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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, the grain-size distribution and the 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 178 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 m² to ~1500 m². 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 dm³, 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.

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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, the grain-size distribution and the 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 178 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 m² to ~1500 m². 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 dm³, 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 material at steep slopes (Figure 1). 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.

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 phenomena 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 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 point 1) and 2), 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 landslide 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 regarding hazard management (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 side, datasets obtained from field observations were used to establish empirical relationships to predict runout as a function of other parameters. On the other side, 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 never 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).

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. An additional objective of the study was to investigate the application of the results to improve the hazard assessment of hillslope debris flows.

2. Analysis of the field data

2.1. Description of the inventories

A systematic inventory of shallow landslides and hillslope debris flows was established for the first time in Switzerland after the catastrophic slope failures in the Sachseln area, Central Switzerland, in August 1997 (Rickli, 2001). Since then, important major rainstorms occurred in different parts of Switzerland in 2002, 2005 and 2012, all of which produced many landslides and hillslope debris flows. Thus, a total of seven inventories with very detailed and comprehensive field measurements and observations are available.

The landslide inventory areas are located in the Pre-Alps and Alps of Central and Eastern Switzerland (Figure 1e) and are representative of mountainous regions affected by shallow landslides and hillslope debris flows. The perimeters of the inventories cover areas from 1.6 to 10.2 km² and have mean

elevations between ~900 and ~1250 m asl. The inventories are located in the main tectonic units of the Molasse Basin, Subalpine Molasse or the Alps (Labhart, 2004). The Sachseln 1997 slope failures occurred in the Helvetic Nappes (tectonic unit: Alps), which principally consist of limestones, marls and sandstones. The Appenzell 2002 slope failures were located in the Lower Freshwater Molasse (Subalpine Molasse) with predominantly alternating sequences of conglomerates, sandstones and marls. The Napf 2002 and 2005 inventories occurred in the Upper Freshwater Molasse of the Molasse Basin with similar lithologies cropping out as in the Lower Freshwater Molasse. In contrast, the Prättigau 2005 inventory area is situated in the tectonic unit of the Alps and the Prättigau Flysch is visible in outcrop and mostly consists of limestones, sandstones and marls. Finally, the Eriz 2012 landslides took place in the Lower Freshwater Molasse (Subalpine Molasse), where the predominant lithologies are marls, sandstones and conglomerates. The bedrock in all study areas is discontinuously covered by surficial quaternary deposits of fluvial, colluvium or sediments of glacial origin. The Napf and Appenzell areas have strongly been shaped by fluvial erosion and hillslope processes, because these regions have mostly been glacier free during the Last Glacial Maximum. In contrast, the Entlebuch, Eriz and Prättigau areas have been affected by glacial erosion with resulting moraines.

The rainfalls that triggered the landslides in the different test areas can be distinguished into two types. First, the 1997, 2002 and 2012 rainfalls, which can be classified as convective thunderstorms with limited aerial extent and high intensities (e.g. 150 mm in 2h for the Sachseln rainfall, Rickli and Graf, 2009). Second, the 2005 rainfalls, which can be described as a rainfall with moderate to high intensities covering extensive areas (e.g. 236 mm in 4 days for the Napf and Entlebuch rainfall, Raetzo and Rickli, 2007).

Details on the inventories and the data collection procedure are extensively described by Rickli et al. (2004), Rickli and Graf (2009) or Steinemann (2013). All the inventory landslides have been visited in the field in the subsequent weeks after their occurrence. The position, width, length, area, soil characteristics and land use, among others, were determined by GPS, visual observation and direct measurements. Only slope failures not affected by road cuts or river erosion were considered and the minimum volume of the shallow landslides was set to 20 m³ in the 1997 inventory, 30 m³ in the 2002 and 2005 datasets and 13 m³ in the 2012 inventory.

In summary, a total number of 548 slope failures are included in the seven inventories (Table 1). The failures of special interest such as landslides with information on the runout distance or with soil samples were sorted into three classes: 1) shallow landslides not transformed into flows, 2) partly transformed

landslides; and 3) shallow slides totally transformed into hillslope debris flows. This classification was performed using the definitions proposed by McKenna et al. (2012) and the information on each slope failure, which included photographs, geomorphologic sketches of the location, orthophotos, etc. Some inventories have been analysed to study the effect of the forest on the slope failures (Rickli and Graf, 2009), to validate numerical models on shallow landsliding (Lehmann and Or, 2012), or to generate susceptibility maps (von Ruetten et al., 2011). However, no specific research has been carried out on the runout characteristics.

2.2. Characteristics of the soils involved

A total of 41 samples were collected during the field campaigns in the seven test areas (Table 1). At each location, 15 to 25 kilograms of material were extracted from the soil layer at the base of the main scarp. All the soil samples were analysed in the laboratory to characterise and classify them.

