INTERPRAEVENT
12th Congress INTERPRAEVENT 2012 – Grenoble / France
Conference Proceedings
www.interpraevent.at

IMPACT PRESSURES OF HILLSLOPE DEBRIS FLOWS

BACK-CALCULATION AND SIMULATION (RAMMS)

Bernard Loup[1], Thomas Egli[2], Maja Stucki[3], Perry Bartelt[4], Brian W. McArdell[5] and Reto Baumann[6]

ABSTRACT

Due to sudden initiation, widespread character, limited forecasting possibilities and often high velocities, hillslope debris flows may represent a major threat for populations and goods. The impact forces exerted on constructions are poorly known; hazard assessment and planning of countermeasures remain therefore bound with relatively large uncertainties. Twenty well-documented events have been studied and the pressures reconstructed using back-calculation (pressures needed to obtain the observed damages) and numerical simulation. The results show an overall correlation between the back-calculated impact pressures and the simulated ones, especially for values in the lower pressure range (< 50 kN/m^2); the results diverge for larger values. Several events could not be properly reproduced: this is mainly due to uncertainties regarding process type, evolution of the flow and inaccuracy of input data. Better understanding of the process itself and calibration of the simulation tool are still needed for use in everyday practice.

Keywords: hillslope debris flow, hazard assessment, simulation, impact pressure, protective measures

INTRODUCTION

According to the analysis of the 2005 flood event in Switzerland (Bezzola and Hegg, 2007; Bezzola and Hegg, 2008), around 5000 superficial landslides and hillslope soil / debris flows have been triggered by the heavy rainfalls from August 2005 (Raetzo and Rickli, 2007; Rickli et al., 2008). Over 100 mm of precipitation have been recorded along the entire northern edge of the Alps in Switzerland on 21 and 22 August 2005, i.e. within a period of 48 hours. Cumulative quantities up to more than 260 mm have been measured during the same reference period in the strongly affected regions (Emmental, Entlebuch, parts of the Bernese Oberland). Rainfall intensities remained however relatively moderate (e.g. 20 mm/h). A reason for the huge consequences of the August rainfall event is the almost complete saturation of the soils at the onset of the event.

The 2005 episode is not unique in Switzerland: similar situations with large numbers of debris flow events occurred in the recent past, for instance in 1997 (Sachseln and Canton Obwald; Rickli, 2001), in 2002 (Cantons of Lucerne, Grisons, Berne and Appenzell; Rickli et al., 2004), in 2007 (west and central Switzerland; Bezzola and Ruf, 2009) and in 2008.

Due to their sudden initiation, their often widespread character, the limited forecasting possibilities and the movement in form of possibly high velocity flows, this type of processes may strongly endanger people, animals as well as infrastructure and material goods. The impact forces exerted by hillslope debris flows on constructions are largely unknown und poorly documented. Better knowledge of these processes and of their physical parameters is needed to establish accurate hazard assessments, or in order to effectively protect existing or new constructions, or to properly dimension technical countermeasures. The flow intensity - a key-parameter for hazard assessment and mapping -

---

[1] Dr. Bernard Loup. Federal Office for the Environment FOEN, 3003 Bern (e-mail: bernard.loup@bafu.admin.ch)
[2] Dr. Thomas Egli. Egli Engineering Ltd, Lerchenfeldstrasse 5, 9014 St. Gallen
[3] Maja Stucki. Egli Engineering Ltd, Lerchenfeldstrasse 5, 9014 St. Gallen
[4] Dr. Perry Bartelt. WSL-SLF, Flüelastrasse 11, 7260 Davos Dorf
[5] Dr. Brian W. McArdell. WSL, Zürcherstrasse 111, 8903 Birmensdorf
[6] Reto Baumann. Federal Office for the Environment FOEN, 3003 Bern

needs to be better understood, both qualitatively and quantitatively. Only a reliable hazard assessment can ensure appropriate implementation of the hazard maps with corresponding risk reduction (land-use planning, technical countermeasures, organizational measures such as preventive evacuation, etc.).
The Swiss Federal Office for the Environment, together with the Egli Enginnering Ltd and the Swiss Federal Institute for Forest, Snow and Landscape WSL has launched a research project in 2008 on these topics.

OBJECTIVES

The main goal of the project is to identify the intensities and stresses exerted on constructions by hillslope debris flows based on real events with documented damages. The following questions should be answered by the end of the project:

1. Which forces lead, by various construction types to which consequences (no damage, partial damage, total damage)?
2. Which relationship can be found, if any, between these forces and the intensity criteria used at present in hazard assessment and mapping (thickness of the possibly unstable layer, thickness of the slide/flow deposit; e.g. OFAT et al., 1997; see Tab. 1)? Is there a need to adapt or to complete the mentioned intensity criteria to ensure a more accurate and reliable hazard mapping?

