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Debris-flow behavior in super- and subcritical conditions

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Abstract

Observations of debris-flow events all over the world cover a wide range of phenomenologically similar processes, consisting of different concentrations of water, fine and coarse sediment, and frequently wooden debris. For this reasons, empirically derived coefficients to be used in prediction models to estimate debris-flow dynamics often show a wide degree of scatter. Two of such empirically derived concepts, originally developed for pure water flows, are presented in this study, showing similar deviations from hydrostatic stress assumption in subcritical flow conditions. The first concept is used to estimate debris-flow velocities, based on superelevation data. Based on our experimental results as well as observations from real debris-flow events at the field monitoring station at Illgraben (canton Valais, Switzerland) we show that the empirical coefficient used in the superelevation equation to account for non-Newtonian flow effects correlates with the Froude number – the dimensionless ratio between gravitational and inertia forces in the flow. Interestingly, a similar relationship – the second concept presented – has been found in recent studies to estimate the maximum impact pressure of a debris-flow event. Our results suggest that for debris flows and decreasing Froude numbers inertia forces become more important and the hydrostatic pressure distribution may be an unrealistic assumption for empirically based prediction models in subcritical conditions.

Keywords: Froude dependency, superelevation, impact estimation, earth pressure, debris-flow behaviour

1. Introduction

The dynamic behavior of debris flows is mainly driven by its water content, the ratio of fine to coarse particles in the flow, and possibly also the degree of agitation induced by the interaction of the flow with the rough channel bed. Iverson (1997), for instance, proposed different dimensionless parameters referring to the various stresses (solid grain shear and normal stress, fluid shear and normal stress, and solid-fluid interaction stress) that characterize the flowing mixture. These controlling factors are variable within any given flow and between individual debris-flow events, but all over the world the term debris flow is widely used to describe a broad range of phenomenologically similar processes. This lead, for instance, to a substantially variability of data on viscosities of debris-flow events in nature (Cui et al., 2005; Tecca et al., 2003), and empirically derived coefficients, which are used in prediction models to estimate for instance maximum impact forces of debris flows, show a wide degree of scatter - although a physically correct concept for its development may be assumed.

For this study we use the Froude number – the dimensionless ratio between gravitational and inertia forces in the flow - to characterize different debris-flow behaviors. In this context, two concepts to derive dynamic characteristics of debris-flow events are analyzed more closely. Originally developed for pure water flows, the first concept to be considered, concerns the estimation of maximum flow velocities based on superelevation information. The other concept, estimation of the maximum impact pressure of a debris-flow event, is an important design parameter for many protection structures. However, with both concepts it is difficult to account for the full range of flow conditions of debris flows.

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2. Bulk mixture variability and flow conditions

2.1. Superelevation

Numerous studies have shown that the destructive power of debris flows is proportional to the flow velocity (Armanini, 1997; Bugnion et al., 2011; Scheidl et al., 2013). A possible approach to estimate (maximum cross-sectional mean) flow velocities of debris flows (for a given event) is based on the vortex equation by using superelevation marks. Superelevation can be observed in curved channels, where the flow-height at the inner bend is lower than the flow-height at the outer bend (Figure 1).

However, to apply the vortex equation also to Non-Newtonian fluids, the vortex formulae was modified by introducing a correction factor. This correction factor can be expressed with equation (1), where *Rc* denotes the centerline radius of the bend, g^* the slope normal component of gravity, Δh denotes superelevation, *B* accounts for the channel width and *v* is the flow velocity.

$$k = \frac{R_C g^* \Delta h}{B v^2} \tag{1}$$

Several studies comparing experimental or observed superelevation data with estimated velocities suggest a wide range of values for the correction factor k - accounting for the viscosity, vertical sorting and the boundary effects in bends for debris flows (e.g.: Hungr et al., 1984; VanDine, 1996; Bulmer et al., 2002; Prochaska et al., 2008). Based on small-scale experiments, Scheidl et al. (2014) analyzed debris-flow velocities in a curved flume and back-calculated correction factors for more than 150 experimental debris-flows. They measured superelevation and investigated the influence of different material mixtures as well as bend geometries. The flume investigations were conducted using a flexible plastic half-pipe, mounted on a wooden plane construction. Two different bend radii (1.0 m and 1.5 m) with a bend angle of 60° were implemented. The total length of the flume, of about 8 m, was covered with 40 grit silicon carbide sandpaper, reflecting a constant basal friction layer. To account for the complexity of a debris-flow process, four different material mixtures based on four different grain size distributions, were defined.

