3.1Model setup and test program

The test setup consists of a 4 m long, 0.3 m wide and 0.3 m high plexiglas channel, which is hinged in the middle as a rocker (Figure 3). It therefore enables experimental runs to either side of the flume at variable channel inclinations. At both ends of the channel, material reservoirs with a length of 0.5 m are connected via tightly closable flaps. The geometric relationships of the model are scaled according to Froude's model law (Feldhaus 2018). This is not a representation of a specific debris flow channel; rather, the results should be transferable to different channels. The scale must therefore be determined individually for each transfer.

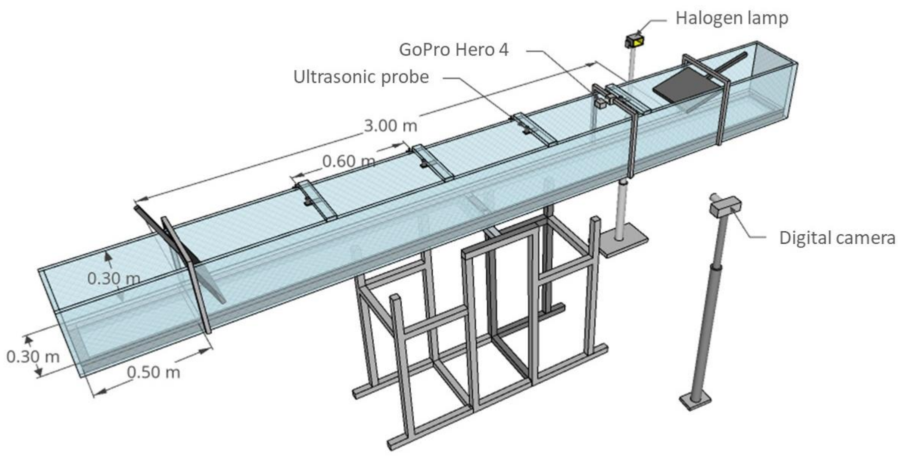

Figure 3: Sketch of the experimental setup; a plexiglas channel is hinged in the middle on a rocker**.**

Nine different experimental scenarios have been considered by varying both inclination and solid content of the material. The inclination of the channel was varied between 20 °, 25 ° and 30 °, the solids content of the three material mixtures was 40 %, 50 % and 60 % by volume with a total volume of 10 l each. Each experimental scenario was repeated at least three times at similar conditions. The density of the dry material is 2693 kg/m³ and the grain size distributions of the solid fractions of each mixture are identical and correspond to the particle size distribution found in the Illgraben material sampling from Wendeler (2008).

To create a rough bed, a plexiglas plate with a thickness of 1 mm was covered with a mixture of natural debris flow material from the Illgraben, with grain sizes ranging from 0.355 to 2 mm. A polyurethane primer was used as the adhesive. The plate was attached to the channel bed with double-sided carpet tape (Figure 4).

Figure 4: Plexiglas plate covered with sediment (left) and experimental setup with integrated rough bed and measuring technique (right).

To attach the measuring equipment, the channel has four sliding tabs on which ultrasonic probes are attached and a fixed bracket for attaching the camera (s. Figure 3).

3.2 Sediments

For the sediment mixtures used in the experiments, material was taken from the Illgraben in the Swiss canton of Valais, where at least one debris flow occurs annually. In 2000, researchers from the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL) installed a debris flow research station at Illgraben with various measuring equipment. Since then, a large number of data relating to parameters such as flow rate, total volume, flow depth and flow velocity has been recorded (Wendeler 2008; McArdell et al. 2007). The channel is located in the southwestern part of Switzerland and stretches from the top of the Illhorn (2716 m above sea level) over the deposition cone (850 m above sea level) to the mouth into the Rhone river (Swiss Rotten, 610 m above sea level). The catchment area is 10.4 km² (Berger et al. 2011).

In the Illgraben a considerable amount of sediment is transported into the Rhone by debris flow events: Between 2000 and 2009, an average of 100,000 m³ per year was transported. The current types of mass movements are strongly variable. Besides granular debris flows and sludge flows, highly concentrated flow and flooding also occur (Berger et al. 2011). Shortly after commissioning of the observation station, precise data were collected for three debris flow events. The values of the collected parameters are shown in Table 2. The values for the debris flow load M were approximated with integration of the discharge hydrograph, the Strickler coefficient k_{St} was recalculated from the other values (Hürlimann et al. 2000).