Tab. 1 Intensity criteria for earth flow / hillslope debris flows (DF) according to the Swiss guidelines. The criteria for snow avalanches (A) (BFF and SLF, 1984) are shown for comparison purposes (see part 'Discussion')

Criterion	Low intensity	Medium intensity	High intensity
DF: thickness of the unstable layer (e)	$e < 0.5$ m	$0.5 < e < 2$ m	$e > 2$ m
DF: thickness of debris deposit (h)	--	$h < 1$ m	$h > 1$ m
A: pressure (P)	$P < 3$ kN/m^2	3 kN/m^2 < P < 30 kN/m^2	$P > 30$ kN/m^2

3. Which recommendations can be issued for proper dimensioning of protective measures (in the slope, or taken directly at the object or construction)?

METHODOLOGY

Twenty well documented cases of buildings partially or totally damaged by superficial slides or hillslope debris flows have been selected (Egli Eng., 2009) and investigated (Egli Eng., 2011). Based on the structure of the building and the observed damages, back-calculations of the impact pressures or pressure domain, which likely occurred during the event, are made in a first step. In a second step, the slide / flow events are simulated to reconstruct the flow path and intensity using the numerical natural hazard simulation tool RAMMS.

Back-calculation

This part of the project has been outsourced to a structural engineer (Bächtold & Moor in Bern). The objects studied show various construction types (wood, brickwork/masonry, concrete wall, combination of several types) and damage magnitudes. Available data to reconstruct the exerted pressures are of variable quality: plans (architect and / or engineer) were sometimes available, whereas for some case studies only photos (before / after event) could be used. As a consequence, the pressures back-calculated from observed damage sometimes have a relatively large uncertainty associated with them (see the examples).

Numerical simulation

In a second step, the slide / flow events are simulated to reconstruct the flow path and intensity using the natural hazard modelling tool RAMMS (RApid Mass MovementS) developed by the "Avalanche, Debris Flow and Rockfall" research unit of the WSL Institute for Snow and Avalanche Research, SLF (Preuth et al., 2010; Schneider et al., 2010; Bartelt et al., 2011; http://ramms.slf.ch/ramms).

RAMMS is a state-of-the-art numerical simulation model to calculate the motion of geophysical mass movements (snow avalanches, debris flows, rockfalls) from initiation to runout in three-dimensional terrain. It was designed to be used in practice by hazard engineers who need solutions to real, everyday problems. New constitutive models have been developed and implemented in RAMMS, thanks to calibration and verification at full scale tests at several sites in Switzerland. These models allow the application of RAMMS to solve both large, extreme avalanche events as well as smaller mass movements such as hillslope debris flows and shallow landslides.

The RAMMS model solves the depth-averaged equation of motion for granular flows in two directions, and it uses the Voellmy rheological relation to describe the frictional behaviour of the flow. Two models can be used in RAMMS to simulate hillslope debris flows: the standard Voellmy model and the so-called extended Voellmy model (Random Kinetic Energy RKE extension).

- The *standard Voellmy* model is simple, stable and contains only two parameters (Coulomb coefficient μ and turbulent flow coefficient ξ); these aspects can be considered as major advantages. This model is however often difficult and time-consuming to calibrate, especially on constant slopes. It should not be used with a single set of parameters but with varying values applied in a calibration procedure; a well-documented historical event is required for this purpose. The fundamental problem with the standard Voellmy model is that flow friction is not well described by constant parameters. Indeed, experiments with hillslope debris flows reveals that friction changes from head to tail of the flow.

  Experience shows that this model should primarily be applied for slopes with $\mu > \tan \varphi$ (φ being the slope of the runout zone).
- The *extended Voellmy* model corrects several problems of the standard Voellmy model. It namely can describe frictional processes in hillslope debris flows by introducing a frictional process by which the Coulomb and turbulent friction coefficients change as a function of the flow speed and overburden stress. The advantage of the extended model is clearly in the stopping behaviour: depending on the choice of μ, the flow will stop on steep, constant slopes. In fact, if μ is selected too high, the flow will not even initiate. Recommendations for the model parameters are given in Table 2.

  Tab. 2 Modelling parameters recommendations for the extended Voellmy model, both for hillslope debris flows and for shallow landslides

		Hillslope debris flows	Shallow landslides
RAMMS notation		*"fluid-type"*	*"landslide-type"*
Coulomb friction [ ]	μ	0.30 - 0.40	0.40 - 0.55
Viscous-turbulent friction [m/s^2]	ξ	400 - 600	200 - 400
Density [kg/m^3]	ρ	1800 - 2000	1800 - 2000

  Extreme care should be taken when using the extended Voellmy model as it is more sensitive to the release conditions, particularly the location and volume of the starting mass: the results will depend on the magnitude of the release zone height. This is realistic, but places more responsibility on the hazard expert who must select a design release height.