The grain size distribution curves (Figure 2a) indicate that the soils have clay contents between ~3 % and more than 25 % and fines (clay and silt) ranging from about 17 % to values exceeding 80 %. Average values of grain size, water content and Atterberg limits are listed in Table 2 for each of the seven test areas. The average water contents generally range from 20 to 38% and the soils are characterised by a rather low plasticity index between 10 and 15%. The USCS-classification of the samples showed that the slope failures occurred in a large variety of soil types including fine-grained clayey and silty soils (e.g. CL or ML) to sandy (e.g. SM) or even gravelly (e.g. GM) soils.

A comparison of the soil properties obtained in this study with similar datasets showed that both the amount of clay and the plasticity index are rather similar with the samples of San Francisco Bay (Ellen and Fleming, 1987). A similar study was performed for eight slope failures in Central California (Gabet and Mudd, 2006). They also proposed that the mobilization from the initial slide into a hillslope debris flow is related to higher (> 45 %) sand fraction of the soils. In our study, however, no effect of grain size on the degree of transformation could be observed (Figure 2b).

2.3. Morphometric features

Information on almost all morphometric parameters was available for the 548 slope failures. Figure 3 shows the histograms of some principal parameters like failure volume, width, length, slope angle, plan

curvature or thickness. These parameters were subsequently used to design the artificial hillslope for the laboratory experiments.

The morphometric parameters indicate that the hillslopes mostly failed as shallow translational slides of up to 400 - 500 m³ at a terrain slope angle between 25 and 45°. The most frequent volumes involve 30 to 250 m³, with an median value of 86 m³ (Figure 3a). Only ten failures mobilized a material volume exceeding 1000 m³ and only one exceeded 5000 m³. Entrainment of material along the runout path is not taken into account because most hillslope debris flows in our database were typically un-channelized, open-slope flows which generally did not significantly erode the underlying grassland (Figure 1).

The investigation of the geometry shows that the median width of the initial slope failures is 12.5 m (Figure 3b). The length of the initial failures has a median value of 17.9 m (Figure 3c), which gives a width to length ratio of about 0.7. The thickness of the initial failure is mostly less than 1.5 m and has an median value of 0.8 m (Figure 3d). The planform curvature, which represents a slope-parallel topographic profile, is mostly linear (60%) and less frequently concave or convex (about 20% each; Figure 3g). This confirms the observation that the mass movements typically were open-slope failures.

The slope angles of the failure plane range from 19° to 50° and have an median value of 35° (Figure 3e), while the slope angles of the downslope area (transit and deposition zones) span a larger range and the histogram is slightly skewed to the left (Figure 3f).

2.4. Runout distance and affected area

Information on the runout distance is only available for 250 failures (Table 1), because this parameter was not measured in the largest inventory (Sachseln). The initial runout dataset was carefully studied and finally seventy-two entries had to be discarded because the natural runout behaviour of the movements was strongly affected by events flowing into a principal torrent (n=68), which greatly increased the maximum runout distance. Moreover, some stopped at an infrastructural obstacle (n=4), which strongly reduced the runout. Thus, the final dataset for the runout analysis contained 178 open-slope (not channelized) failures (Figure 4a).

The runout distances in the final dataset are mostly smaller than 100 m and range from 7 m to 467 m with a median of 45 m (Figure 4a). Although a large degree of scatter is present in the data, the trend of increasing mobility for larger volumes is clearly visible (Figure 4b). The relatively poor correlation is due to a number of factors including natural variation in internal and basal friction, topographic constraint

along the runout path (e.g. decrease in slope angle) and the fact that different types of processes are involved. Thus, the failures in the dataset were distinguished into the different classes: 1) shallow landslides completely transformed into hillslope debris flows, 2) partially mobilized landslides, and 3) not transformed landslides. This classification clearly reveals that hillslope debris flows have a larger runout distance than not transformed shallow slides. The relations between maximum runout distance and volume were fit using power-law regressions (Table 3). The exponents of the three types of processes in Eq. (1), (2) and (3) are relatively constant (~ 0.45), but slightly larger than the ones proposed for debris flows in other studies (Rickenmann, 1999; Legros, 2002), where the exponents are between 0.33 and 0.39 (see Section 4.2). Comparing different datasets on runout distances is sometimes difficult because the procedure to calculate the runout distance can differ from one study to another. Herein the runout was determined for each slope failure in the field by measuring the distance from the highest point of the failure to the lowest point of the accumulation; and then this value was transformed to a horizontal runout distance for comparison with data from other studies.

