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Discussions

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Laboratory tests for the optimization of mesh size for flexible debris-flow barriers

C. Wendeler[1,*] and A. Volkwein[1]

[1]WSL Swiss Federal Institute for Forest, Snow and Landscape Research, Zuercherstr. 111, 8903 Birmensdorf, Switzerland
[*]now at: Geobrugg AG Protection Systems, Aachstr. 11, 8590 Romanshorn, Switzerland

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Correspondence to: A. Volkwein (volkwein@wsl.ch)

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Abstract

Laboratory tests were performed to study the loading aspects of flexible debris-flow barriers. Debris material from the Milibach river (Canton Berne, Switzerland) has been used to quantify the influence of different mesh sizes and the gap between the lower barrier edge and the river bed compared to the maximum grain size.

It was possible to study the filling process and the retaining behaviour of the barriers as a function of the mesh size. A reasonable retention was reached with the net having a mesh size and a basal gap smaller than d_{90} where d_{90} is the maximum diameter of 90 % of the grains. By scaling the laboratory tests to the natural size using Froude similarity a recommendation is given for the best net mesh size and the gap in natural conditions. The conclusions are supported by the results of numerous laboratory tests using different debris material, e.g. from the Illgraben river (Canton Valais).

1 Introduction

Flexible debris-flow barriers (Wendeler, 2008) derived from rock fall and snow slide protection systems are still an innovative protection measure against small and medium-sized debris flows (see example in Fig. 1). The typical net structure is very light compared to concrete check dams and can be installed easily in practically inaccessible mountain regions using a helicopter (Monney et al., 2007). The main retention mechanism of such barriers is the dewatering of the debris through the net structure. Another advantage is the positive effect of the energy absorption of such a flexible deforming system retaining the debris by providing an elongated braking distance and resulting in a soft stop, which again reduces the peak loads in the barrier components and the anchorage (Wendeler, 2008).

To investigate the loading aspects of debris flow barrier systems laboratory tests as described in Canelli et al. (2012), Moriguchi et al. (2009) or Wendeler (2008) are useful. The laboratory chute of Swiss Federal Research Institute WSL (Weber, 2000) enables tests with artificial debris flows from natural debris material impacting different barrier systems. Wendeler (2008) used this chute to examine different mesh stiffness's and mesh sizes. The tests also allow to study the stopping and overtopping processes of the barriers. The basis of the study presented here were more than 40 precedent standardized laboratory tests carried out with material from the river Illgraben (Wendeler, 2008). The six additional laboratory tests with debris flow material taken from the river Milibach (Monney et al., 2007) were carried out to study the influence of different mesh sizes and the basal gap between the lower net edge and the river bed in relation to the grain size distribution. The background for the laboratory tests presented here was an engineering project dealing with possible debris flow protection measures in the Hasliberg region of Switzerland (Monney et al., 2007; Schatzmann, 2006; Roth et al., 2006). The river Milibach above the two villages Hasliberg and Meiringen is fed by the rivers Louwenenbach and Schlüochtbach. The narrow valley of the river Schlüochtbach is mainly composed of moraine material whereas that of the river Louwenenbach is composed of strongly weathered schist material as shown in Fig. 2. The debris-flow material was taken from the Louwenenbach river and transported by helicopter down to the main valley and then trucked to the laboratory.

2 Testing methods

The laboratory chute consists of two main parts. The first one is a 0.15 m^3 start reservoir followed by an acceleration section. The second part is a 3.88 m long and 30 cm wide channel in which the velocity and flow height measurements are carried out (see Fig. 3). Along the channel four laser devices are installed to measure the current flow height (Fig. 4). The data sample rate of 2.2 kHz allows the detection of fast passing objects and also captures the debris-flow front properly. The local velocity of the front is back-calculated from of the front arrival and the time span between the laser devices.

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A so-called “sledge” is situated at the lower end, in front of the channel, which is axially supported. On this sledge different kinds of barrier types can be installed (Fig. 5). Two load cells measure the forces in the flow direction during the impact.