  Experience shows that this model should primarily be applied for slopes with $\mu \cong \tan \varphi$ (φ being the slope of the runout zone).

In the following, three representative examples (among the twenty events studied) are presented.

EXAMPLE / ALPNACHSTAD

Event

Two houses in Alpnachstad have been damaged by several debris flows on 21 August 2005 (Fig. 1). The damaged building (marked with a circle) was protected by a wall, which suffered relatively little damage in the form of cracks. The house is situated at the foot of a steep pasture where six debris flows were triggered by the heavy rainfalls; two debris flows hit the house. The thickness of the unstable layer was near 0.5 m whereas the thickness of the deposit pressed against the protective wall reached 2 m.

Fig. 1 Debris flows from August 2005 in Alpnachstad

Back-calculation

The damaged building investigated is a two-storey house, partly built "in" the slope. Uphill, basement and first floor have no openings and lie underneath the natural ground surface. The uphill wall is made of concrete and acts simultaneously as a protective wall. Pressures between 7-30 kN/m^2 have been necessary to generate the cracks observed in this wall after the flow impact.

Numerical simulation

The following input parameters have been used for the simulations:

Model	Release zone thickness [m]	Volume [m^3]	μ	ξ [m/s^2]
standard Voellmy	0.5	71	0.4	150
extended Voellmy	0.5	71	0.4	100

The simulation provided the following maximal values (see also Fig. 2 and 3):

Method	Max. pressure [kN/m^2]	Max. flow height [m]	Max. velocity [m/s]
standard Voellmy	9 - 13	0.4	2.5
extended Voellmy	47	0.25	4.8
structural engineer	*7 - 30*	--	--

Fig. 2 Debris flow simulation (Alpnachstad / extended Voellmy)

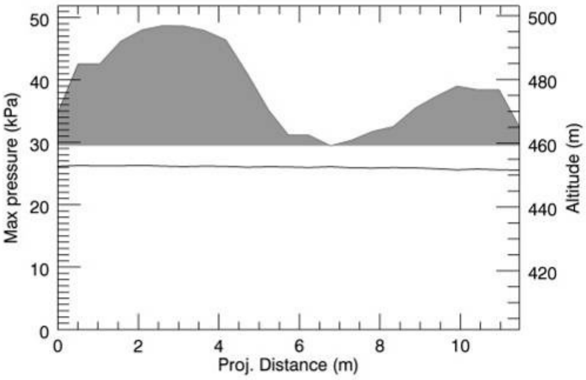

Fig. 3 Cross section of the maximal pressure distribution (along the white dotted line shown in Fig. 2) (Alpnachstad / extended Voellmy)

Comment

The impact pressures calculated with *standard Voellmy* (9-13 kN/m^2) lie in the lower part of the range specified by the structural engineer (7-30 kN/m^2); the simulated values are thus plausible but appears to be somewhat underestimated.

The simulation with the *extended Voellmy* model gives values (47 kN/m^2) which appear to be overestimated. Pressures of this order of magnitude would have led to much greater damages than those effectively observed; the values provided by the *extended* simulation appear to be unrealistic for this example.

EXAMPLE / RÜEGGISBERG

Event

The 'Helgisried' school in Rüeggisberg has been hit by a debris flow on 6 June 2010 (Fig. 4). The material penetrated the first floor completely. As the event occurred on a Sunday, fortunately nobody was killed or even injured.

Heavy rainfall triggered the displacement of a 40 cm thick layer of loose material. The underlying marls und sandstones ("Molasse") acted as a detachment horizon; the Molasse was completely uncovered by the event. The width of the scar was 23 m and steepness of the slope is 38°.

In the lower gentler part of the slope the material probably slid with several meters per second on the soaked grass and saturated underground; no eye-witness accounts are available to confirm this scenario, but it is consistent with the field evidence. Two trees and bushes were also transported down the slope (see Fig. 4).

Fig. 4 School in Rüeggisberg damaged by a debris flow; the initiation zone and scar can be seen in the background

Back-calculation

The back-calculation by the structural engineer indicates that pressures should have been between 7 kN/m^2 (± 50%) and 40 kN/m^2 (± 50%).

As parts of walls were still laying on the stairs, it is assumed that the collapse occurred rather abruptly ("shockwave") and that, afterwards, pressure and streaming decreased very rapidly. If so, the value of 40 kN/m^2 (± 50%) could have been briefly exceeded, but not by a large amount.

