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Field and laboratory analysis of the runout characteristics of hillslope debris flows in Switzerland

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ABSTRACT

Hillslope debris flows are unconfined flows that originate by shallow failures in unconsolidated material at steep slopes. In spite of their significant hazard for persons and infrastructure in mountainous regions, research on hillslope debris flows is rather scarce in comparison to other landslide types. This study focusses on the runout characteristics of hillslope debris flows applying two different approaches. First, detailed landslide inventories, which include field measurements of 548 slope failures that occurred during the last two decades in seven parts of Switzerland, were analysed. Second, laboratory tests were carried out to study the effect of the soil water content, grain-size distribution and mobilized volume on the runout behaviour of hillslope debris flows. Most of the failures in the field started as shallow translational slides at terrain slopes between 25° and 45° and involved volumes of some tens to a few hundred cubic meters. An analysis of the runout distance of 117 hillslope debris flows showed that they normally travelled some tens of meters, but sometimes the runout exceeded 300 m. A positive relation between volume and runout distance and between volume and affected area was observed, although there is considerable scatter in the data. The affected area of 63 hillslope debris flows ranged from ~100 to ~1500 m^2. Based on the field data, a 7.5 m long laboratory hillslope was designed with a geometrical scale factor of 20. A total of 75 runs with volumes from 4 to 20 dm^3, water contents from 18% to 38%, and four grain-size distributions were carried out. The laboratory tests revealed that water content is the dominant control, but also the clay content strongly influences the runout distance and the affected area. Even a small increase in water or clay content produces a considerably larger or smaller runout distance, respectively. In contrast, the influence of the volume on the runout was smaller, and a positive relation was observed between these two parameters. The field and laboratory results are in general agreement and consistent with the results of other studies. The results of this work improve the understanding of hillslope debris flows and may aid in the hazard assessments of these processes.

1. Introduction

Hillslope or open-slope debris flows are unconfined mass movements that originate by shallow failures in colluvium or other unconsolidated soil material at steep slopes (Fig. 1). In contrast to channelized flows, hillslope debris flows can spread laterally after their mobilisation. After the new classification proposed by Hungr et al. (2013), hillslope debris flows can also be called debris avalanches and are defined as very rapid to extremely rapid flows of partially or fully saturated debris. Unlike the relatively large debris avalanches described by Hungr et al. (2013), which can entrain large amounts of soil material, especially when they enter an established drainage network and become confined flows, the hillslope debris flows described herein rarely entrain sediment along their runout path.

Although hillslope debris flows represent a significant hazard in mountainous regions (Bezzola and Hegg, 2007) little research has been performed on them in comparison with other types of rapid mass movements. The overall assessment of hillslope debris flows includes three aspects: 1) the mechanics of the initial slope failure in the superficial deposits, 2) the transformation from the initial sliding into a process dominated by deformation and flow, and 3) the kinematics of the resulting hillslope debris flow. While the initial failure of shallow landslides has been extensively investigated by theoretical approaches, numerical modelling, in-situ monitoring or laboratory experiments (Iverson, 2000; Olivares and Picarelli, 2003; Collins and Znidarcic, 2004; Ng et al., 2008; Klubertanz et al., 2009; Godt et al., 2012; Lehmann and Or, 2012), the transformation of the failure into a flow-like movement is complex with many influencing factors (Iverson et al., 1997). This slide-to-flow phenomenon has been treated applying concepts of soil mechanics and a so-called "mobility index approach" (Johnson and Rodine, 1984; Ellen and Fleming, 1987). Later, a detailed analysis on both the theoretical aspects and the data gathered by the