[Table 3 which includes Eq. 1 – 4 should be inserted near here]

Besides the maximum runout distance, the affected area of landslides is another important topic for hazard assessment and zonation. Because the affected area was not measured during the field surveys, this parameter was later determined using post-event orthophotos to calculate the planimetric area. The affected area of 63 selected hillslope debris flows was calculated in the Entlebuch and Prättigau sites (2005 slope failures) and the Eriz site (2012 slope failures, Table 1). The areas range from 87 m^2 to 9460 m^2 with an average of 1140 m^2 (Figure 5) and the relation between the affected area, A_{field} , and the volume, V_{field} , can be expressed by the best-fit power law

$$A_{field} = 30.7 V_{field}^{0.70} \quad (5)$$

with a coefficient of determination R^2 of 0.54.

3. Laboratory experiments

The laboratory tests focussed on the influence of three different factors—soil water content, grain-size distribution and mobilised volume—on the runout characteristics of hillslope debris flows. Special attention was given to the maximum runout distance, but also the width and area of the deposit were

analysed. A total of 75 experiments were performed in the laboratory at the WSL, of which 17 were preliminary runs to test the set-up and the material mixtures and 58 runs were made for the final analysis.

3.1. Experimental set-up and procedure

The design of the experimental hillslope consisted of four parts (Figure 6): 1) a 0.54 m long and 0.4 m wide storage container (also called “head box”) with an inclination of 30°, 2) a 4.46 m long and 1.2 m wide steep runout zone with a slope of 30°, 3) a 2.5 m long and 1.2 m wide lower-angle runout zone with an inclination of 10°; and, 4) a retention basin. The roughness of a natural hillslope was approximated by a standard anti-slip mat with a studded structure (manufactured by AGOFORM GmbH; www.agoform.de). The studded structure with circular elevations (diameter of ~3.6 mm, height of ~0.25 mm and a spacing of 1.5 mm in flow direction and 2.5 mm perpendicular to the flow direction) was selected because it adequately induced a realistic-appearing basal friction during preliminary tests where we compared different artificial roughness configurations, and because it was easy to clean after each experiment.

The geometric scaling factor between the laboratory experiment and the prototype (field measurements) was defined to be 20, i.e. a characteristic length scale in the laboratory hillslope is 20 times smaller than in reality (prototype or field scale). A summary of the most important laboratory parameters and a comparison with the data collected in the field is listed in

Table 4.

Flow depth and travel time in the laboratory were determined using four laser devices spaced along the channel centreline on the steep runout zone (Figure 6). They were triggered by the opening of the box gate and recorded for 20 seconds at 2000 Hz. The flow depth is apparent from the change in distance from the laser and the travel time between the sensors was used to calculate the front velocity. Herein, the laser data were not used extensively because the focus of this work was on the effect of water content, grain-size distribution and volume on the runout characteristics. The flow behaviour was recorded using a camcorder and selected runs were also recorded using a high-speed camera. The deposits of some experiments were analysed using a terrestrial laser scanner (FARO Focus 3D) or a multistation (LEICA MS50) to document the morphologic features of the deposits. Because the accuracy of these devices was in the range of a few millimetres and many deposits had a thickness of up to 1 centimetre, only runs with relatively thick deposits could be analysed using this method. Therefore, manual measurements of the runout distance and the deposit width (at 0.2 m intervals) were made after each run, and the thickness of the deposit was measured at some points. In addition, a sketch of the deposit shape was drawn after each run.

The procedure of the experiments was identical during the entire laboratory work. First, the sediment mixture was prepared in a bucket by adding the desired amount of water and then the solids starting with the fine fraction and ending with the coarsest particles. The mass was continuously mixed using a drill-mounted paint mixer, until a homogeneous consistency was reached. Then, the mixture was filled into the head box as quickly as possible and the gate was opened manually. The time from the start of mixing to the material release was typically about 3 to 5 minutes. The water and sediment mixture was close to laboratory temperature, measured at 18 degrees Celsius during several experiments.

3.2. Experimental sediment mixtures

The laboratory tests were performed with volumes ranging from 4 to 20 dm³ and water contents between 18 and 38% by weight (Table 5). Four different grain-size distributions were utilised to analyse the effect of the clay amount and the content of fines on the runout behaviour of the flows. The sediment was constructed from five parent mixtures including crushed (angular) medium to fine gravel and coarse to medium sand, and a natural clay-silt mixture, which was also used in previous experiments in the same

laboratory (Scheidl et al., in press). The mineralogical characteristics of the clay fraction were determined by X-ray diffraction at 53% smectite, 24% kaolinite and 22% illite (Ottner, 2010).

A comparison between the laboratory and the field data shows that the four grain-size distributions used in the tests generally contain less fines than the samples collected in the test areas (Figure 7a). However, the selected range of water content during the laboratory tests (18–38 %) are nearly identical to those measured in the field samples (17–38%).

Our selection of the grain-size distribution and the water content in the laboratory mixtures is also supported by the definition of McKenna et al. (2012), who distinguished hillslope debris flows (“flow”) from shallow landslides (“slide”) by the content of fines and the dry density (Figure 7b) applying a dry density threshold. Using their definition, our experimental mixtures are in the “flow” domain, with the exception of one run of mixture A, which has a comparatively large dry density.