Numerical simulation

The following input parameters have been used for the simulations:

Model	Release zone thickness [m]	Volume [m^3]	μ	ξ [m/s^2]
standard Voellmy	0.49	290	0.2	1000
extended Voellmy	0.49	293	0.7	800

The simulation provided the following maximal values (see also Fig. 5 to 8):

Method	Max. pressure [kN/m^2]	Max. flow height [m]	Max. velocity [m/s]
standard Voellmy	20	0.35	2 - 3
extended Voellmy	70	0.25	6
structural engineer	*7 - 40*	--	--

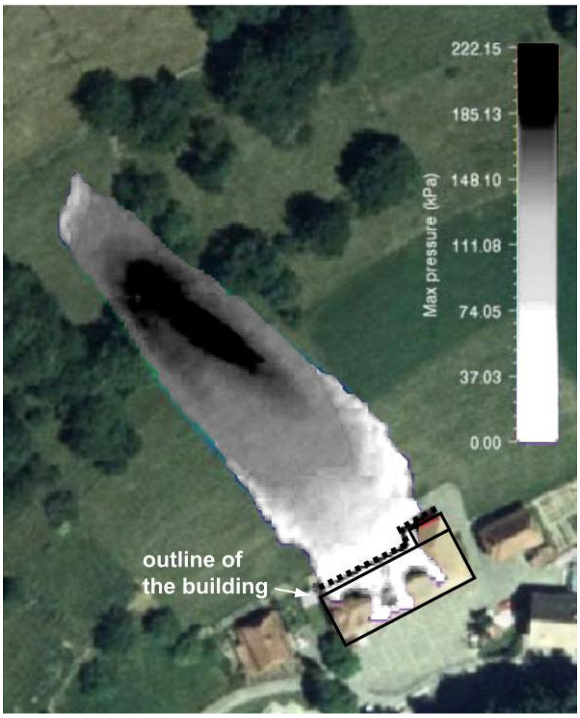

Fig. 5 Debris flow simulation (Rüeggisberg / standard Voellmy)

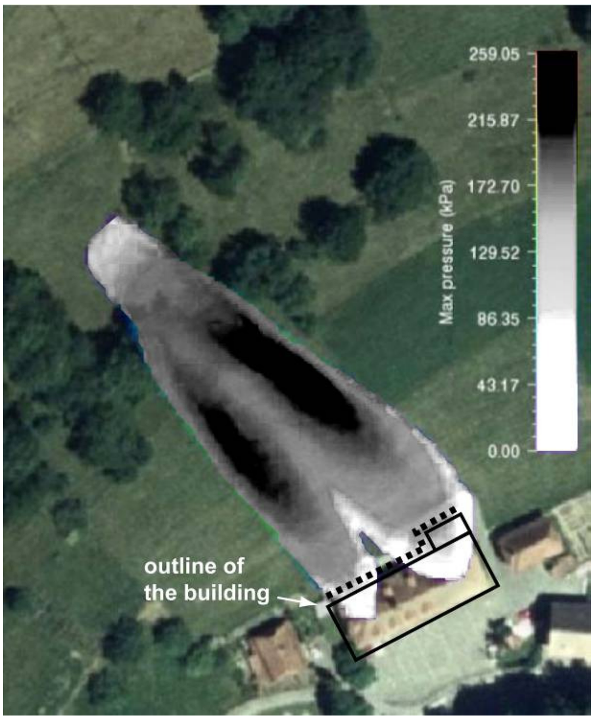

Fig. 6 Debris flow simulation (Rüeggisberg / extended Voellmy)

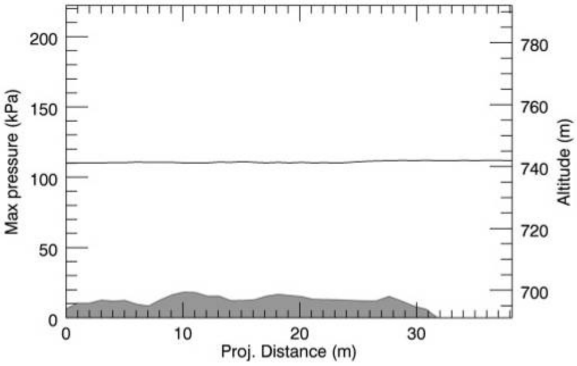

Fig. 7 Cross section of the maximal pressure distribution (along the black dotted line shown in Fig. 5) (Rüeggisberg / standard Voellmy)

