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Basal shear stress of debris flow in the runout phase

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ABSTRACT

A laboratory device is proposed to assess the basal shear stresses generated by debris-flow mixtures during their runout phase. The device consists of an inclinable box with a gate facing a deposition plane. The box is filled with a selected debris-flow mixture, and after sudden opening of the gate, the features of the dam-break deposit can be measured. Based on some simplified assumptions of the energy balance, a methodology is proposed to assess basal shear stresses. The device has been tested using sediment samples from debris-flow deposits generated by two catchments of the Dolomites (Cortina d'Ampezzo, Belluno, Italy) by carrying out runout tests for different sediment concentrations by volume. The results show how the static Coulomb friction law is valid in the runout phase, with friction angles on the order of the angle of repose of the same material in dry conditions. The data elaboration also yields an innovative constitutive equation for shear stresses. This relation merges the Coulomb mixture approach with the concept of a one-phase flow with a certain rheology. This integration offers a useful insight into the weaknesses of the rheological approach if it is not properly scaled up to the ambient pressure of interest.

1. Introduction

Debris flow is a typical gravity-driven mass flow whose classification is open to different views. A debris-flow surge can be composed of a mixture of water and sediments entrained due to destabilisation and erosion, and even large pieces of wood structures (e.g., check dams, bridges, and houses). Common characteristics of all debris flows are high peak values of the volumetric sediment concentration (C_V = sediment volume/total volume = 0.50–0.65) and high ratios of solid mass to fluid mass per unit volume (N_m = 3–4). The assessment of debris-flow hazard in mountain catchments particularly in alluvial-fan areas depends greatly on 1) the triggering probability, mainly due to critical rainfalls and antecedent soil moisture conditions triggering landslides (Wieczorek, 1987; Anderson and Sitar, 1995); bed erosion (Johnson and Rodine, 1984) and channel-bed failure (Gregoretti and Dalla Fontana, 2008); and 2) the mode of debris-flow propagation during transport and deposition (Bertoldi et al., 2012). The difficulties that exist in debris-flow research can be summarised as follows: i) the overall medium in motion is not a Newtonian fluid but rather a mixture of quasi-Newtonian interior fluid and solids in agitation; ii) a one-phase rheological approach is prohibited by the evolution of granular temperature, non-equilibrium pore-fluid pressure (Iverson and Vallance, 2011) and variation of fluid characteristics from the snout and deposit margins to the tail (Iverson et al., 2010); iii) the adoption of a two-phase flow requires simultaneous knowledge of boundary friction and basal bed pore pressure, as well as the hypothesis of particle stratification with a friction-dominated regime close to the bottom and a collisional regime in the upper flow body (Ancey and Evesque, 2000); and iv) mass exchanges between the flow and the deformable channel occur, causing variation of the flowing mass and momentum (Berger et al., 2011; Iverson et al., 2011).

In spite of these difficulties, field-scale measurements monitoring basal pressures and shear stresses during debris-flow motion have shown that basal friction may be estimated using a Coulomb-like basal friction approach due to the prevalence of gravity-driven grain stresses (Iverson and Vallance, 2011), which are particularly evident at the surge front. This hypothesis also comes from Bagnold (1954) through the extension of the concept of the friction angle to a dynamic inter-granular angle, and it is currently adopted in several 1D and 2D numerical models for simulating debris-flow motion (Hungr and McDougall, 2009). Iverson (1997) and Iverson et al. (2010) proposed that the basal stress (τ_b) of the solid phase be expressed in terms of effective basal normal stress ($p_e = \sigma_b - p$), as follows:

$$\tau_b = (\sigma_b - p)\tan\phi + c \qquad (1)$$

where τ_b is the basal traction; p is the pore fluid pressure; c is the effective cohesion, which is negligible for granular debris flows subject to large deformations (Iverson, 2005), particularly in the case of contact between a basal debris-flow layer and a fixed bottom; σ_b is the bulked intergranular normal stress; and ϕ is the basal friction angle related to the grain-bed interface. The value of σ_b is given by the product of the bulk density, the height of the vertical column of debris flow (corrected,

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if necessary, taking into account the main flow orientation with respect to the horizontal direction) and the total vertical acceleration, which is the sum of the gravity component and the vertical component. The last parameter is normally disregarded in depth-averaged modelling.

Two main consequences descend from Eq. (1): i) when large deformations exist, cohesive forces may be negligible; and ii) the equation is apparently independent of the shear rate and thus of the deformation rate, even though some authors have investigated dense granular flows (G.D.R. Midi, 2004) and found that the friction coefficient increases ($\mu = \tan \phi$; $\mu = 0.2$–0.8 down a rough inclined bed) with the shear rate.

McArdell et al. (2007) detected the basal stresses of a debris-flow event in the Illgraben catchment in southwestern Switzerland, using an instrumented force plate. They split p into two components: the hydrostatic pressure and the dynamic pressure, the latter of which is generated by the collisional grain-inertial regime whose pulsation reinforces the pore fluid pressure. A debris-flow event at Chalk Cliffs (McCoy et al., 2013) generated total pore-fluid pressures that varied widely from less than hydrostatic to higher than two times hydrostatic for finer-grained material pushing along coarse-grained front of the flow. McArdell et al. (2007) detected a weak dependence of the dynamic pressure on the number of impulses recorded by geophones, as well as a remarkable difference between the total normal stress (σ_b) and the effective pressure ($p_e = \sigma_b - p$), which was found to be approximately 20% of the total normal stress (thus $p = 0.8\ \sigma_b$). The same research showed an upper envelopment of τ_b versus p_e data, confirming the trend of Eq. (1), with an apparent cohesion of 0.45 kPa and a basal friction angle of $\phi = 26°$ ($\mu = 0.49$). The difference between Eq. (1) from Iverson et al. (2010) and that obtained by McArdell et al. (2007) concerns the physical meaning of τ_b. The former considers τ_b to be related to the solid phase only, while the latter considers τ_b to be related to the total flow (granular plus interior fluid). Two further experimental records at the Illgraben catchment (Berger et al., 2011) showed shear stresses in full-motion conditions, which were in the range of 1/10 to 1/20 of the total normal force.