The volume was also varied during some of the laboratory experiments (Table 5). The majority of the runs were carried out with a bulk volume of 4 dm³, with another series made using a bulk volume of 10 dm³. In addition, grain-size distribution C with a water content of 0.28 was used to investigate the influence of failure volume on the runout characteristics with bulk volumes ranging from 4 to 20 dm³.

3.3. Laboratory results

3.3.1 Hydrographs and morphologic features of the deposits

The flow hydrographs from the laboratory experiments showed realistic morphological features including a sharp front and secondary surges. The hydrographs of experiment with a volume of 12 dm³, 28% water content and the grain-size distribution C was selected to illustrate some features (Figure 8). The sharp front is clearly visible at the four laser positions, while secondary surges can be observed especially in the two most downslope positions (L3 and L4). A total of three secondary surges were observed at L4.

During some experiments the sediment deposit was remobilized after an initial stop. This behaviour occurred generally only in the low viscosity mixtures within a few seconds to minutes. Occasionally the remobilization was associated with the reactivation of a secondary surge in the deposit, at other times the remobilization was not associated with any obvious morphological features. The effect of remobilization especially affected the maximum runout distance sometimes increasing it up to 0.5 m or 1 m in an exceptional case. Intermediate front stopping locations were not systematically recorded.

The morphologic features observed during the experiments strongly depended on the grain-size distribution and water content selected for the mixtures. The shape of the accumulated material was

generally an elongated lobe (Figure 9a), although a bifurcation of the front into two tongues was occasionally observed. The distal end of the deposit was characterised by a well-defined front (Figure 9b). A segregation and accumulation of the coarse particles was observed in the distal part of the deposit and in the lateral levees (Figure 9b and c). Lateral levees were observed in most of the runs, except the ones with short runout (relatively strong viscous behaviour) and consequently relatively little grain-size sorting. Some runs reached the lower-angle part of the laboratory hillslope. There, the abrupt change in slope from 30° to 10° strongly altered the flow kinematics and behaviour: the velocity markedly decreased and flow width slightly increased. The final accumulation at this low-angle slope often had a circular or ellipsoid shape with morphological ridges (Figure 9d), which are also sometimes observed in the field in the central part of the deposit (probably analogous to pressure ridges, e.g. Johnson and Rodine, 1984).

3.3.2 Effect of grain-size distribution and water content on runout characteristics

One of the major goals of the laboratory experiments was on the effect of grain-size distribution and water content on the runout characteristics. This aspect was investigated by a series of runs with a constant bulk volume of 4 dm⁴. For each of the four grain-size distributions, at least five different water contents were used. Runout increased with increasing water content (Figure 10a). Small variations of the water content are associated with large changes in the maximum runout distances. This effect was especially apparent in grain-size distributions containing relatively small amounts of clay and silt (mixtures A and B). The influence of water content on runout was weaker in the mixture with the largest amount of clay and silt (mixture D). The influence of the slope change from 30° to 10° is clearly illustrated using the results of mixture A: after the reduction in slope the change in runout distance with increasing water content is subdued in comparison with the experimental runs, which stopped on the steep section. The relation between water content and maximum runout distance was approximated using an exponential function (Table 6). Note that for the runs using grain-size distribution A, the two largest runout distances were not taken into account due to the strong influence of the slope change mentioned above. Nevertheless, the results from grain-size distribution A was the only series of runs with a coefficient of determination R^2 considerably smaller (0.84) than the R^2 -values of the other grain sizes (between 0.98 and 0.99). The relation between water content and runout is similar to the exponential trend controlling water content and yield shear strength (e.g. Major and Pierson, 1992; Sosio et al., 2007). The

results of our experiments also coincide with the findings of D'Agostino et al. (2010), who analysed the effect of water content on the mobility of debris flows in their “dynamic runs.”

In additional experiments, grain-size distributions A and C were tested with a bulk volume of 10 m³ (Figure 10b) and similar trends were observed as in the 4 dm³ runs. However, larger runout distances were measured (see next section). The experiments of 10 dm³ volume again reveal an exponential relation between water content and runout (Table 6).

[Table 6 which includes Eq. 6 – 11 should be inserted near here]

An unambiguous positive linear correlation between the water content and both width and affected area was observed for each grain-size distribution (Figure 11). As for the relation between water content and maximum runout distance, the effect of the water content is more pronounced for the grain-size distributions with smaller contents of clay and silt than for the other sediment mixtures. The maximum widths of the material accumulated on the laboratory hillslope ranged from 0.47 m to 0.58 m. Video images and photographs of the final deposit (Figure 9a) indicate a rapid lateral expansion just downslope the head box.