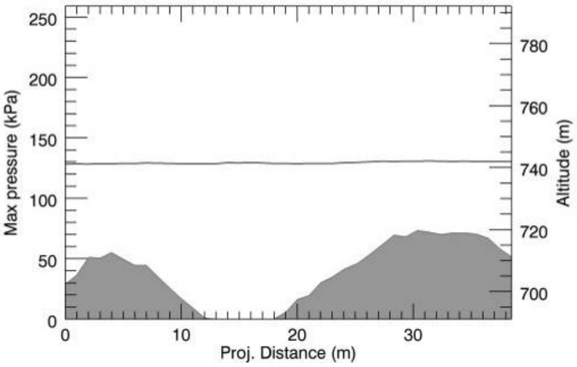

Fig. 8 Cross section of the maximal pressure distribution (along the black dotted line shown in Fig. 6) (Rüeggisberg / extended Voellmy)

Comment

The impact pressures calculated with the *standard Voellmy* model (20 kN/m^2) lie in the middle part of the range specified by the structural engineer (7-40 kN/m^2); the simulated values thus appear to be realistic.

The simulation with the *extended* model provides values (70 kN/m^2) which are clearly too large as compared to the maximal range given by the structural engineer; conversely, the flow height appears to be quite low. As a consequence the pressures provided by the *extended* simulation seems unrealistic for this case study.

EXAMPLE / KÖNIZ

Event

A house in Köniz (located in the region of Bern) has been hit by a debris flow on 8 August 2008; the adjacent barn part was also damaged. The event uprooted many trees which were carried with the flow down the slope (Fig. 9).

The barn part, which has been added in 2001, was torn away completely; this in turn pushed and displaced the roof structure of the habitation part of the house. The displaced trees caused further damages to the roof, and the earth masses to the uphill walls of the house.

As a result of all damages caused by the debris flow the whole building had to be demolished.

Fig. 9 The debris flow of 8 August 2008 in Köniz. Many trees were uprooted and probably acted as point-loads against the house

Back-calculation

According to the calculations of the structural engineer, pressures between 20 kN/m^2 (± 20%) and 35 kN/m^2 (± 50%) were required to produce the observed damages in Köniz.

Numerical simulation

The following input parameters have been used for the simulations:

Model	Release zone thickness [m]	Volume [m^3]	μ	ξ [m/s^2]
standard Voellmy	0.18	30	0.1	500
extended Voellmy	0.18	30	0.7	200

The simulation provided the following maximal values (see also Fig. 10 to 13):

Method	Max. pressure [kN/m^2]	Max. flow height [m]	Max. velocity [m/s]
standard Voellmy	20 -40	0.2 - 0.35	0.45
extended Voellmy	15 - 25	0.1 - 0.2	0.35
structural engineer	*20 - 35*	--	--

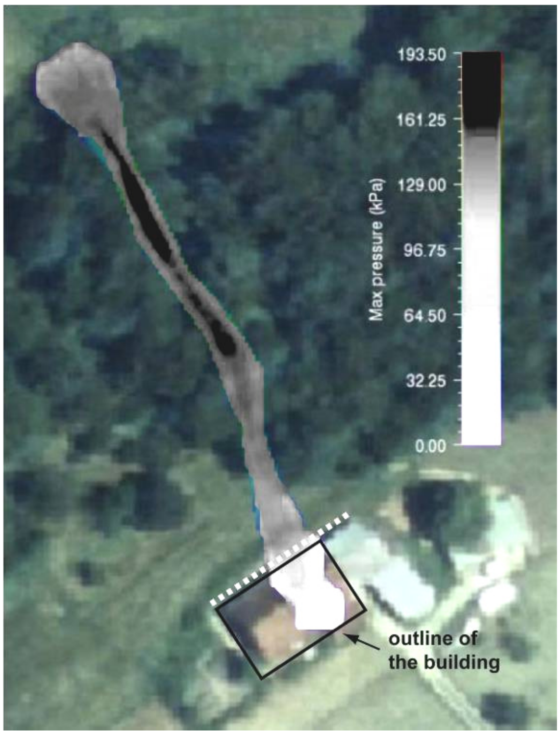

Fig. 10 Debris flow simulation (Köniz / standard Voellmy)

Fig. 11 Debris flow simulation (Köniz / extended Voellmy)

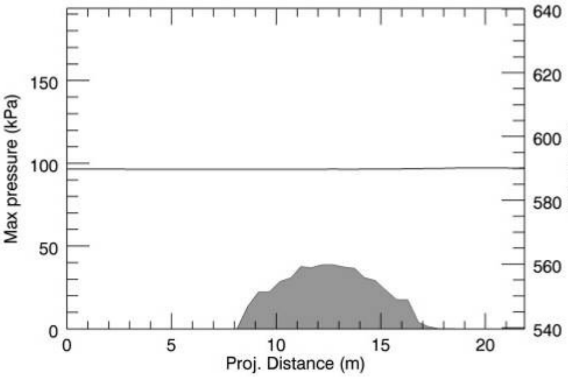

Fig. 12 Cross section of the maximal pressure distribution (along the white dotted line shown in Fig. 10)
(Köniz / standard Voellmy)