To get a redundant confirmation of the impact velocity high-speed cameras are situated on top and in front of the sledge to record the filling process. Their images are post-analysed over time. After the test, a laser device mounted on a linear guide unit scans the topography of the channel and the filled barrier with a raster size of 7.5 mm in the longitudinal and transversal directions. Out of this raster data a topographic map of the retained debris-flow volume (Fig. 6) and the cone inclination behind the barrier can be calculated.

A single laboratory test is carried out as follows: first, a certain amount of debris is mixed with water in a concrete mixer. The mixture is then filled in the release box of the laboratory chute. Afterwards, an immediate release of the material takes place to avoid segregation of the mixture. To ensure the complete release of all material, the box’s front wall opens at once. This action triggers also the measuring system.

At the lower end of the chute, the mixture gets caught by the installed barrier. Front speed and deposition mass balance are analysed afterwards.

The numbering of the tests follows the naming convention *a*-*b*-*c*-*d* with *a* being test number, *b* describing the chute’s inclination in degrees, *c* the volumetric water content and *d* the material volume in litres (e.g. 01-55-0.30-100).

3 Test results

3.1 Test material

An overview of the laboratory tests carried out with additional results is provided in Table 1 with the details of the single material mixtures according to above naming convention. Sieve analyses of the natural test material were carried out to get information

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on the grain size distribution. Ninety percent of the grain sizes of the used material were smaller than 3 cm (Fig. 7), i.e. the d_{90} grain size was 3 cm.

The water content was varied to obtain granular debris-flow fronts. The first test had a water content of 40 vol-%. It was found to be too small to get a sufficient debris flow because the flow came to rest without reaching the net despite the highest possible inclination of the chute. The next test was a very muddy looking debris flow with a higher water content of 50 %. The subsequent tests had all a water content of 45 % producing well shaped and granular debris-flow fronts.

3.2 Retained volume

We started the tests with a mesh size equal to the d_{90} grain size in order to see whether the debris is retained or not. Based on the result, it could be decided whether and how to change the mesh size for the subsequent tests. In addition, the gap between the barrier and the river bed was also chosen as 3 cm, i.e. equal to the d_{90} grain size. Both the mesh size and also the gap of 3 cm worked very well and nearly all the debris was retained.

Afterwards bigger mesh sizes and bigger gaps were tested. With a wider mesh size of 4 cm still about 80 % of the debris at a d_{90} grain size of 3 cm was retained. The 6 cm mesh size still retained about 2/3 of the debris. With a 6 cm basal gap underneath the barrier with a 3 cm mesh sized barrier no debris was retained at all. The flow height in the chute of this test was 7 cm and all the debris passed beneath the barrier. Summarized, the best retention effect of the barrier was achieved with a mesh size and basal gap equal to the d_{90} grain size whereas the limit size of the mesh is twice the d_{90} grain size. For details on mesh size and the basal gap, see Table 2 for the situation before and after the single tests.

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3.3 Velocity profile and impact forces

The velocity development of the 45 % water content tests is shown in Fig. 8a. The 43, 44 and 45 (Table 2) test velocity profiles are quite similar. The 42-50-0.45-50 test is missing because of a defect laser signal from the uppermost laser. Test 46 turned out to be an outlier because the velocity at the third laser is $4.5\,\mathrm{m\,s^{-1}}$ and consequently higher than the others with only $3\,\mathrm{m\,s^{-1}}$. The reason was identified by an increased percentage of fine material in the debris mixture because test 46 used the remaining material from box taken from the field and this rest contained more fine material.

The impact velocity was nearly the same in every test with $3.5\,\mathrm{m\,s^{-1}}$. In Fig. 8b a curve of the measured forces in function of the impact velocity is shown. The highest impact force occurs in the second test with a water content of 50 % and for this reason also a higher impact velocity. The six tests with material from the river Louwenen are too few to make a final statement regarding the relationship between impact forces and impact velocities, but it is obvious that higher impact velocities result in higher impact forces.