3.3.3 Effect of volume on runout characteristics

Scale effects in landslide research is a well-known topic and many have reported a relation between volume and both maximum runout distance and affected area (e.g. Corominas, 1996; Rickenmann, 1999; Legros, 2002). To explore this effect we selected grain-size distribution C with a water content of 28% as the base mixture (Figure 7b) for a series of 17 experiments with volumes from 4 dm³ to 20 dm³. As expected, the maximum runout distance increased with volume (Figure 12Figure 12a). However, this increase is mostly clearly visible for runs that stopped on the steep (30°) part slope, while only a slight positive effect of larger volumes on the runout was observed in the lower-gradient (10°) section. The effect between volume, V_{lab} , and maximum runout distance, L_{lab} , can be approximated by a power-law relation, first for the experiments that stopped at 30°

$$L_{lab} = 0.56 V_{lab}^{0.77} \quad (12)$$

with a R^2 – value of 0.95, and subsequently for all the experiments ($R^2 = 0.93$)

$$L_{lab} = 0.74 V_{lab}^{0.63} \quad (13)$$

In addition, the relation between the volume and the affected area was analysed (Figure 12b), which can be expressed by

$$A_{lab} = 0.19 V_{lab}^{0.95} \quad (14)$$

where A_{lab} is the affected area ($R^2 = 0.97$). As in the relation between volume and runout, the affected area is also somewhat influenced by the slope change along the laboratory hillslope. Finally, the relation between volume and the maximum width of the flow is plotted (Figure 12b). The maximum width is typically located in the first third of the deposit and the width increases with volume.

4. Discussion

The prediction of runout characteristics (including runout distance, area, width,) is important for landslide hazard assessment (e.g. Fell et al., 2008). In contrast to channelized debris flows, field and laboratory data on the runout of hillslope debris flows is uncommon. First, we compare our laboratory and field results, including data from other studies, to explore their generality. Then we describe the sensitivity of laboratory runout distance to landslide volume, water content, and clay content, which may be helpful in applying these results to field problems.

4.1. Comparison between laboratory and field data

To compare the laboratory runout distance and inundated areas with the field data, the values obtained from the experiments have to be scaled up by a factor of 20 to obtain prototype values. First, the relation between prototype volume, V_{pro} , and prototype maximum runout distance, L_{pro} , was compared with the field data. Only the events defined as hillslope debris flows in the field datasets were considered (see Eq. 1) and compared with the prototype values of the laboratory experiments. The relation between the prototype volume and runout can be given by

$$L_{pro} = 3.34 V_{pro}^{0.63} \quad (15)$$

which has a R^2 -value of 0.93. The results shown in Figure 13a overlap and have similar trends, indicating that the laboratory experiments may be an appropriate method for exploring the runout of hillslope debris flows. However the best-fit power law curve of the laboratory experiments has a somewhat larger exponent in Eq. (15) and thus a larger slope on Figure 13a. This observation may have several explanations: First, the maximum volume of the experiments was smaller (at the prototype scale) than those observed in the field. Runs with a volume larger than 14 dm^3 (prototype volume of 112 m^3) rapidly stopped when they reached the lower-gradient part of the laboratory hillslope (Figure 12a), so it was not

possible to explore this problem with the current laboratory configuration. Second, the laboratory set-up might be too simplified with a steep (30°) zone that abruptly changes into a less steep (10°) part, whereas longitudinal profiles in the field are characterised by a more continuous convex shape, which may have produced shorter runout distances in the field. Third, the surface of the laboratory hillslope may be smoother than conditions in the field and thus enlarged runout in the steep part.

The relations between volume and runout distance obtained in this study were also compared with other data (Figure 14a). Channelized debris flows and also landslides from worldwide datasets (Legros, 2002) have a proportionally longer runout than the hillslope debris flows analysed in this study. In contrast, the relation between volume and debris-flows runout on the fan (Rickenmann, 1999) fits rather well with the runout of hillslope debris flows.

In a second step, the relation between volume and affected area was studied. This topic was recently reviewed in Scheidl and Rickenmann (2010), who compared many different datasets by the general power-law equation

$$A = k_B' V^\beta \quad (16)$$

where k_B' is an empirical coefficient and β the exponent. The laboratory data of our study can be expressed by this equation as