An indirect assessment of the friction angle that could be in play in the case of debris-flow catchments in the Dolomites was conducted by D'Agostino et al. (2010). Data from after-event surveys indicate that the hillslope gradients in the depositional reach of such granular- and silt-dominated debris flows fall in the range of 16°–26°, with a mean value close to 20°. The remarkably high angles at deposition express mirror maximum friction angles on the order of 30° just before the stop.

Several large-scale experiments have been carried out at the notable USGS debris-flow flume in Blue River, Oregon, USA (Major and Iverson, 1999; Iverson et al., 2010, 2011) and have underscored the role of pore pressure during debris-flow motion and deposition. USGS experiments have shown the fluid pressure p to range from approximately 0.3–$1.2\sigma_b$, with modal values in the range of 0.5–$1.0\sigma_b$, considering data collected both in the flume channel and in the deposition area. The following additional key findings emerged from the USGS experiment by Major and Iverson (1999): i) a time lag between the peak σ_b at the front arrival and the corresponding peak of p proved that leading edges possess a negligible positive p, thus emphasising the flow energy dissipation via grain–grain and grain–bed friction and collisions of an unsaturated front; and ii) when the flow front stopped directly over the sensor, the σ_b stresses rose abruptly while the p values remained almost null. These observations of the runout phase suggest that the application of the method of Johnson (1970) to estimate the basal yield stress during the deposition, assumed here as the shear component of the bulked weight of the deposit thickness, is questionable and that the application of Eq. (1) over time is somewhat more complex. In fact, the possible growth of the debris-flow snout at the expense of the liquefied part behind it makes uncertain the influence of the two debris-flow parts in contributing to a medium basal shear stress as the debris flow slows down. Furthermore, Johnson's methodology for assessing basal shear stress is extremely dependent on local values of the ground slope in the area of deposition and is practically inapplicable when debris-flow lobes stop at angles close to zero.

Given that the primary concern is to properly assess and model the runout distance of a debris flow, this study was conducted to increase our knowledge of geomorphic work dissipation and effective basal shear stress in the runout phase. A small-scale physical model was set up to test different debris-flow mixtures and volumes and partially account for scaling effects. The investigation was conducted to verify the applicability of Eq. (1) at the deposition, to quantify approximately how the dynamic shear stresses in full motion (McArdell et al., 2007) may change when rapid deceleration takes place in null slope areas, and finally, to determine whether the concept of a debris-flow rheology is inapplicable to the runout phase or rather can be adapted to Eq. (1).

2. Materials and methods

The experimental tests described in this paper were carried out at the Institute for Hydrological and Geological Protection of the Italian National Research Council (CNR-IRPI) in Padova (Italy). The experimental device consists of a tilting-plane rheometer (D'Agostino et al., 2010) composed of a 2 × 1 m tilting plane, inclinable up to 38°, on which a steel tank with a removable gate is installed (Fig. 1). A fixed horizontal plane (1.5 × 1 m) serves as the deposition area downstream of the sloped plane and consists of a steel plate with a surface lenticular roughness of 2 mm (Fig. 1b). Dam-break tests on debris-flow mixtures were performed by positioning a tank at the lower end of the tilting plane. Two tanks of different sizes were utilised to assess the influence of the volume on the results. The largest tank (LT) is a parallelepiped with a square base of 0.15 × 0.15 m and a height of 0.33 m, which corresponds to a maximum storage volume of

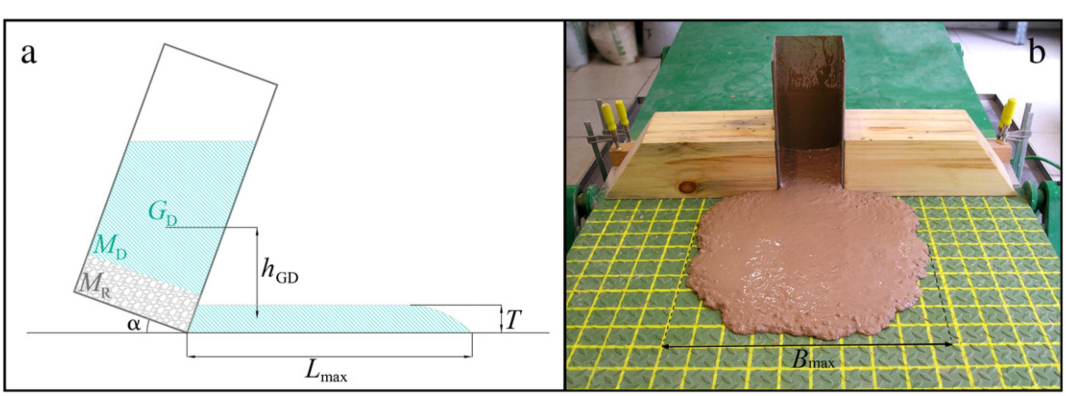

Fig. 1. Experimental device setup at the CNR-IRPI laboratory of Padova. a) Graphical sketch showing the main variables. b) Image taken at the end of the experiment. The size of the square grid is 5 × 5 cm.