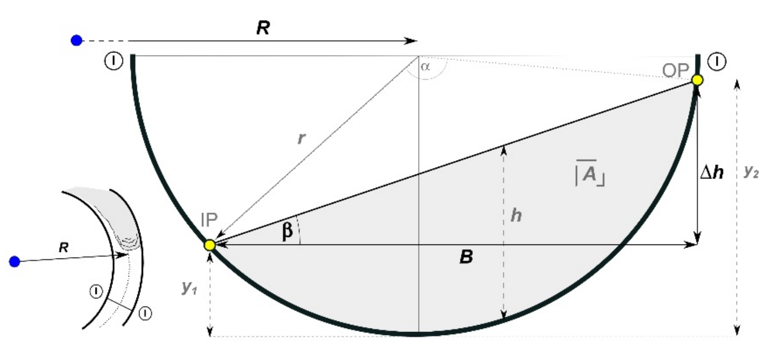

Fig. 1. Illustration of parameters used for estimating debris-flow velocities based on superelevation, modified after Scheidl et al. (2014).

Scheidl et al. (2014) found systematic deviations of observed superelevation heights as compared to those estimated by applying the simple vortex equation for a Newtonian fluid, and these deviations appeared to be a function of the Froude number, $F = = v/\sqrt{gh}$. The experimental results suggest that superelevation of debris flows cannot be solely described with approaches from the pure water hydraulics. This is also confirmed by an analysis of superelevation data from real debris-flow events observed at the Illgraben (Valais, CH), and back-calculated correction factors for these events presented below.

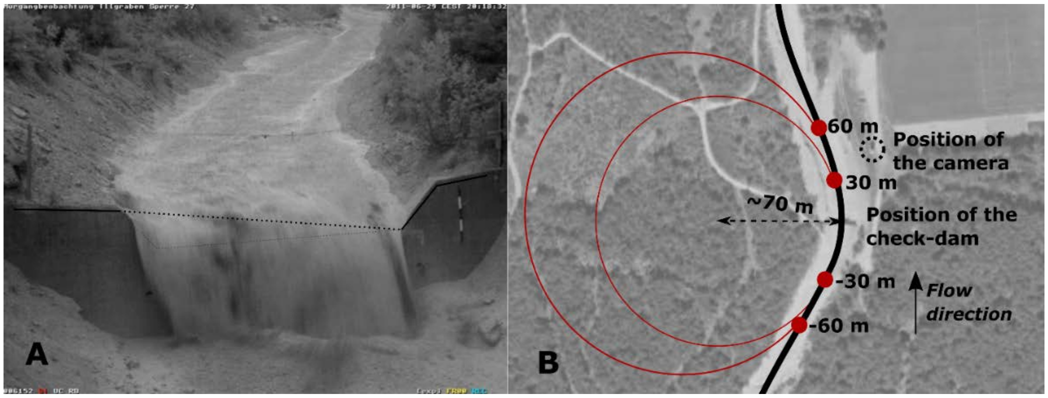

Fig. 2. Superelevation observation from a real debris-flow event at the Illgraben. A) Maximum superelevation of the debris-flow event at the Illgraben on June 29, 2011. B) The relevant curve radius R_c were determined based on circular arcs fit to sets of points marked on the bend, following a method proposed by Prochaska et al. (2008).