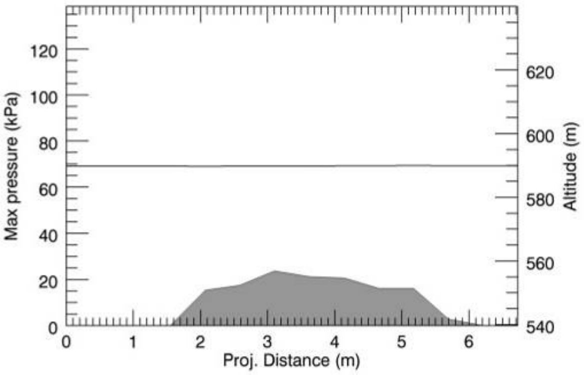

Fig. 13 Cross section of the maximal pressure distribution (along the white dotted line shown in Fig. 11)
(Köniz / extended Voellmy)

Comment

All values, from both simulation methods (*standard* and *extended Voellmy* models) as well as from the back-calculation, are in good agreement. The simulation results are hence realistic.

DISCUSSION

Back-calculation and simulation

- Events with reconstructed and simulated pressures smaller than 50 kN/m^2 show an overall good correlation of the results (12 events), as far as pressure domains and not exact values are considered (Fig. 14). For 4 examples of this set, pressures simulated with *extended Voellmy* are however overestimated by a factor 2 to 5 with respect to the back-calculation and *standard Voellmy* calculations.
- The dispersion of the results tends to increase with increasing pressures (from 50 kN/m^2 up to 100 - 150 kN/m^2) and the pressure domains (both reconstructed and simulated) also become broader (5 examples / number 7, 10, 12, 13 and 14 in Fig. 14).
- In three cases, it was not possible to achieve a realistic simulation of the event:
  - the process as simulated "missed" " the building under investigation (the runout path bypassed the buildings; examples 11 and 19 in Fig. 14). Two reasons can be evoked: the accuracy of the digital terrain model (DTM) is not sufficient and / or the process - a very liquefied mudflow with exceptionally long runout distance - lies at the limits of the simulation capabilities and physics of RAMMS;
  - in the third example (event "Flühli", not represented in Fig. 14), the slide's movement corresponds to a single mass rotation (talus slide) without much displacement; RAMMS is a runout simulation tool and was not designed to simulate such a process.
- The *extended Voellmy* model tends to deliver values generally larger than those simulated with *standard Voellmy*.
- The simulation results are very sensitive to the choice of the modelling parameters μ and ξ. Many simulations have been performed for each example. The parameters have been adapted within an iterative process until the runout distance (controlled mainly by ξ) and the starting conditions (mainly controlled by μ) best match the observations. The values needed to properly reproduce the event are sometimes to a slightly out of the range of the standard values given in Table 2 (Alpnachstad: ξ is rather low / Rüeggisberg: ξ is rather high with μ slightly over the upper range for *extended Voellmy* / Köniz: the μ values are a little low for *standard Voellmy* and a little high for *extended Voellmy*).

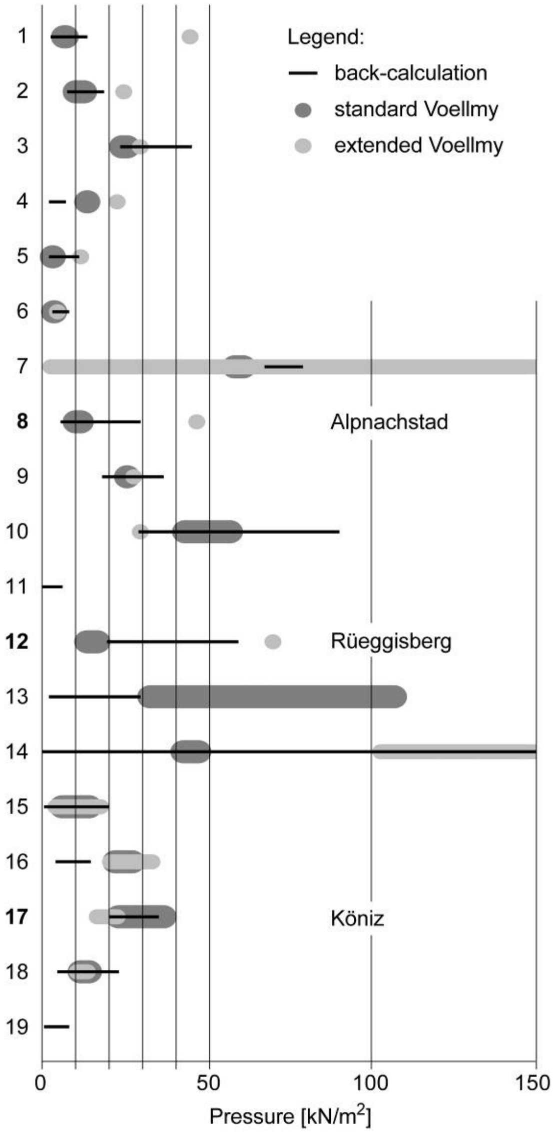

Fig. 14 Summary of the obtained pressures (back-calculated and simulated according *standard Voellmy* and *extended Voellmy*) for the studied events (note: the event "Flühli" is not represented)