4 Comparison with nature – scaling effects

4.1 Geometrical scaling

If one compares the geometrical length of the test site to the length in the field a factor of $2\,\mathrm{m}/0.071\,\mathrm{m} = 29$ is obtained for, e.g., the highest flow height (Schatzmann, 2006). Calculating the same quotient for the minimal flow height in the field with 1 m and in laboratory value of 0.045 m one obtains a quotient of 33. Comparing the average width of the torrent to the width of the chute one gets $10\,\mathrm{m}/0.3\,\mathrm{m} = 33.3$. From these results an average geometrical scaling quotient of 30 is found to be adequate. The scaling law

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for the velocity of the model is described using equations 1, 2 and 3.

$$L_s = \frac{L_R}{L_m} = 30 \quad (1)$$

$$V_s = \sqrt{L_s} = 5.47 \quad (2)$$

$$V_m = \frac{V_R}{V_s} \quad (3)$$

with V_s = scaling parameter velocity, V_m = velocity of the model and V_R = velocity in reality. If the maximum velocity in nature is $V_R = 18\,\mathrm{m\,s^{-1}}$ as described in Schatzmann (2006) the velocity in the laboratory tests must be $V_m = V_R/V_s = 18/5.47 = 3.3\,\mathrm{m\,s^{-1}}$. This velocity range is reached in the tests as shown in Table 3.

Upscaling the geometrical mesh parameters, we now seek the best mesh size in nature. Referring to a d_{90} grain size of 3 cm, which at the same time is the mesh size of the barrier, we get a maximum field mesh size of $0.03\,\mathrm{m} \times 30 = 0.9\,\mathrm{m}$. The maximum possible basal gap between the barrier and the river bed is of the same magnitude.

4.2 Froude scaling

If gravitationally driven forces prevail in a flow regime and if the flow has an open water surface, Froude number scaling is a reasonable possibility (Bollrich and Preissler, 1980). The Froude number $Fr = v/\sqrt{g \cdot h \cdot \cos\alpha}$ (where v is the centre front velocity, g the acceleration due to gravity, h the flow height and α the inclination of the river bed) is proportional to inertial forces and characterizes the flow regime. If the Froude number is below 1 the flow is subcritical, if it is 1 the flow becomes critical and bigger than 1 means a rapid flowing supercritical flow. For upscaling the laboratory model to the field, the Froude number should be the same for both the laboratory and the field and is compared in Table 3.

Based on a Froude scaling scheme, a factor of $L_s = 10$ results (Rickenmann, 1999; Weber, 2000). Comparing laboratory barrier height with a potential field barrier height we obtain $L_s = 5\,\text{m}/0.3\,\text{m} = 16.7$. If we now scale the mesh size by 10 to 16.7 we have a required mesh size in nature between $0.03\,\text{m} \times 10 = 0.3$ and $0.03\,\text{m} \times 16.7 = 0.5\,\text{m}$. So, mesh size and basal gap should be in a range between 0.3 m up to 0.5 m for good retention behaviour of a barrier for these specific location.

5 Conclusions

The series of 6 laboratory tests with debris-flow material out of the Louwenenbach/Milibach at Meiringen/Hasliberg proves that it is possible to study the filling process and the retaining behaviour of the barrier dependent on the mesh size. A reasonable result was found with a net mesh size and a basal gap of 3 cm each. Almost the complete debris material was retained even if 90 % of the investigated debris material grain size was smaller than 3 cm.

The results of the laboratory tests are helpful to design and construct new debris-flow barriers in the Hasliberg region. In general, laboratory tests are always difficult to transfer to real natural conditions because of scaling problems (Wendeler, 2008; Canelli et al., 2012). But in this case, Froude number scaling seems to be a reasonable method. Both, velocity and flow height are parameters of the Froude number equation and they are also the most important parameters to describe the retention process of debris-flow material.

Upscaling the laboratory test to field conditions revealed a need to construct barriers with mesh sizes of 0.3 m up to 0.5 m. The gap between the lower support rope and the river bed should also be between 0.3 m up to 0.5 m to achieve an adequate blocking of the debris-flow material. The gap itself is necessary to let the normal mean high water discharge pass without filling up the barrier. Of course a stable river bed below the barrier is required to keep a more or less constant basal gap.

The full design of barriers in the field can then been calculated as, e.g., described in Wendeler (2008).

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Table 1. Test run overview.