For this purpose, video recordings of debris-flow events were analyzed at a location where the flow passed over a check dam, which served as the basis for the determination of the event-related superelevation height (Fig. 2A and B). The relevant curve radius R_c to be used in equation (1), is estimated based on a method proposed by Prochaska et al. (2008). For field analyzes, they recommend the channel curve to be approximated by three points at intervals of 30 m, 60 m or 90 m (Fig. 2B). The determination of the maximum flow velocities v for the respective events is based on the time of maximum flow intensity according to geophone recordings. The maximum flow height h was determined from radar measurements perpendicular to the check-dam crown. From this, the Froude numbers F of the respective events could be determined. Figure 3 (left panel) shows the relation between correction factors k and Froude numbers F for all experiments of Scheidl et al. (2014) and for superelevation data based on real debris-flow events observed at the Illgraben monitoring station. The regression model (black line) is based on the experimental data of Scheidl et al. (2014) and follows a power law model ($R^2 = 0.77$):

$$k = 4.4F^{-1.2} \qquad (2)$$

2.2. Impact modelling

Interestingly, a similar relationship with the Froude number has been found for the empirical pressure coefficient a of the general form of the dynamic impact model:

$$a = \frac{p}{\rho v^2} \qquad (3)$$

where p is the impact pressure, ρ is the debris-flow density and v are the approach flow velocity. For clear water a has been found to be between 1 and 2 (Watanabe and Ikeya, 1981). However, numerous studies suggest that a can vary significantly for debris flows, depending on the flow type. Watanabe and Ikeya (1981), for example, estimated a = 2.0 for laminar flow and fine-grained material. Egli (2005) proposed values up to a = 4.0 for coarse material. Zhang (1993) recommended values of a between 3.0 and 5.0, based on field measurements of over 70 debris flows. Based on laboratory impact measurements on flexible debris-flow barriers, Wendeler et al. (2007) list up scaled field values of a between 0.7 and 2.0. For granular debris flows, theoretical considerations by Coussot (1997) result in values of a = 5 to a = 15. A similar range of a values was proposed for debris flows by Daido (1993).

Cui et al. (2015) fitted the pressure coefficient a as a power law function to the Froude number F, based on their experiments and experiments conducted by Hübl and Holzinger (2003); Scheidl et al. (2013), Tiberghien et al. (2007) as well as estimations of field events of Costa (1984) and Zhang and Yuan (1985):

$$a = 5.3F^{-1.5} \qquad (4)$$

Considering both the hydrostatic pressure and the hydrodynamic pressure of a debris-flow impact, Vagnon and

Segalini (2016) as well as Wang et al. (2018) showed that the total pressure coefficient a' follows the general form of:

$$a' = \beta F^{-2} + c \tag{5}$$

In equation (5) the static impact coefficient □ denotes the exceedance from the hydrostatic pressure whereas the dynamic impact coefficient c acts as a drag coefficient depending on v^2. Wang et al. (2018) propose □ = 3.8 and c =0.8, according to the experimental results.

3. Results and Discussion

Empirically derived coefficients, back-calculated from the simple equations to (i) estimate debris-flow velocity based on superelevation (left) and (ii) predict maximum impact pressures (right), as a function of the corresponding Froude numbers, are shown in Figure (3). It must be noted that there is some spurious correlation between the coefficients and the Froude number determined from debris-flow experiments and field observations.