Forces, construction types and damages

No trend between exerted pressure, construction type (wood, brickwork/masonry, concrete wall or combination of several types) and damage extent can be inferred from the twenty studied events. It could however be observed that unarmored brickwork/masonry walls withstand pressures up to 10 kN/m^2. Damage extent however not only depends on pressure and construction type but also in particular on the flow composition (presence of boulders and blocks, or trees acting as point-loads) and impact angle. Further analyses are needed in this domain.

Forces and intensity criteria (as used for hazard assessment and mapping)

The *e* and *h* criteria (see Tab. 1) have been applied to the twenty studied events in order to determine the process intensities and the expected corresponding damages as would be done in hazard assessment. Comparing in turn these assumptions with the effective damages shows that the *e* and *h* criteria lead to a correct evaluation of the intensity for 9 cases, to an overestimation for 4 cases, and (more problematical in terms of prevention) to an underestimation for 7 cases (35%).

The same procedure applied with the pressure criterion (as used in snow avalanches hazard assessment; see Tab. 1) gives following results: correct evaluation: 13 / overestimation: 4 / underestimation: 3 (15%).

Dimensioning of protective measures

As mentioned above, the usual criteria *e* and *h* give an overall reliable assessment of the intensity for 65% of the studied cases. If these indications can be sufficient to establish hazard maps, further geological-geotechnical investigations are needed in order to proper dimension new buildings or protective measures. Key parameters such as thickness and surface area of the possibly unstable layer or more precisely the initiation zone must be determined carefully to accurately use simulation tools as RAMMS with a certain reliability; moreover calibration must be performed on historical events in the study area or, at least, in adjacent zones depicting similar conditions (slope, geology, cover, land-use, etc.).

CONCLUSIONS

- The results show an overall good correspondence between the impact pressures reconstructed by the structural engineer and those simulated using RAMMS. Both methods (back-calculation and numerical simulation) appear suitable to *reconstruct* the range of pressures exerted by hillslope debris flows events. The pressures simulated with the *standard Voellmy* model better correlate with the results from the back-calculation than those from the *extended Voellmy*.
- Using the 'hillslope debris flow module' of RAMMS in a *forecasting framework,* e.g. for detailed hazard studies and dimensioning of protective measures, is more delicate, requires very good and reliable input data (DTM incl.) and rigorous calibration; results must be carefully interpreted. These reserves are however not specific to RAMMS but apply to all numerical simulation tools. Additional tests and calibration with well-documented events as well as further development are still needed before using RAMMS (hillslope) for general use in hazard analysis and mitigation without careful calibration and appropriate scenario simulation design. A test-phase involving several bureaus specialized in hazard assessment and design of countermeasures is currently running under the lead of the WSL - SLF.
- A main problem remains the great spatial variability of the debris mixture and of the processes, ranging from "true" soil/debris slides, experiencing only minor displacement, to flow processes with very long and broad runout zones. Better understanding of the process is therefore needed: release conditions (basic conditions + release mechanisms / thresholds), typology (from slide to flow), dynamics (flow height, velocity, energy), parameters changes during flow, etc. This enhanced understanding should then lead to better supported recommendations for the parameters μ and ξ.
- The application of the usual intensity criteria for hillslope debris flows (thickness of the unstable layer *e*, thickness of the deposit *h*) allows to determine intensity classes which actually correspond to the real recorded damages for around two thirds of the studied events. The intensity

appears however underestimated for the last third; this could lead to the implementation of inadequate (because "underdimensioned") preventive measures. Taking this into account and also the fact that the two key parameters *e* and *h* are still difficult to assess in the field, a reconsideration, refinement (adaptation of the thresholds) or completion of the intensity criteria for hillslope debris flow could be taken into account for the Swiss guidelines. Until new advances on these topics are made, the actual criteria, although partly unsatisfying, must still be used for hazard assessment and mapping.

REFERENCES

Bartelt P., Buehler Y., Christen M., Deubelbeiss Y., Graf C., McArdell B.W. (2011): RAMMS - A modelling system for debris flows in research and practice - User Manuel v.1.01 / Hillslope debris flow. WSL Institute for Snow and Avalanche Research SLF: 91 p.