$$A_{pro} = 10.4 V_{pro}^{0.95} \quad (17)$$

where A_{pro} is the prototype value of the affected area ($R^2 = 0.97$). The comparison of the laboratory results with the field measurements shows again a larger slope for the laboratory experiments (Figure 13b). While the β - value of the field dataset is 0.7 (Eq. 5), which is close to 2/3 and the concept of geometric similarity proposed by Iverson et al. (1998), the β - value of the laboratory data is larger, approaching a value of 1. If the exponent β is fixed at a value 2/3 to retain natural dimensions in the power law equation, only the coefficient k_B' needs to be fit to the data; in this case k_B' ranges from 6.2 to 44.7 for debris flows (see Table III in Scheidl and Rickenmann, 2010). Regarding our study and a 2/3 exponent, the k_B' - value of the field data is 43.6 with a coefficient of determination of 0.51, while the k_B' - value of the laboratory data is 38.7 with $R^2 = 0.93$. In Figure 14b, we compare our data with the data of debris flows in Italy (Berti and Simoni, 2007), worldwide debris flows (Griswold and Iverson, 2008) and debris flows from the Alps (Scheidl and Rickenmann, 2010), all of them determined using a β - value of 2/3. The results show that the hillslope debris flows have slightly larger affected areas than channelized debris flows, although the scatter of the raw data is significant in most of the datasets.

4.2. Sensitivity of volume, water content and clay amount to the runout distance

The understanding on how the characteristics of the initial slope failure influence the runout behaviour of hillslope debris flows is a key-point to accurately predict their runout distance. A sensitivity analysis was carried out by normalizing the results achieved by the laboratory experiments and included three parameters: 1) the water content, 2) the grain-size distribution which was characterized by the clay content, and 3) the volume. First, the relation between the water content and the runout distance was normalized using the mean water content for all the data presented in Figure 10a. Then, the same was performed for the relation between the volume and the runout distance incorporating for the data of Figure 12a. Finally, the effect of the clay content on the runout distance was analysed by normalizing the results obtained from Equations (6) – (9) assuming a constant water content of 0.25.

The results of this sensitivity analysis show that the runout distance has the largest rate of change for an increase in the water content (Figure 15). The clay content also strongly influences the runout, however in a negative correlation. Both of these relations are highly non-linear. Finally, mobilized volume has the smallest influence, showing a linear trend.

Our sensitivity analysis emphasizes only the runout behaviour and not the stability conditions or the possible transformation of the initial failure. For example, the compressibility of the initial undisturbed sediment body under deformation affects the development of the pore-water pressure field, which in turn influences the effective strength of the initial landslide mass and the style of failure (a single failure versus retrogressive multi-surge failure; e.g. Iverson et al., 1997). Our experiments were all started with a well-mixed sediment body. While it would be possible to repeat the experiments using minimally-disturbed field soil samples, it is likely that the strength of roots in a real soil sample would be proportionally too strong when scaled-up to the prototype. Our results suggest that physical scale-model experiments are helpful for understanding the runout of hillslope debris flows, however more research is necessary to better understand the influence of the initial soil condition on runout properties before the results can be unambiguously applied to the field.

5. Conclusions

In spite of the hazards associated with hillslope debris flows, research on this type of mass movement is not as widespread as on channelized debris flows for example. In particular the runout characteristics are

important for a comprehensive hazard assessment, but data and analyses on this topic are lacking in literature. This research focussed on the runout characteristics of both extensive field data gathered in seven Swiss landslide inventories and measurements using physical-scale-model laboratory experiments. The field inventories include 548 individual slope failures. About 75% of the landslides started as shallow translational slides. The maximum thickness of the failures was generally less than ~1.5 m, with a median value of 0.8 m. The initial failure had normally a volume of a few tens to a few hundreds cubic meters and was located at slope angles between 25° and 45°. Of the 250 landslides in the inventory where the runout distance was reported, 178 met our criteria for unobstructed runout and span the spectrum from short-travel landslides, which have very small runout distances and which retain much of their original structure, to fully mixed long-runout hillslope debris flows. Horizontal runout distances were analysed dividing the slope failures into three classes after their degree of transformation from a slide to a flow: 1) hillslope debris flows, 2) partly transformed slides, and 3) not transformed slides. A positive correlation between volume and runout is apparent in the field data, with a proportionally larger runout distance for hillslope debris flows than for the other two classes. Focusing on hillslope debris flows, the runout distances were normally some tens of meters for small to medium volumes, but reached as far as 450 m for large volumes. In addition, the planimetric affected area of 63 hillslope debris flows mostly ranged from ~100 m² to ~1500 m² and showed a positive trend with volume. The laboratory experiments revealed a strong influence of the water content on the runout distance of the hillslope debris flows. Even a very small increase of this parameter (e.g. 1 – 2%) markedly enlarged the runout distance because of the exponential relation between water content and runout. The effect of different grain-size distributions was also analysed and showed that an increase of clay content (e.g. 5 %) considerably augmented the maximum runout. A positive relation between bulk volume and runout was observed, however with a smaller influence than the other two factors. The comparison between our field measurements and the laboratory experiments shows that in spite of the large scatter in the field datasets the general trends are statistically similar and are also in agreement with channelized debris flows and other types of flowing landslides. The large scatter of the data in the field inventories in comparison with the laboratory experiments can be explained due to a number of factors including natural variation in internal and basal friction or topographic differences along the flow path.

