A comparison of physical and computer-based debris flow modelling of a deflection structure at Illgraben, Switzerland

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ABSTRACT

On the fan of the Illgraben (Switzerland), settlements and infrastructure are endangered by large debris flows. A protection concept was therefore elaborated to partially deflect large debris flows into a forest for deposition and in order to reduce discharge and flow volume in the channel on the fan. Because deflection structures for debris flows are uncommon, a physical model was built at a scale of 1:60 to test functionality and optimize the design. Afterwards, the computer-based model RAMMS::DEBRIS FLOW was compared with the physical model results and to further analyze functionality and robustness especially for rare debris flows. In general, the numerical model runs with RAMMS showed a similar flow behavior as in the physical experiments, and separation effects of the deflection structure were confirmed. The standard Voellmy model was not able to reproduce the constant velocities found in the experiments before the dosing structure. Therefore, a version of the Voellmy model including cohesion was used and showed good agreement with the physical modelling.

KEYWORDS

Debris Flow; physical modelling; computer-based modelling; protection measures

INTRODUCTION

The Illgraben (Switzerland) experiences several debris flows per year and is one of the most active torrents in the Alps. The village Susten located on the Illgraben fan is endangered by large debris flows and protection measures are required. In the present protection concept, large debris flows shall be partially deflected into the Pfyn Forest for deposition. Smaller debris flows, not exceeding the channel capacity on the fan, will continue to flow into the River Rhone. Due to the complex processes, the functionality and geometry of the deflection structure were studied in a physical model. Afterwards, the initial and final geometry of the

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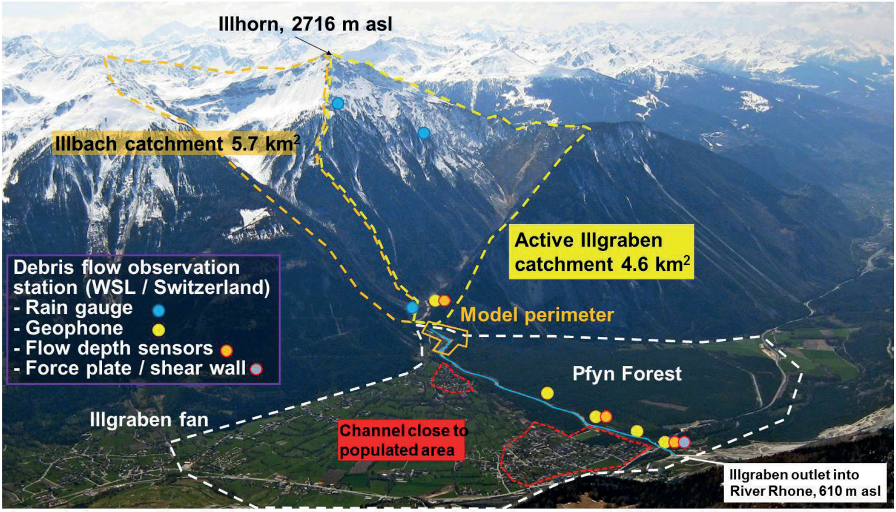
deflection structure were evaluated using the computational runout model RAMMS::DEBRIS FLOW to compare flow behavior and functionality of both model approaches.



Scenario / frequency	**Max. discharge [m^3/s]**	**Total / reduced volume [m^3]**	**Laboratory experiments**	**RAMMS model, 1 m grid**	**RAMMS model, 2 m grid**
Frequent (30 y)	250	100,000 / 40,000	x	x	
Medium (100 y)	500	250,000 / 65,000	x	x	
Rare (300 y)	1,000	500,000 / 87,000		x	x

Figure 1: Overview of the Illgraben catchment and fan including physical model perimeter, instrumentation of the observation station, event scenarios and overview on the performed modellings (marked with “x” where the method was applied).