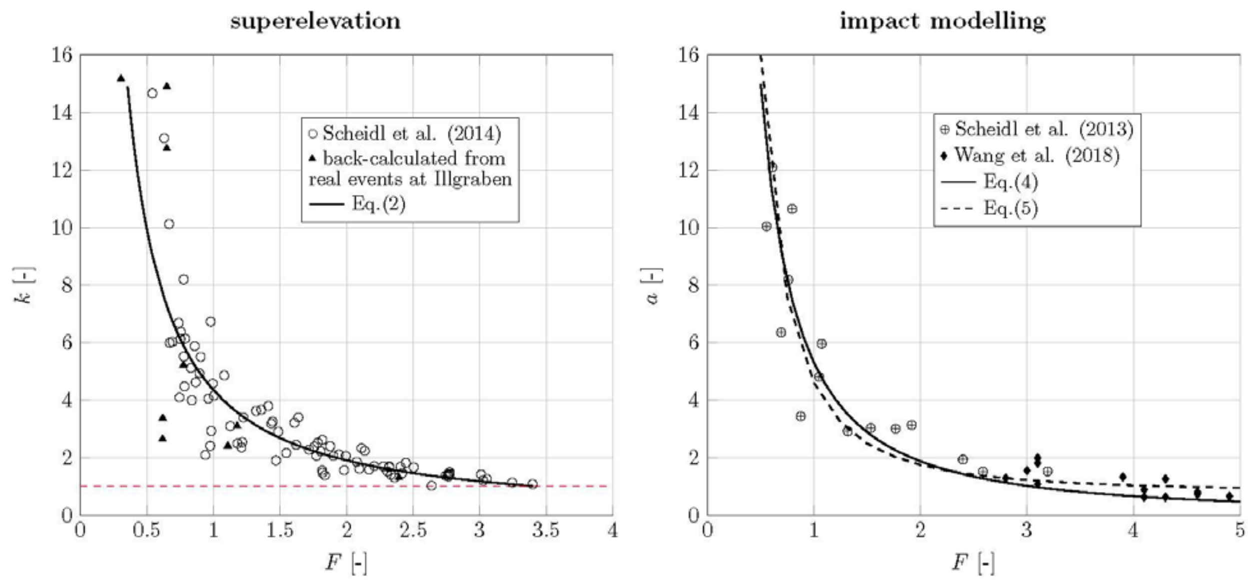

Fig.3. Relation of empirical derived coefficients of modified prediction models to estimate debris-flow velocity (left) and debris-flow impact pressure (right) and Froude number. Left: The empirical correction factors *k* of the vortex equation (eq.1) are based i) on superelevation experiments from Scheidl et al. (2014) and ii) from superelevation field investigations at the debris-flow monitoring station at Illgraben (CH). The horizontal dashed line shows a constant relation of $k = 1$ with the Froude number as expected for clear water flows. The black line indicates the power model (eq. 2) based on the superelevation experimental data of Scheidl et al. (2014). Right: The prediction of the empirical coefficient *a* of the impact model (eq. 3) is based on the power model (eq.4) as proposed by Cui et al. (2015) and on the general form (eq. 5), accounting also for hydrostatic pressure with $\beta = 3.8$ and $a = 0.8$. Additionally the experimental data of Scheidl et al. (2013) and Wang et al. (2018) are included.

The results in the context of superelevation estimates indicate that the vortex equation (1) together with correction factors of $1 < k < 5$ might be considered for supercritical flow. However, secondary flow or spiral flow phenomena in the lateral direction could limit the estimation of the maximum front velocity based on superelevation, because the vortex equation is derived to apply only for conditions where no cross-wave disturbance patterns within the bend section is produced.

For subcritical flow conditions the correction factor determined from the flume experiments shows a higher deviation in comparison to a pure Newtonian fluid, which is also confirmed by field observations from real events at Illgraben. We assume that for subcritical flow conditions the mixture properties and the internal flow mechanism result in an enhanced deviation from the simple force balance considering only hydrostatic and centrifugal forces in the superelevation equation for Newtonian fluids. Considering a debris flow as a single phase (bulk) mixture, one possibility to account for the deviation in subcritical conditions was proposed by Scheidl et al. (2014) who assumed a correction factor k_{ep} to be a function of active and passive earth pressure as well as inundated flow heights on the inner (y_1) and outer (y_2) sides of the curve :

$$k_{ep} = \left[K_p + \left(K_p - K_a\right)\left(\frac{y_2^2}{y_2^2 - y_1^2} - 1\right)\right]^{-1} \quad (6)$$

Equation (7) is based on a force balance approach and on the assumption of a rectangular cross section. K_p and K_a denote the passive, respectively active earth pressure coefficient. However, the results of the experiments and from field observations suggest higher variability of induced anisotropic stress distributions in the bulk mixture of debris flows for subcritical flow regimes.