The results of this study not only improve the understanding of the runout characteristics of hillslope debris flows, but also provide useful inputs in order to establish a correct hazard assessment of this common geomorphologic process. Since the volume of the initial slope failure as well as the water content and the clay amount of the involved soil layers may be determined by field observations, existing geotechnical maps and numerical models, the runout characteristics can firstly be approximated and subsequently be incorporated in the hazard zonation.

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List of Tables:

Table 1

Summary of the inventories used herein. Literature sources for the inventories are described in the text.

Test area	Date	Area	Number of events (-)			
			total	with data of	with data of	with soil
	(mm/yyyy)	(km ²)		runout distance *	affected area	samples
Sachseln	08/1997	8.2	244	0 (0)	0	9
Napf	06/2002	2.5	51	33 (23)	0	2
Appenzell	09/2002	10.2	82	76 (44)	0	5
Entlebuch	08/2005	5.1	46	42 (29)	12	4
Prättigau	08/2005	4.7	55	43 (30)	37	7
Napf	08/2005	1.6	45	42 (38)	0	5
Eriz	07/2012	9.5	25	14 (14)	14	9
Overall		41.8	548	250 (178)	63	41

*: values in brackets indicate the number of events after filtering the dataset to exclude events entering a torrent or constrained by infrastructure.

Table 2

Mean values of the soil properties determined in each test area (w_L is the liquid limit, w_P the plastic limit and IP the plasticity index).

test area	Clay content (%)	Content of fines (%)	Water content (-)	w_L (%)	w_P (%)	IP (%)
Sachseln	11.5	49.0	26.0	31.8	22.2	9.6
Napf 2002	11.8	42.8	28.8	35.0	20.0	15.0
Appenzell	18.6	64.0	25.5	29.4	15.8	13.6
Entlebuch	17.8	51.2	30.8	32.1	20.9	11.2
Prätigau	10.4	43.4	21.7	37.1	27.0	10.1
Napf 2005	7.0	30.7	17.2	32.1	23.0	9.1
Eriz	9.0	41.7	38.1	35.7	25.6	10.2

Table 3

Equations of the best power-law fits of the maximum runout, L_{field} , as a function of volume, V_{field} , for the three types of events distinguished in the final field dataset.

Type of event	Best power-law fit	R^2	Equation
Hillslope debris flows (n = 117)	$L_{field} = 7.48 V_{field}^{0.45}$	0.41	(1)
Partly transformed slides (n = 32)	$L_{field} = 4.47 V_{field}^{0.45}$	0.55	(2)
Not transformed slides (n = 29)	$L_{field} = 2.17 V_{field}^{0.47}$	0.61	(3)
Entire dataset(n = 178)	$L_{field} = 5.29 V_{field}^{0.46}$	0.32	(4)

Table 4

Summary of the parameter ranges for the laboratory experiments prototype (scaling factor is 20) and field data shown in Figure 3.

	Laboratory	Prototype	Field data*
Width of the box/failure (m)	0.4	8	12.5 (7.5)
Length of the box filling/failure (m)	0.17 – 0.5	3.4 - 10	17.9 (11.2)
Mean failure depth (m)	0.05 – 0.11 ⁺	1.0 – 2.2	0.8 (0.5)
Volume (m ³)	0.004 – 0.018	32 – 144	86 (344)
Slope angle of runout path (°)	30	30	35 (8.0)

* median value and standard deviation (in brackets)

⁺ average value of triangle shape mixture in the box

Table 5

Parameters of the different mixtures used in the experiments.

Name of GSD*	Clay content (%)	Content of fines (%)	Water content (-)	Dry density (g/cm ³)	Mixture density (g/cm ³)	Bulk volume (dm ³)
A	5.2	22.4	0.18 - 0.22	1.52 - 1.68	1.94 - 2.04	4, 10
B	7.8	30.4	0.23 - 0.255	1.39 - 1.48	1.87 - 1.92	4
C	10.4	38.3	0.24 - 0.3	1.24 - 1.44	1.77 - 1.90	4 - 20
D	15.7	54.1	0.31 - 0.38	1.01 - 1.21	1.63 - 1.75	4, 10

* GSD stands for grain-size distribution

Table 6

Equations of the best exponential-law fits of the maximum runout observed in the laboratory experiments, L_{lab} , versus water content, w , for the four grain-size distributions (*GSD*) mixtures and volumes.