Table 2: Main data of the first debris flows in the Illgraben recorded by the research station (Hürlimann et al. 2000).

Date	Number of Surges	M [m³]	Q_{max} [m³/s]	H_{max} [m]	v [m/s]	k_{St} [m$^{1/3}$/s]
3rd June 2000	1	11000	19	1.3	1,3	4,3
28th June 2000	1	35000	125	2.2	4,7	11,3
24th July 2000	>3	6000	22	0.75	2,7	11,9

The variability of the debris flow events, even within one channel, underlines the different dynamic characteristic of each individual event. Developing a physical model with the aim of representing debris flows in general must therefore be based on average values instead of a specific site.

3.3 Measurement

In the present study, we used two measuring techniques for the experiments: Water level measurement with ultrasonic probes and flow velocity measurement using LSPIV.

Ultrasonic probes are non-intrusive level measurement systems that are frequently used in hydraulic engineering experiments. They belong to the category of acoustic water level measurement and use the physical effects of the transit time of a sound pulse (Morgenschweis 2018). Four pico+35/I ultrasonic sensors from Microsonic were used for the debris flow tests. The frontal velocity of the debris flows in the model was indirectly measured via temporal correlation of the recordings and the known distance between the measuring devices.

We used the LSPIV method to determine the flow velocity distribution on the flow surface. This method is an easy-to-use variation of the Particle Image Velocimetry (PIV). Both methods use the basic principle of particle tracking in successive image sequences with known time intervals (Figure 5). While in standardized PIV applications a laser beam is used to generate a light section to expose the measuring plane, this is not necessary with the modified LSPIV method. With LSPIV, the surface velocity is recorded, while PIV measurements are made over the entire flow depth (Fujita et al. 1998). Furthermore, LSPIV was developed for the analysis of flow velocities on large surfaces like rivers during flood events, while PIV is applied on small scales in laboratories.

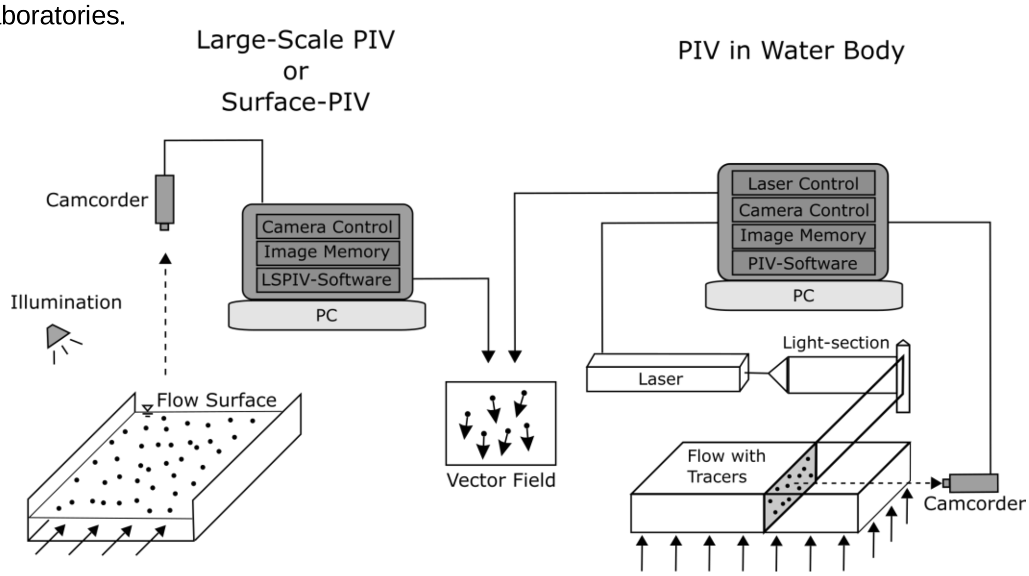

Figure 5: Schematic drawing of the LSPIV and PIV methods (based on Weitbrecht et al. 2007).

The flow surface was recorded vertically from above with a GoPro Hero 4 camera with a resolution of 1920 x 1080 pixels (HD) and a frame rate of 120 fps.

For the image processing, we used the free software Fudaa-LSPIV, that was developed jointly by the French electricity company EDF and the French National Research Institute of Science and Technology for Environment and Agriculture (Irstea).