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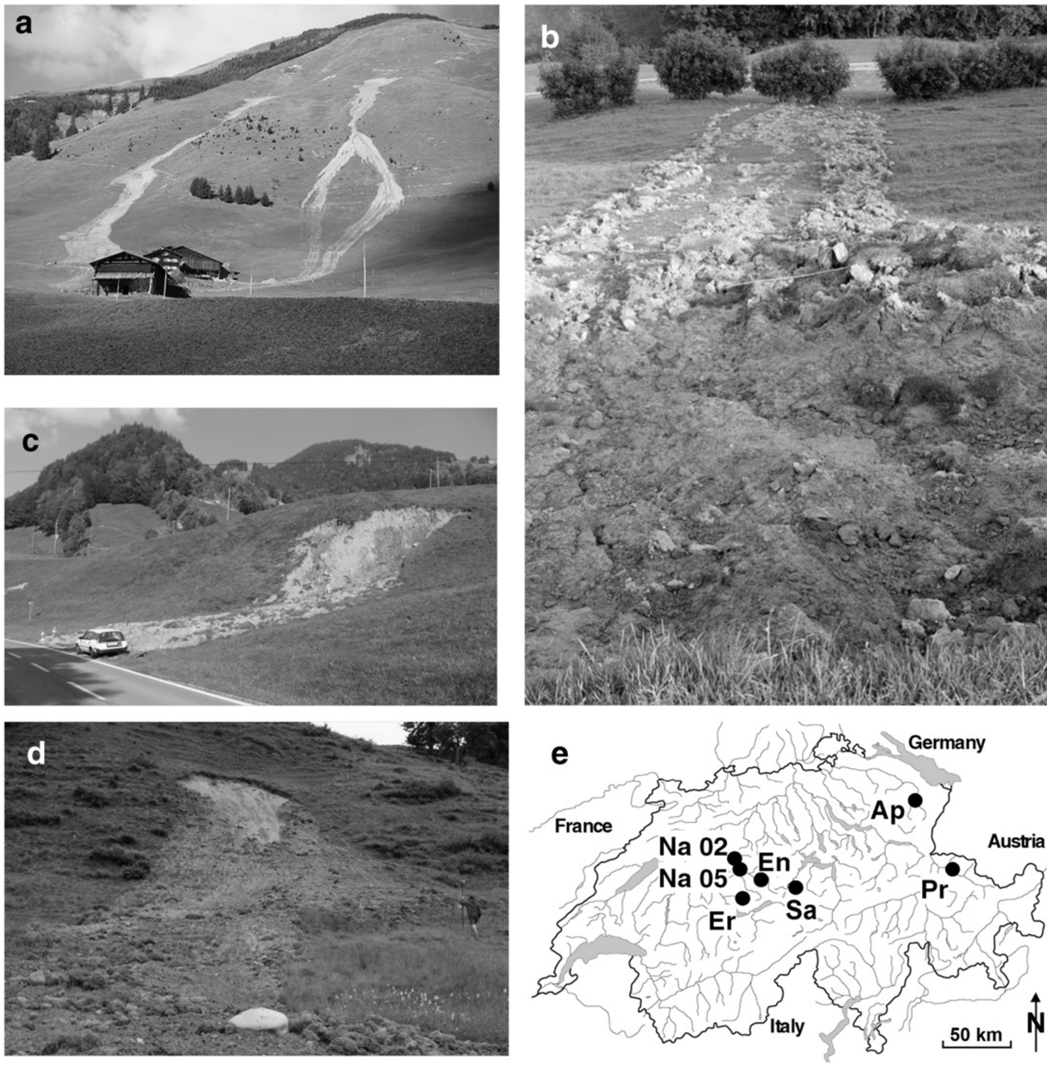

Fig. 1. Hillslope debris flows that occurred in a) the Prättigau area in 2005, b) the Appenzell area in 2002, c) the Entlebuch area in 2005, and d) the Eriz area in 2012. e) Location of areas dealt with in the seven landslide inventories (the labels correspond to the first two letters of the inventory area).

USGS large-scale flume experiments were presented (Iverson et al., 1997). Recently, field observations and laboratory experiments improved the understanding on the transformation from a shallow slide into a hillslope debris flow (Gabet and Mudd, 2006; McKenna et al., 2012). In contrast to the points 1) and 2) noted above, the kinematics of hillslope debris flows has only rarely been analysed (e.g. Bugnion et al., 2012; Loup et al., 2012), because the major focus in debris flow research has been directed to channelized flows.

In contrast to other mass movement types, there are not many detailed inventories on hillslope debris flows available. After the 1982 rainstorm in the California Bay Region, the mobilization of shallow landslides into hillslope debris flows was analysed (Ellen and Fleming, 1987). Also in Canada, several inventories were established, but many times a distinction between channelized and open-slope debris flows was not included (Hungr et al., 2008; Guthrie et al., 2010). The catastrophic events in 1998 in the Campania Region (Italy) were also analysed in detail focussing on the initiation zone and the so-called "apex angle" used for the characterisation of relevant geomorphological parameters (Guadagno et al., 2005). Finally, multiple-occurrence regional landslide events in New Zealand were described in a hazard-management context (Crozier, 2005).

The runout behaviour of landslides and debris flows has been investigated by different methods, which have recently been reviewed (e.g. Hungr et al., 2005; Rickenmann, 2005; Hürlimann et al., 2008). On one hand, datasets obtained from field observations were used to establish empirical relationships to predict runout as a function of other parameters. Not only the relationship volume versus runout was analysed (e.g. Rickenmann, 1999), but also the correlation between landslide area and volume (e.g. Larsen et al., 2010). On the other hand, back-analyses of past events were performed using numerical models. In addition, laboratory experiments were carried out to study the kinematics of the moving mass. However, these experiments have seldom focused on hillslope debris flows, but instead on channelized debris flows and other mass movements (e.g. Denlinger and Iverson, 2001; Lacerda, 2007; D'Agostino et al., 2010, 2013). In summary, the behaviour of hillslope debris flows and channelized debris flows in terms of travel distance and basic dynamics has rarely been investigated and no comprehensive comparison has been carried out. It is reasonable to expect that hillslope debris flows would have shorter runout distances than an equivalent channelized debris flow due to lateral spreading and thinning of the flow.

The main purpose of this work was twofold. First, the database of seven landslide inventories established in Switzerland were analysed focussing on morphometric factors and especially on the runout characteristics. Second, the runout characteristics of hillslope debris flows were investigated by laboratory experiments. In these experiments, the effect of water content, grain-size distribution and volume on the runout characteristics was studied. Finally, empirical relationships on