Type of <i>GSD</i>	Volume (dm ³)	Best exponential-law fit	R ²	Equation
A	4	$L_{lab} = 8 \cdot 10^{-6} e^{61.2 w}$	0.84	(6)
B	4	$L_{lab} = 4 \cdot 10^{-7} e^{63.5 w}$	0.98	(7)
C	4	$L_{lab} = 1 \cdot 10^{-5} e^{42.6 w}$	0.98	(8)
D	4	$L_{lab} = 1 \cdot 10^{-4} e^{27.6 w}$	0.99	(9)
A	10	$L_{lab} = 6 \cdot 10^{-5} e^{54.1 w}$	0.98	(10)
C	10	$L_{lab} = 1 \cdot 10^{-3} e^{27.2 w}$	0.94	(11)

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

Figure 2. a) Grain size distribution of the samples collected in the field illustrated by curves. The legend indicates the year and the first two letters of the inventory area (cf. Table 1 and Figure 1). b) Ternary diagram with the data plotted for landslides not transformed into hillslope debris flows, partly transformed slides and fully transformed landslides.

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652 Figure 3. Histogram and normal distribution of the morphometric characteristics of the slope failures in
 653 the field datasets. a) volume, b) width, c) length of initial failure, d) mean failure thickness, e) slope angle
 654 of the failure plane, f), slope angle of the downslope area; and, g) planform curvature.

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Figure 4. Maximum runout distance of the hillslope debris flows observed in the field. a) Histogram and normal distribution comparing the initial dataset and the final one, which excludes the events that entered a torrent or stopped at an artificial obstacle. b) Relation between runout distance and volume for the final dataset distinguishing between landslides, partly transformed landslides and hillslope debris flows (totally transformed slides). See Table 3 for the equations of the power-law regressions indicated in this graph.

Figure 5. Affected area of the hillslope debris flows observed in the field. a) histogram and normal distribution; and, b) relation between the affected area and volume.

Figure 6. Laboratory set-up for the experiments of hillslope debris flows. a) Geometry of the hillslope and location of the head box, the retention basin and the four point lasers (L1 - L4); b) Photograph of the set-up in the WSL laboratory.

Figure 7. a) Grain-size distribution curves of the four sediment mixtures used in the experiments with the clay content of each mixture is given in parentheses. The scaled curves of the field data are represented by the grey-shaded area. b) Dry density threshold distinguishing between flows and slides (from McKenna et al., 2012) and the property ranges of the four laboratory mixtures. The circle indicates the mixture used to analyse the volume effect on the runout distance and the affected area.

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683 Figure 8. Flow depth measured at the four point lasers (L1 – L4, cf. Figure 6a) for the experiment with a
 684 total volume of 12 dm³, 28% water content and grain-size distribution C. The mean values of 100 Hz bins
 685 (symbols) with their standard deviation (thin lines) are plotted for each laser data series.

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689 Figure 9. Morphological features observed in the deposits of the laboratory experiments. a) Oblique aerial
 690 view of the accumulation of experiment with a volume, V_{lab} , of 18 dm^3 , 28 % water content, w , and grain-
 691 size distribution, GSD , C. b) Accumulation at the leading edge of the deposit with $V_{lab} = 10 \text{ dm}^3$, $w = 26$
 692 % and GSD C. c) Levee of experiment with $V_{lab} = 10 \text{ dm}^3$, $w = 20$ % and GSD A, d) Front and pressure
 693 ridges of experiment with $V_{lab} = 10 \text{ dm}^3$, $w = 20.5$ % and GSD A.

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Figure 10. Effect of grain-size distribution (GSD A, B, C or D) and water content on the maximum runout distance observed in the laboratory experiments for bulk volumes of 4 dm³ (a) and 10 dm³ (b). The best-fit exponential curve for each GSD is shown (see Eq. 6 –11 in Table 6). The symbols surrounded by an ellipse refer to runs that stopped at the low-angle (10°) portion of the laboratory hillslope (cf. Figure 6).

Figure 11. Effect of grain-size distribution (GSD A, B, C or D) and soil water content on the affected area (a) and the maximum width (b) observed in the laboratory experiments for bulk volumes of 4 dm³. Straight lines indicate the best-fit linear relation for each mixture.

Figure 12. a) Relation between volume and maximum runout for the laboratory experiments. The two lines show the best-fit power law curves expressed in Eq. (12) and (13). The grey-shaded symbols refer to runs that stopped on the low-gradient portion of the laboratory hillslope (cf. Figure 6). b) Relation between volume and maximum width and affected area. The continuous line indicates the best-fit power law of Eq. (14). See a) for explanation of the grey-shaded symbols.

718

719 Figure 13. Comparison between laboratory experiments (prototype values) and field data (only hillslope
 720 debris flows are plotted). a) Relation between volume and runout distance. b) Relation between volume
 721 and total affected area. The confidence interval for the best-fit regression of the field data is added.

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726 Figure 14. Comparison of results from this work with data published from other studies. a) Relation

727 between volume and runout distance. b) Relation between volume and affected area.

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733 Figure 15. Sensitivity of the volume, V , water content, w , and clay content, CC , to the runout distance, L .

734 All the parameters are normalized (subscript “norm”) as described in the text. The value ranges observed

735 in the field are indicated at the bottom of the plot.

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