STUDY SITE

The Illgraben catchment (10.3 km², Figure 1) located in southwestern Switzerland in the community of Leuk extends from 2716 m asl at the Illhorn to the outlet of the Illgraben into the Rhone River at 610 m asl. The climate is temperate-humid and influenced by the rain shadow effect within an interalpine valley which generates relatively low annual precipitation. Several debris flows occur every year and are initiated in the steep sub-catchment (4.6 km²) on the north face of the Illhorn where abundant sediment is available (Berger et al., 2011) and annual sediment transport into the Rhone River is about 70,000 m³ (Badoux et al., 2009). The Illgraben fan has a radius of about 2 km with channel slopes of 6 % to 10 %. In the catchment and upper third of the fan, the channel is deeply incised and normally has a double-trapezoidal shape with a low and high water zone. On the lowest part of the fan, a single trapezoidal-shaped channel is observed and discharge capacity is reduced considerably. About 30 check dams stabilize the channel on the fan and of the lower trunk channel in the catchment. The village Susten and a settlement below the fan apex are located on the right side of the fan and are partially within the highly (red) and intermediate (blue) danger areas according to Swiss guidelines for hazard zonation (BUWAL, 1998). The left side of the fan is covered by the Pfyn Forest which is part of the Federal Inventory of Landscapes and Natural Monuments of National Importance of Switzerland. A debris flow observation station is run by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL since 2000 and a large variety of flow types have been observed (McArdell et al., 2007; Badoux et al., 2009).

DESCRIPTION OF PROTECTION MEASURES

After defining event scenarios (Figure 1), hazard maps and initial protection concepts were elaborated. Due to very frequent debris flows and large expected volumes, retention of the debris in the catchment is inappropriate. Conveying very large debris flows into the River Rhone by enlarging the present channel may cause undesired backwater effects in the Rhone and stopping of debris flows on the fan, and consequent outbreak and flooding of settlements and infrastructure could be expected as a consequence. Therefore, we focused on a partial deflection of large, endangering debris flows at the fan apex in order to reduce peak discharge in the present channel. Smaller debris flows not exceeding the capacity of the channel on the fan will remain in the channel and flow into the River Rhone.

Within the protection concept, all debris flows are led to the deflection structure through a broad channel (discharge area 300 m^2) stabilized with check dams (Figure 2). The deflection structure is located in a tight curve (radius about 30 m) and consists of a crossover duct / breach joining the channel with the Pfyn Forest and a dosing dam. Because of their inertia and front height, large debris flows are intended to overshoot the curve and flow into the crossover duct and are thereby partially deflected into the forest for deposition. Smaller debris flows pass the dosing structure and are conveyed to the present streambed through a smaller channel (discharge area 45 m^2) stabilized with a slightly steeper block ramp and check dams. A simplified geometry with trapezoidal channel shapes and channel slopes at 6 % were used for modelling and initial planning. Minimum channel capacity on the fan and back-calculations of events where backwater effects in the River Rhone were dominant, were used for dimensioning and to estimate the activation point of the deflection structure: annual and frequent debris flows are conveyed back to the present channel and flow into the River Rhone, whereas for medium events (Figure 1) the deflection is activated. The activation threshold was set at a discharge area of 45 m^2 and equals the capacity of the lower trapezoid in the broad channel or of the channel returning to the present streambed.

The volume of debris-flow material deflected into the Pfyn Forest will increase with front speed and front height. However, it is important that dosage of debris flows is governed by maximum discharge or wetted area and a direct control on the deflected volume is not possible. Therefore, debris flows with a comparatively small front or several smaller surges would not be deflected and could transport large debris volumes into the River Rhone and backwater effects therefore cannot be excluded.