4 RESULTS

The measured levels show the characteristic longitudinal profile of debris flows in the model. It should be noted that the frontal velocities (Figure 6) measured by the ultrasonic probes merely represent average values over a length of 1.80 m in the middle of the channel cross-section (s. Figure 3). They serve as comparison values for the results obtained with the LSPIV method.

As expected, the flow velocity increases with increasing slope. The increase is not linear, as would be expected with a Coulomb friction approach.

With regard to the influence of the solids content, the results indicate a coupled effect: At 20 ° and 25 ° slope the test mixture with 40 % solids content shows the highest velocities of the three mixtures, while the others hardly differ. At 30 ° slope again the 40 % mixture runs fastest, while the 50 % mixture shows the lowest values.

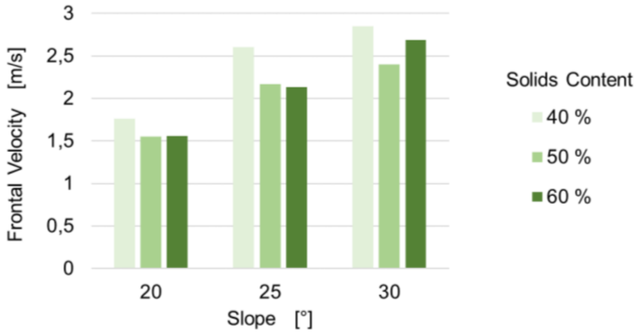

Figure 6: Front velocities from the ultrasonic measurements, averaged over a length of 1.80 m of the channel and over three test runs for each slope and solid content (s. Figure 7).

In addition to level measurements, in each experiment 60 frames were evaluated with the LSPIV system, which corresponds to a period of half a second. The results of the velocity calculation in Fudaa-LSPIV are displayed as vector fields. For each experiment, we created two vector fields with average velocities: For the first 60 frames from the appearance of the debris flow head in the image and for the first 20 frames after the passage of the head through the image. The results of the average speeds for 60 frames as ranges between minimum and maximum values are graphically shown in Figure 7. For each of the three sediment mixtures, the very first test run at 20 ° inclination shows a strong deviation from the other three runs at the same inclination. This is due to the initially dry bed and hence different initial conditions. The results of these first test runs therefore need to be analyzed separately.

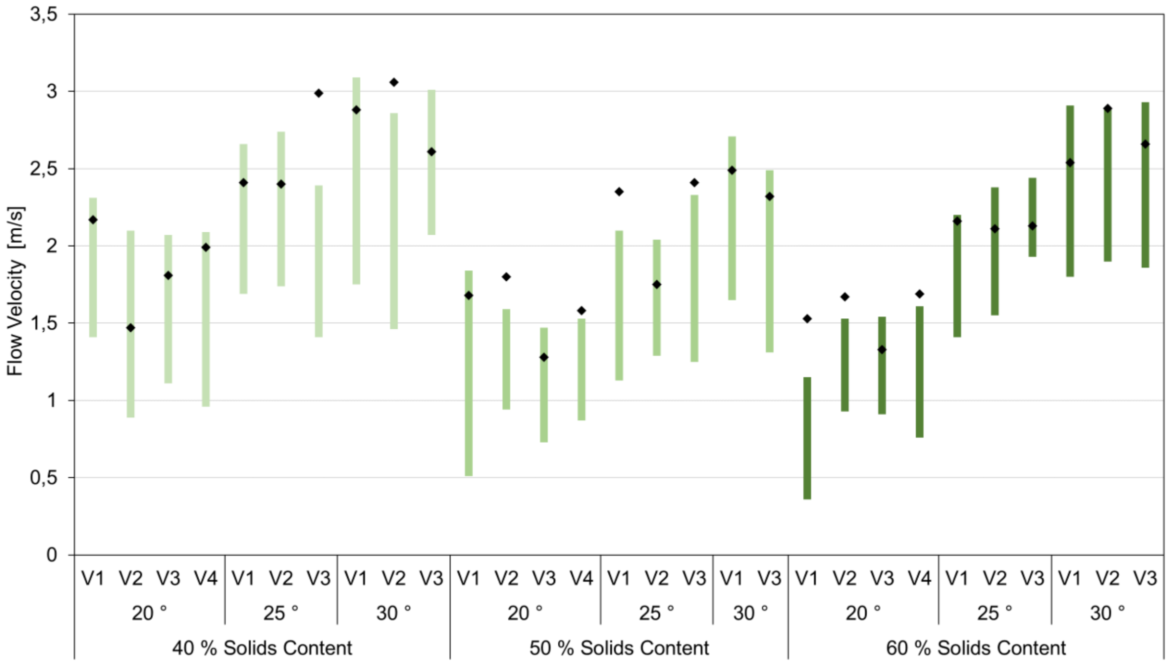

Figure 7: Order of magnitude of the averaged flow velocities, calculated with Fudaa-LSPIV for the first 60 frames (bars) and values of the averaged front velocities of each test run (black rhombs).