Test*	Mesh size/basal gap	Water content	Retained volume	Comments
40-50-0.40-50	3 cm/–	40 %	–	Debris flow stopped before barrier
41-50-0.50-50	3 cm/–	50 %	30 dm^3	Muddy debris flow
42-50-0.45-50	3 cm/–	45 %	30 dm^3	Typical debris-flow front
43-50-0.45-50	3 cm/3 cm	45 %	30 dm^3	Typical debris-flow front
44-50-0.45-50	3 cm/6 cm	45 %	–	Typical debris-flow front
45-50-0.45-50	4 cm/–	45 %	25 dm^3	Typical debris-flow front
46-50-0.45-50	6 cm/–	45 %	22 dm^3	Typical debris-flow front

* = test no. – inclination of chute – water content (%) – total start volume

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Table 2. Overview over the tests and the retained volume.

Test number	Before the test	After the test
41-50-0.50-50		
42-50-0.45-50		
43-50-0.45-50		
44-50-0.45-50		
45-50-0.45-50		
46-50-0.45-50		

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Table 3. Froude number of laboratory test compared with design values in the field (Q_{max} = max. discharge, H_{max} = max flow height, V_{max} = max. front velocity).

	V_{max} ($m\,s^{-1}$)			H_{max} (cm)			Froude no.		
Milibach[a]	18			200			4.152		
Laboratory test no.	Measurement at laser No.								
	1	→	3	1	→	3	1	→	1
41	2.76	→	4.16	20	→	5	2.084	→	6.281
42	3.78	→	–	4.5	→	–	6.016	→	–
43	2.75	→	3.48	17	→	7.1	2.252	→	4.409
44	2.77	→	3.68	22	→	6	1.994	→	5.072
45	2.79	→	3.18	16	→	6	2.355	→	4.369
46	2.71	→	4.47	19	→	–	2.099	→	–

[a] design slope inclination 16.7°, max. discharge 100–150 $m^3\,s^{-1}$ – no measurement

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Figure 1. Filled debris-flow barrier in the Illgraben, Switzerland (Wendeler, 2008).

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Figure 2. The schist material in/of the Louwenenbach river bed.

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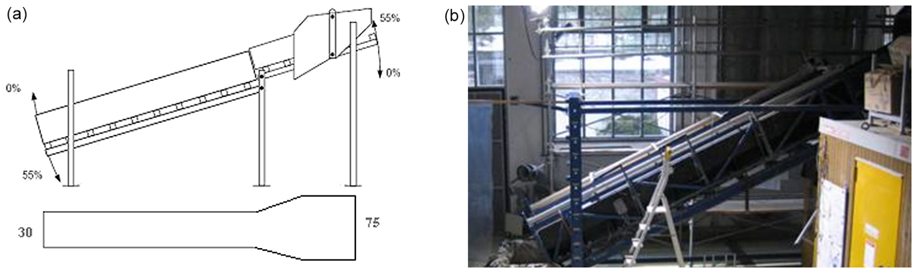

Figure 3. (a) Layout of the chute with its variation of the inclination and **(b)** photograph of the chute at the WSL laboratory.

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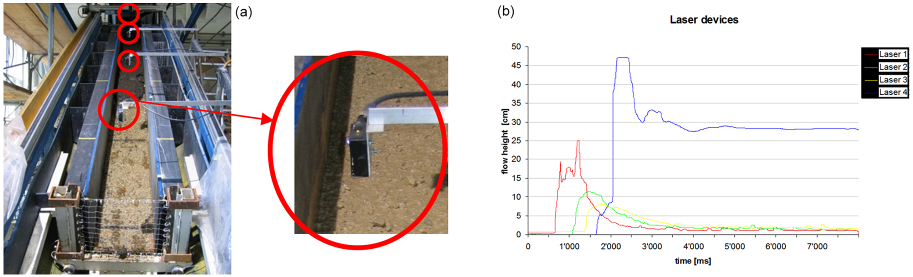

Figure 4. (a) Four laser devices along the channel measuring the flow height and allowing the determination of the front velocity. **(b)** Example diagram of the measuring results of a debris flow passing the four laser devices. The blue curve belongs to the laser installed on top of the barrier. It measures the filling height.