PHYSICAL MODELLING OF THE DEFLECTION

Because deflection structures for debris flows are uncommon, a physical model was built at a scale of 1:60 (Figure 2) to test functionality and optimize the design (Berger et al., 2014). Due to the large event volumes and physical limitations, modelling was limited to events within the activation range of the deflection structure and therefore to frequent events (redirection of the flows to the present channel / no activation) and medium events (deflection activated, Figure 1). For these events, target values based on event scenarios, derived from measured events at the observation station and field estimates were defined for model

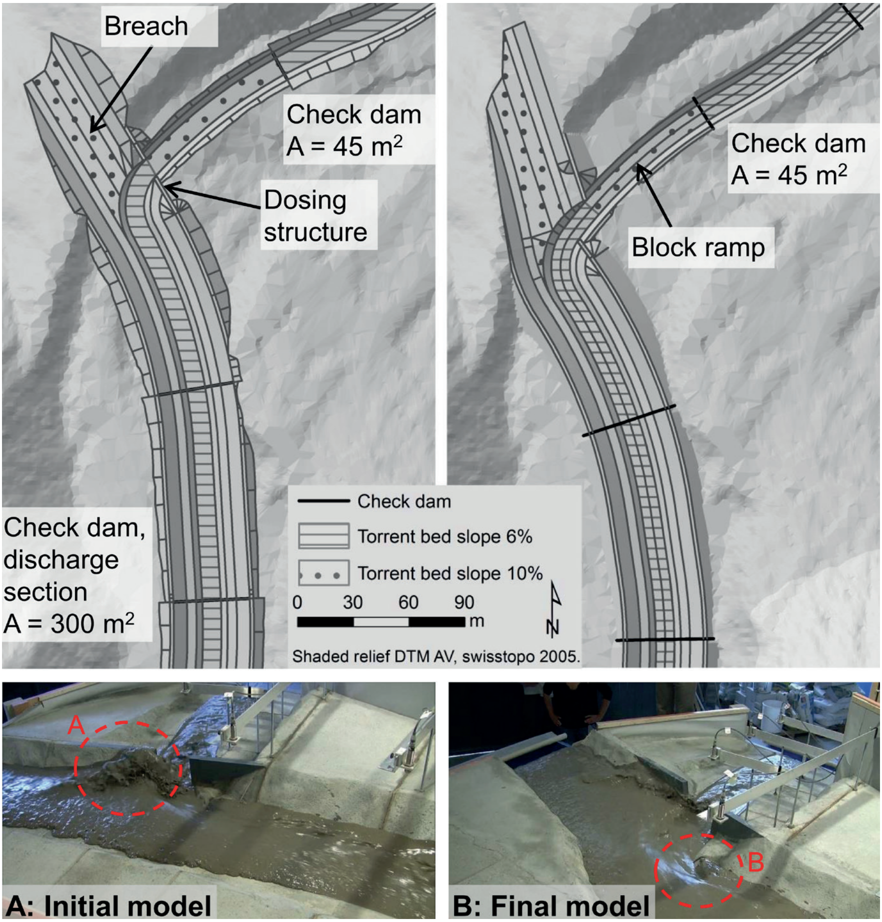


Figure 2: Initial model (left) and final model (right) of the deflection structure with indication of the structural elements and performance at medium events. Circle A: impact and surging on the left wall of the dosing structure, circle B: superelevation of the surface in the curve.

calibration and analysis of the model results. Sediment mixture, volume and discharge were scaled using Froude similarity, and flow properties (height, velocity, volume deflected) were measured at several locations. Reduced volumes (Figure 1) were used because the tail of a debris flow is not controlling the main functionality of the deflection structure, and target peak discharges were obtained with smaller volumes.

For the initial geometry (Figure 2), the following behavior was observed:

- Smaller debris flows (frequent events) below the activation threshold of the deflection were reverted to the present channel without overtopping of the banks downstream of the dosing structure. However, debris material was deposited in the breach by spillover.
- Larger debris flows (medium events) activated the deflection. However, the flow impacted and surged on the left wall of the dosing structure (Figure 2, circle A).

Improvements were therefore needed, mainly with respect to flow behavior and separation effects. Consequently, the geometry was optimized iteratively in six model setups and a total of 40 experiments, to optimize the functionality and robustness of the structure.

In the final geometry, the following features were changed compared to the initial model (Figure 2):

- The breach was rotated downstream to reduce impact on the dosing structure.
- The leading part of the left side of the dosing structure was designed without banks to reduce impact and surging.
- The channel bed in the breach was raised by 1 m to account for superelevation and obtain less deposition in the breach during events below the activation threshold of the deflection.

