearly to an increase in impact and shear forces. Increasing clay and solid fractions results in a non-linear response in the magnitude of impact and shear forces. This is because the abundance and viscosity of the interstitial fluid affect the velocity of the flow, the granular temperature, and the transfer of pore pressure from the debris flow to the bed. The complex interaction between these factors results in the non-linear response we observe.

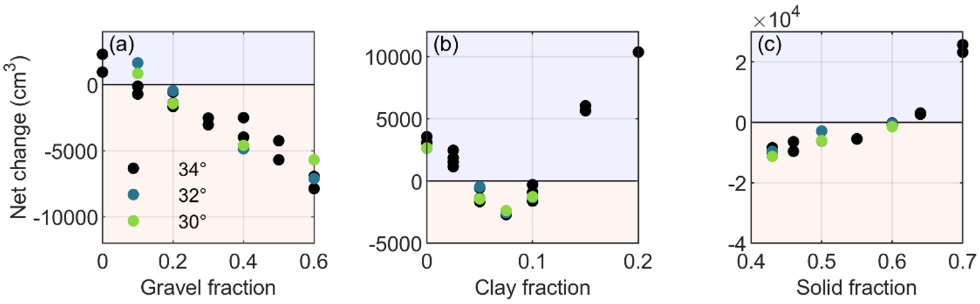

Fig 2 Net change above the erodible bed (cm3) for the three different debris flow composition parameters tested: gravel fraction (a), clay fraction (b), solid fraction (c). Gravel and clay fractions are given as a volume fraction of the total solid volume and solid content is given as a fraction of the total debris-flow volume. Note that a negative net change implies net erosion and a positive net change implies net deposition. Figure previously published in [13].

3.2 Bed composition and erosion

Increasing the clay fraction of the bed gives a non-linear response to erosion (Fig 3.a). The trend is similar in nature to the non-linear response of erosion to an increase in the clay fraction of the debris flow (Fig 2.b). Erosion increases up to a bed clay fraction (dry volume %) of 0.04, after which it decreases again. Increasing the water fraction of the bed does not influence erosion until total weight fractions higher than 0.13 are reached. Hereafter, erosion increases exponentially (Fig 3.b).

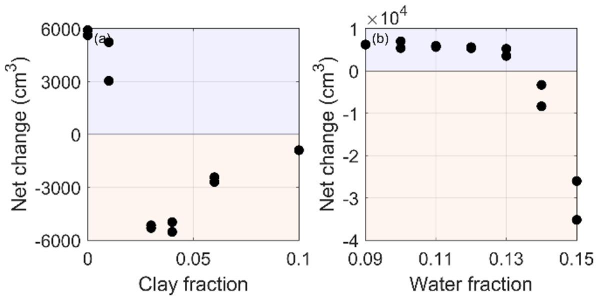

Fig 3 Net change above the erodible bed (cm3) with a flume angle of 34° for the two different bed composition parameters tested: (a), clay fraction (b), water fraction. Clay fraction is given as a volume fraction of the total solid volume and water fraction is given as a fraction of the bed volume. Note that a negative net change implies net erosion and a positive net change implies net deposition.

4 Discussion and conclusions

Our results show that the composition of the debris flow and the unconsolidated erodible bed has a significant influence on the amount of material a debris flow can erode and the relative importance of the involved mechanisms (see [13]).

For different debris-flow compositions, the influence on erosion is correlated to the combined effects of the magnitude of the forces working on the bed, impact and shear, and the effectiveness of pore pressure transfer to the bed (see [13]). Increasing gravel content in the bed linearly increases erosion, related to a linear increase in both impact and shear stresses on the bed. Increasing clay and solid content of the debris flow have a more complex non-linear effect on the forces working on the bed. The complex response is related to the effects water and clay have on the pore pressure in the debris flow [13]. Different bed compositions influence the erosion magnitude of debris flows by enhancing or inhibiting the effective transfer of pore pressure into the bed. The means of this transfer determine if the loading of the bed is drained or undrained, and determines if the upper part of the bed experiences liquefaction.

When the clay content of the debris flow and/or the bed is low, the transfer of pore pressure and water from the debris flow to the bed is relatively effective. Drained loading of the bed occurs, and the debris flow loses water and internal pore pressure quickly. This causes the debris flow to slow down and little erosion to occur.

Under very high clay content of both the debris flow and the bed, the transfer of pore pressure and interstitial fluid from the debris flow to the bed is inhibited. Almost no interaction between the flow and the bed occurs under these conditions, leading to minimal erosion.

Between these two extremes lies an optimum for debris flow erosion. Under a clay content of the debris flow of 0.075 (volume %) or a clay content of the bed of 0.04 (volume %) erosion magnitude reaches its maximum. Under these conditions, pore pressure is transferred from debris flow to bed, but the clay in the interstitial fluid and the bed inhibits the immediate dissipation of this pressure to deeper parts of the bed. This causes temporarily undrained loading of the bed, instigating high pore pressures in the upper layer of the bed, which decrease frictional forces between the grains, enhancing erosion. When pore pressure is so high that all shear strength of the bed disappears, liquefaction of the upper layer occurs.

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