The flow velocities averaged over 60 frames are in almost all experiments with identical boundary conditions in the same order of magnitude and are therefore reproducible. Any variation within this set hence corresponds to an intrinsic variation of the debris flow. All test series show an increasing velocity with increasing slope of the channel, which resembles results of the averaged velocities. As with the evaluation of the ultrasonic measurement, a coupled effect of the solids content on the flow velocity can be detected. The average flow velocities of the 50 % test mixture have lower values than those of the 40 % mixture, but they are in the same order of magnitude as that of the 60 % mixture. At 25 ° and 30 ° gradients, the velocities of the 60 % mixture are even slightly higher.

In general, the average flow velocities for the evaluation of 20 frames are higher than the values averaged over 60 frames. As a result, the values of the front velocity are within the range calculated with Fudaa-LSPIV for most of the tests. Apart from this, the reproducibility and influence of the solids content and the gradient are similar to those of the evaluation of 60 frames. The average velocites of the experiments with identical boundary conditions are usually in the same order of magnitude.

Besides the evaluation of averaged velocities, we studied the velocity distribution on the flow surface. For that purpose, the vector fields created with Fudaa-LSPIV can be converted into colored areas. Such a flat marked image was created for the speed averaged over 60 frames for each experiment. The results show no significant trend for the velocity distribution of experiments with identical boundary conditions. The expected velocity distribution with high flow velocities in the middle of the channel and low velocities at the sides did not occur in most experiments.

5 DISCUSSION

Based on the results obtained we evaluate the objectives of the present study as follows:

(a) Development of an experimental setup with reproducible initial and boundary conditions as well as short repetition times of experimental runs.

Within the present study we developed the first rocker-like experimental debris flow model. The characteristics of this experimental setup show several advantages over a “classic” ramp-like setup. First of all, the application of Plexiglas allows a free view on the modelled debris flows. Therefore, the LSPIV technique could also be applied through the channel walls to determine lateral velocity distributions.

As the test material remains in the flume after an experimental run, several tests can be run one after another within a short time period with the same material. Furthermore, the initial and boundary conditions are reproducible due to no change of the sediment mixtures between each experimental run. However, uncertainties regarding these conditions remain with the manual handling of some parts such as the mixing of material and opening of the reservoir gates.

The most important variable boundary condition is the bed roughness in the flume. A comparison of the Plexiglas plates covered with sediment before and after the experiments shows a clear change in the bed roughness. During the experiments, a part of the bottom grains was detached and transferred to the respective test mixture. This affects both the composition of the mixture and the nature of the bed. The change in the test mixture is classified as negligible. The change of the bed composition, however, has a significant influence on the flow dynamics, especially in regions of shallow heights. It remains open how strong this influence is and whether the differences in the velocity distributions can thus be explained. Additional test runs are needed to account for this.

(b) Determination of suitable measuring techniques to estimate the velocity distribution and application to surface velocities.

The applied hard- and software was largely feasible for the estimation of front velocities as well as velocity distributions on the flow surface as we gained similar results with both techniques. In general, the LSPIV measuring technique is suitable for the estimation of velocity distributions of sediment-water-mixtures. The results of our experiments indicate a coupled effect of velocity distribution (s. objective (c)).

The software Fudaa-LSPIV proved largely useful for the application on debris flow models, but it is limited regarding the options of data processing. The results are primarily available in the form of images with vector fields or colored areas. The size of the vectors depends on the selected measurement network and cannot be changed afterwards. In addition, the results can be exported as SLF files (Symantec License File).

In order to gain additional results with further options of data processing, we applied the MATLAB application PIVlab in addition. The calculated vectors show a large distribution regarding the flow velocity and direction of flow. Therefore, these results are not plausible, which is probably due to the large grain sizes of the debris flow mixtures. Since PIVlab is originally developed for Laser-PIV applications (Figure 5), it requires small tracer particles and appropriate illumination. Thus, we need to improve these conditions for the successful application of PIVlab.