COMPUTER-BASED MODELLING OF THE DEFLECTION

A computational model was used for comparison with the physical modelling and to analyze functionality and robustness for rare and extreme debris flows which could not be modelled in the laboratory. RAMMS::DEBRIS FLOW is a 2D numerical simulation tool developed by WSL. The core of the program is a second-order numerical solution of the depth-averaged equations of motion for granular flows (Christen et al., 2012).

The debris rheology was described by an extended Voellmy-model which includes cohesion (Bartelt et al., 2015). In this model shear stress S is calculated according to the relation,

$$S = \mu N - [1-\mu] N_0 \exp\left[-\frac{N}{N_0}\right] + [1-\mu] N_0 + \rho g \frac{\|U\|^2}{\xi}$$

where N is the basal normal stress, $\|U\|$ is the norm of the velocity U, ρ the debris flow density, g the acceleration due to gravity and N_0 is the cohesion. When $N_0=0$, the model reduces to the standard two-parameter (μ, ξ) Voellmy model. When $\mu=0$, the model describes an ideal plastic material where N_0 acts similar to a yield stress, see Figure 3. Moreover, the stress never exceeds N_0 for large flow heights.

The model was calibrated using data from the Illgraben observation station and target values defined for the physical model and 3-point hydrographs were defined at the inlet into the model perimeter. Model runs were performed at two spatial extents and grid resolutions:

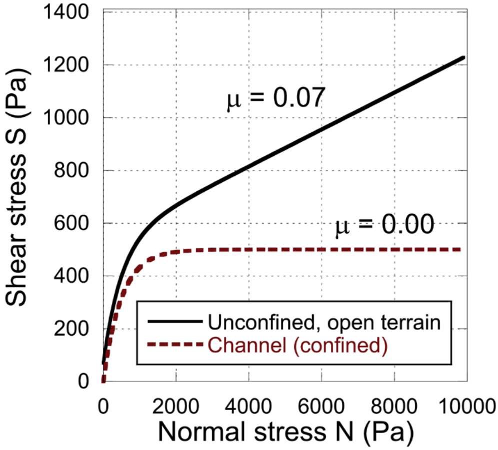


Figure 3: Shear vs. normal stress relation used to model debris flow motion in confined and unconfined terrain. In the channel we set N0 = 500 Pa and μ = 0.00. This produces the ideal plastic behavior depicted above. In unconfined flow, wet set μ =0.07. Note the similarity to actual debris flow measurements shown in McArdell et al. (2007).

a smaller extent (1 m grid) representing the perimeter of the physical model for the initial and final geometry of the deflection and a larger extent (2 m grid) covering the fan apex at a grid resolution of 2 m using the final geometry of the deflection and present topography without deflection. A summary of modelled scenarios and applied spatial extents is listed in Figure 1. For each model run, maximum flow height, maximum velocity and final deposition were exported to ESRI ArcGIS for analysis. Furthermore, cross-sections at different locations were extracted in RAMMS::DEBRIS FLOW to estimate maximum discharge from maximum values of flow height and velocity (Figure 4) and final deposition was used to estimate the deflected debris volume.

RESULTS AND DISCUSSION

The standard Voellmy model was not able to reproduce the constant velocities found in the experiments before the dosing structure. The modified Voellmy model (including cohesion) predicted both the debris flow velocities and flow heights with the parameter combination $\mu = 0.00$, $\xi = 600\ m/s^2$ and $N0 = 500\ Pa$. This suggests that in the channel the debris is fluidized and the flow is well lubricated ($\mu = 0$). The cohesion describes the visco-plastic behavior of the fluidized debris mixture. This approach could not be applied to model debris motion outside the channel. To take into account unconfined, open terrain outside the channel it was necessary to increase the Coulomb friction from $\mu=0.00$ (visco-plastic) to $\mu = 0.07$, thus introducing a type of plastic hardening into the flow rheology. This allows plausible modeling of the flow stopping behavior outside the channel.