The power law models to describe the empirical pressure coefficient a, and the total pressure coefficient a', respectively, as a function of the Froude number, closely match. This implies that the general form of eq. (7) can be used in subcritical as well as in supercritical flow conditions to predict the total pressure coefficient. However, Wang et al. (2018) used also the grain Reynolds number (N_R) as well as the modified Savage number (N_{Sav}) (e.g. Iverson, 1997) to distinguish between different debris-flow types for impact pressure estimations. Based on experiments, they found the dynamic impact model (eq. 4) only applicable for debris flows with $N_R > 1$ and $N_{Sav} < 0.002$, characterized either as dilute and turbulent or dense and steady debris-flow type. Both types have been indicated by Wang et al. (2018) to behave like fluids, and the related experiments were associated with Froude numbers > 2. For debris-flow types with grain Reynolds numbers and Savage numbers different from the thresholds given above, Wang et al. (2018) suspect debris flows not to behave fluid-like - discarding the dynamic impact model given in eq. (4).

Similar to the coefficient k, determined from superelevation experiments, the hydrodynamic impact coefficients a and a' show a comparable variation with the Froude number. Higher deviation of both impact coefficients can be observed for low Froude numbers, hence for subcritical flow conditions. Following the general equation (5), prediction of the pressure coefficient a' for Froude conditions $F < 1$ is mainly influenced by the hydrostatic term (β), accounting for the exceedance from the hydrostatic pressure. Considering debris flows as single-phase flows and applying a similar approach as assumed for the derivation of equation (3) or proposed by Vagnon and Segalini (2016) we can rewrite equation (5) tentatively replacing a^* by the passive earth pressure coefficient K_p:

$$K_p = F^{-2} + c \quad (7)$$

The passive earth pressure coefficient is the ratio between bed-normal and bed-parallel (longitudinal) stresses within the bulk mixture. According to Savage and Hutter (1989) and modified by Hungr (2008) this ratio can be described by:

$$K_p = 2\left[\frac{1+\sqrt{1-\cos^2\varphi_i(1+\tan^2\varphi_e)}}{\cos^2\varphi_i}\right] - 1 \quad (8)$$

In equation (8), φ_i denotes the internal friction angle and φ_e, the basal friction angle, is modified by Hungr (2008) to account for the rotation of principal stresses in spreading flows. If φ_i as well as φ_e get zero, then $K_p = 1$, reflecting hydrostatic conditions. proposed Static impact coefficients (β in eq. 5, respectively K_p in eq. 7) have been proposed by Lichtenhahn (1973), ranging from 2.8 – 4.4. Armanini (1997) stated a static impact coefficient of 5, and based on miniaturized tests, Scotton and Deganutti (1997) found values between 2.5 and 7.5. This is in accordance of passive earth pressure values proposed by Hungr (1995) for numerical 1-d modelling of debris-flow propagation.
He proposed passive earth pressure values up to 5.0. The dependence of a^* and possibly K_p with the Froude number, as stated by equation (7), seems also to be in line with the superelevation analysis from Scheidl et al. (2014). Based on the theoretical Smooth Momentum Flux model to estimate run-up heights, Rickenmann et al. (this proceeding) observed a tendency for lower K_p values with increasing $F-$ values.

4. Conclusions

Our results suggest that for debris flows and decreasing Froude numbers inertia forces become more important, and the evolution of internal stresses governing deformation is largely dominated by constitutive stress conditions of the bulk mixture -- as an effect of rheological characteristics. For both presented concepts, applicable to derive dynamic characteristics of debris-flow events, it seems that hydrostatic pressure distribution may be unrealistic when dealing with the flow of granular material that has internal strength due to its frictional nature (Savage and Hutter 1989).

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