Bezzola G.R., Hegg C. (Ed.) (2007). Ereignisanalyse Hochwasser 2005, Teil 1 – Prozesse, Schäden und erste Einordnung. Bundesamt für Umwelt BAFU, Eidgenössische Forschungsanstalt WSL. Umwelt-Wissen 0707: 215 p. / www.bafu.admin.ch/publikationen/publikation/00044

Bezzola G.R., Hegg C. (Ed.) (2008). Ereignisanalyse Hochwasser 2005, Teil 2 – Analyse von Prozessen, Massnahmen und Gefahrengrundlagen. Bundesamt für Umwelt BAFU, Eidgenössische Forschungsanstalt WSL. Umwelt-Wissen 0825: 429 p.
www.bafu.admin.ch/publikationen/publikation/00100

Bezzola G.R., Ruf W. (Ed.) (2009). Ereignisanalyse Hochwasser August 2007. Analyse der Meteo- und Abflussvorhersagen; vertiefte Analyse der Hochwasserregulierung der Jurarandgewässer. Bundesamt für Umwelt, Bern. Umwelt-Wissen 0927: 209 p.
www.bafu.admin.ch/publikationen/publikation/01073

BFF, SLF (1984). Richtlinien zur Berücksichtigung der Lawinengefahr bei raumwirksamen Tätigkeiten. Bundesamt für Forstwesen (BFF), Eidg. Institut für Schnee- und Lawinenforschung (SLF) / www.bafu.admin.ch/publikationen/publikation/00778

Egli Engineering (2009). Die Einwirkung von Hangmuren auf Gebäude - Sammlung, Sichtung und Auswahl der Fallbeispiele. Auftrag des Bundesamts für Umwelt. Internal report, unpublished.

Egli Engineering (2011). Die Einwirkung von Hangmuren auf Gebäude - Anaylse, Dokumentaiton und Interpretation von Schadenfällen. Auftrag des Bundesamts für Umwelt. Internal report, unpublished.

OFAT, OFEE, OFEFP (1997). Prise en compte des dangers dus aux mouvements de terrain dans le cadre de l'aménagement du territoire. Recommandations. Office fédéral de l'aménagement du territoire (OFAT), Office fédéral de l'économie des eaux (OFEE), Office fédéral de l'environnement, des forêts et du paysage (OFEFP). Berne (in French; German version also available) / www.bafu.admin.ch/publikationen/publikation/00783/index.html?lang=fr

Preuth T., Bartelt P., Korup O., McArdell B.W. (2010). A random kinetic energy model for rock avalanches: Eight case studies. J. Geophys. Res. 115, 22 p., F03036, doi:10.1029/2009JF001640.

Raetzo H., Rickli C. (2007). Rutschungen. In: Bezzola G. R., Hegg C. (Ed.) (2007). Ereignisanalyse Hochwasser 2005, Teil 1 – Prozesse, Schäden und erste Einordnung. Bundesamt für Umwelt BAFU, Eidgenössische Forschungsanstalt WSL. Umwelt-Wissen 0707: 195-209.
(in: www.bafu.admin.ch/publikationen/publikation/00044)

Rickli C. (2001). Vegetationswirkungen und Rutschungen – Untersuchung zum Einfluss der Vegetation auf oberflächennahe Rutschprozesse anhand der Unwetterereignisse in Sachseln OW am 15. August 1997. Eidg. Forschungsanstalt WSL, Bundesamt für Umwelt, Wald und Landschaft BUWAL: 97 p.
www.waldwissen.net/technik/naturgefahren/wildbach/wsl_vegetation_rutschungen/index_DE

Rickli C., Bucher H., Böll A., Raetzo H. (2004). Untersuchungen zu oberflächennahen Rutschungen des Jahres 2002 im Napfgebiet und in der Region Appenzell. Bull. angew. Geol. 9/1: 37–49.

Rickli C., Raetzo H., McArdell B.W., Presler J. (2008). In: Bezzola G. R., Hegg C. (Ed.) (2008). Ereignisanalyse Hochwasser 2005, Teil 2 – Analyse von Prozessen, Massnahmen und Gefahrengrundlagen. Bundesamt für Umwelt BAFU, Eidgenössische Forschungsanstalt WSL. Umwelt-Wissen 0825: 97-116. (in: www.bafu.admin.ch/publikationen/publikation/00100)

Schneider D., Bartelt, P., Caplan-Auerbach J., Christen M., Huggel C., McArdell B.W. (2010). Insights into rock-ice avalanche dynamics by combined analysis of seismic recordings and a numerical avalanche model. J. Geophys. Res. 115: 20 p., F04026, doi:10.1029/2010JF001734.