In general, the simulations with RAMMS showed a similar flow behavior as in the physical experiments. The reduction of debris-flow discharge due to the diversion structure also

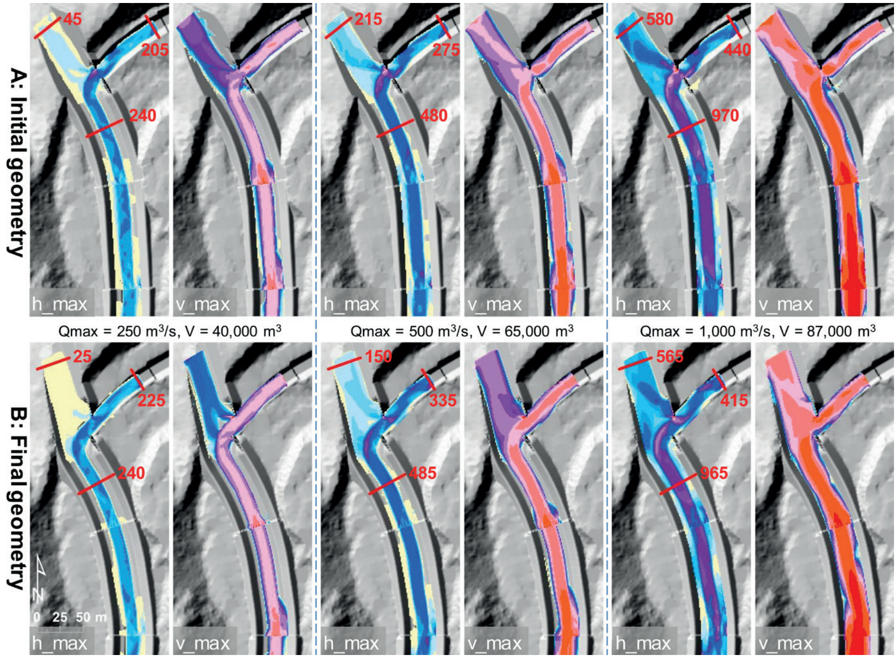


Figure 4: Maximum flow height and maximum velocity for the initial and final geometry of the deflection using three event scenarios and indicating maximum discharge at cross-sections (numbers in red). See Figure 5 for the color legend.

provided plausible results for events with discharges > 950 m^3/s and the channel capacity below the deflection structure was not exceeded (Figure 4). The impact of the flow front on the left wall of the dosing structure was reduced by the improvements from the initial to the final geometry. As in the laboratory experiments, superelevation of the debris flow surface in the narrow curve was observed (see Figures 2 and 4) and overtopping into the breach occurred at frequent events (Q = 250 m^3/s). However, discharge at the edge of the breach was reduced from 45 to 25 m^3/s (see Figure 4) due to the raised channel surface in the final geometry.

With respect to the larger spatial extent (Figure 5), overtopping at the planned location of the breach and deposition in the Pfyn Forest was observed in the numerical model runs on the present topography without deflection. This partly corresponds with recent observations of debris flow deposits and indicates a natural tendency of debris flows to break out at the channel curve and flow towards Pfyn Forest. However, the magnitude and extend of the outbreak in the computer model partly is attributed to overtopping, as explained in Berger et al. (2012). Using the final geometry of the deflection, about 115,000 m^3 or about 25 % of the initial volume were deposited in the Pfyn Forest. The representation of the deflection structure was good and showed a similar behavior to the results with the 1 m grid.