(c) Implementation of a proof of concept study: estimation of the impact of channel inclination and solid content on surface flow velocity.

All experiments obviously show the clear influence of the bed slope on the flow velocity: with increasing slope the flow velocity increases. However, the data indicates a nonlinear relationship between slope and flow velocity. With the 40 % mixture and the ultrasonic measurements, e.g., the increase of flow velocity between 20 ° and 25 ° is almost 1 m/s and between 25 ° and 30 ° only 0.2 m/s. The other mixtures and the LSPIV measurements yielded similar results.

The influence of the solids content on flow velocities is less obvious than that of the channel inclination. All in all, the results lead to the assumption of a coupled effect of the solids content: In all results, the flow rates of the 40 % test mixture are higher than those of the 50 %. Based on this it can be assumed that the test mixture becomes more viscous with increasing solids content and therefore runs slower. However, the results of the tests with the 60 % mixture contradict this. Here, the velocities at 20 ° and 25 ° slope are about the same as those of the 50 % test mixture. At 30 ° they are significantly (almost 0.5 m/s) higher than the velocities of the 50 % mixture. The flow velocity therefore appears to decrease initially with increasing solids content and increase again from a critical concentration. A common friction law for debris flows is a Coulomb type friction that scales with the normal force superposed by some turbulent Chezy type friction law that scale with the velocity. The data clearly indicate that a purely Coulomb type friction with a constant friction coefficient alone is not consistent with the data. The solids content affects the effective density of the mixture, which might reduce the friction force from a certain, yet unknown, value on and therefore leads to higher flow velocity.

De Haas et al. (2015) recognized a similar relationship with regard to the influence of the material composition on the runout characteristics of debris flows: A higher proportion of coarse-grained material initially leads to an increase in the outlets, but frontal friction counteracts this from a critical value. Similarly, a higher clay content initially leads to increased runouts until the increase in viscosity reduces the runouts again.

We assume an influence of solids concentration on flow velocity by the interaction of slope, mixture mass and gravity: First of all, the flow velocity decreases with increasing solids content. However, the same volume weights more with a bigger solids content. From a critical proportion onwards, the higher weight leads to higher flow velocities due to gravity. The critical value changes with the slope of the flume. This relationship must first be regarded as a hypothesis and should be tested in further experiments with more variations of the solids content and channel inclination. The critical solids content must also be determined individually for each slope.

6 SUMMARY AND OUTLOOK

Debris flows are part of the natural relief erosion within the rock cycle. For humans, their destructive potential turns them into natural disaster from which they must be protected. The development of protective and countermeasures requires a comprehensive understanding of the process. Especially the knowledge of flow velocity distributions is important for the understanding of the process, because the flow velocity affects the impact forces and the runout.

In this study, a physical model was setup to investigate the characteristics of debris flow movement, using reproducible initial and boundary conditions. Experiments were carried out with material from the Illgraben, Switzerland, and the distribution of flow velocities was determined with the LSPIV measuring technique.

Experiments carried out with identical slope and solids content were largely reproducible except for the very first run of each series, when the flume was initially dry. The setup has the advantage of carrying out several runs with the same material remaining in the flume with negligible losses.

We found that the LSPIV method is suitable for the investigation of flow velocities on the flow surface. The results are in good agreement with the ultrasonic measurements. Additional evaluation programs could be added. PIVlab for example reacts sensitively to poor lightning conditions and large tracer particles, but offers various possibilities of data processing.

The results of the test evaluation allow first conclusions on the influence of the varied parameters. As the slope increases, the flow velocity increases. However, this influence seems to be nonlinear and should be quantified in further experiments. The following hypothesis could be made for the influence of the solids content, which should be tested in further experiments: An increasing solids content initially leads to a reduced flow velocity, but the flow velocity is increased by the higher effective density from a critical content onwards. The critical fraction varies depending on the slope of the channel.

Based on these first results obtained, we are going to implement further investigations to first improve the reproducibility of the experiments and second quantify the influence of the variable parameters. Additionally, the results serve as basis for the development of a numerical model. A 2D numerical chute flow model with capabilities for uncertainty quantification and sensitivity analysis tailored to the experimental setup is currently under development.

ACKNOWLEDGEMENTS

The set-up of the laboratory model was supported by the Excellence Initiative of the German Federal and State Governments through experimental funds of the Aachen Institute for Advanced Studies in Computational Engineering Sciences (AICES).

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