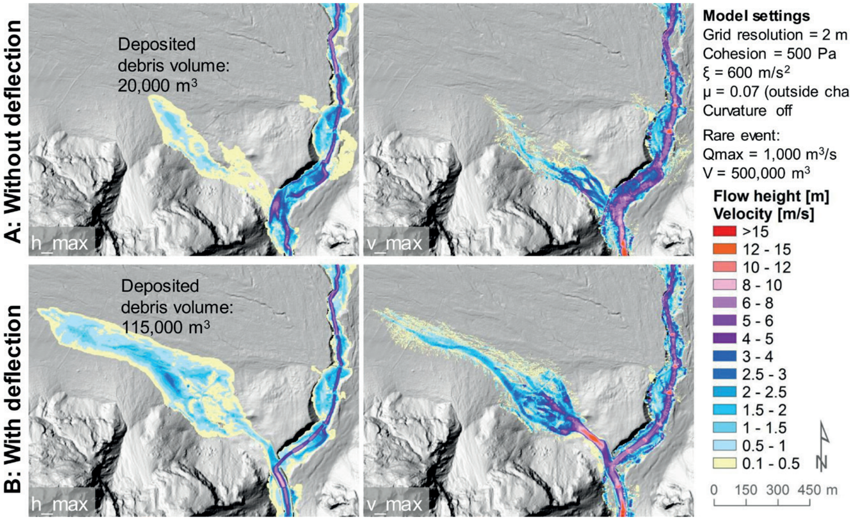


Figure 5: Maximum flow height on the large model extent with and without the deflection structure for a rare event and indication of model settings.

CONCLUSIONS AND OUTLOOK

Functionality and geometry of the deflection structure in-planning at the apex of the Illgraben fan were tested and improved using physical scale-model experiments and afterwards verified using the debris-flow runout simulation model RAMMS::DEBRIS FLOW. In general, the functionality of the deflection structure, i.e. reducing peak discharge and the total volume of large debris flows, could be demonstrated. However, the work also indicates that maintenance of the structure is essential to minimize separation effects of the deflection due to overtopping and deposition of debris in the breach during smaller events. This is important to ensure that the deflection structure only directly controls maximum discharge of debris flows. Because events with a comparatively small discharge yet a large total volume could pass the deflection structure and might cause backwater effects and flooding of settlements and infrastructure on the fan, overall risk management remains an essential part of the mitigation, including e.g. periodical observation of the catchment and the channel, land use planning or emergency plans.

Using two different models, further questions arise on the limitations of both approaches, model artifacts in the results and finally on the representation of nature. However, no direct comparison with nature is available and corroborating results only can be achieved in a multi-method approach using different models and estimates.

REFERENCES

- Badoux A., Graf C., Rhyner J., Kuntner R., McArdell, B.W. (2009). A debris-flow alarm system for the Alpine Illgraben catchment: design and performance. Natural Hazards 49(3): 517-539.
- Bartelt P., Vera Valero C., Feistl T., Christen M., Bühler Y., Buser O. (2015), Modelling cohesion in snow avalanche flow, Journal of Glaciology, Vol. 61, No. 229, 2015 doi: 10.3189/2015JoG14J126.
- Berger C., McArdell B.W., Schlunegger F. (2011). Sediment transfer patterns at the Illgraben catchment, Switzerland: Implications for the scales of debris flow activities. Geomorphology 125: 421-432.
- Berger C., McArdell B.W., Lauber G. (2012). Murgangmodellierung im Illgraben, Schweiz, mit dem numerischen 2D-Modell RAMMS. Interpraevent Conference Proceedings.
- Berger C., Ulrich M., Lauber G., Speerli J. (2014). Hochwasserschutz Illgraben: Ausleitbauwerk für grosse Murgänge. Tagungsband Internationales Symposium Wasser- und Flussbau im Alpenraum.
- BWW, BRP, BUWAL (1998). Empfehlungen, Berücksichtigung der Hochwassergefahren bei raumwirksamen Tätigkeiten. Biel, Switzerland.
- Christen M., Bühler Y., Bartelt P., Leine R., Glover J., Schweizer A., Graf C., McArdell B.W., Gerber W., Deubelbeiss Y., Feistl T., Volkwein A. (2012). Integral hazard management using a unified software environment: numerical simulation tool „RAMMS“ for gravitational natural hazards. Interpraevent Conference Proceedings.
- McArdell B.W., Bartelt P., Kowalski J. (2007). Field observations of basal forces and fluid pore pressure in a debris flow. Geophys. Res. Lett. 34, L07406, doi:10.1029/2006GL029183: 4 pp.