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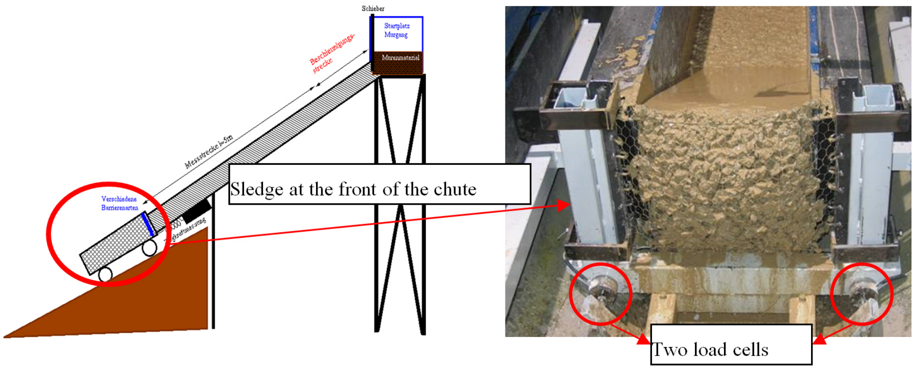

Figure 5. Situation and a photograph of the sledge in front of the chute with load cells and a filled barrier.

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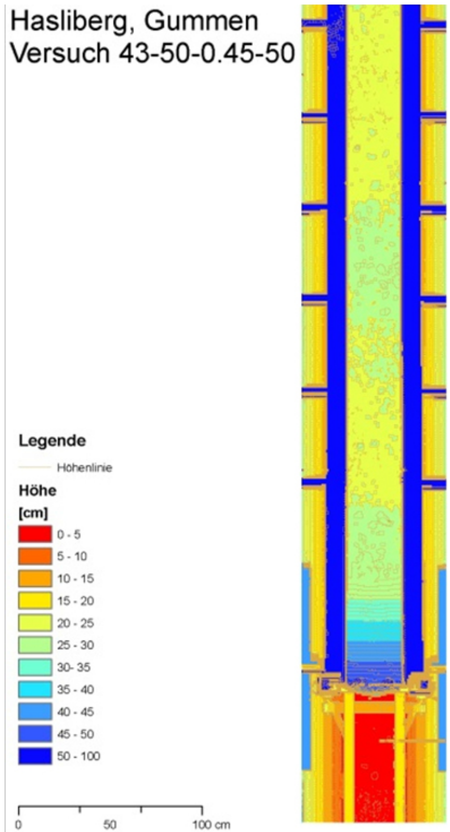

Figure 6. Topography profile of the channel after test 43.

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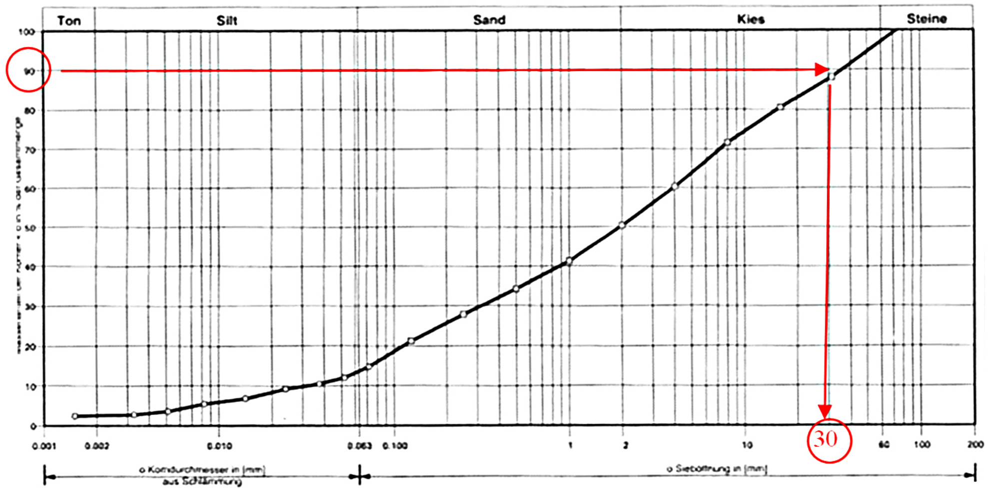

Figure 7. One of 5 sieving curves of the test material (Legend: “Ton” = clay, “Kies” = gravel, “Steine” = stones).

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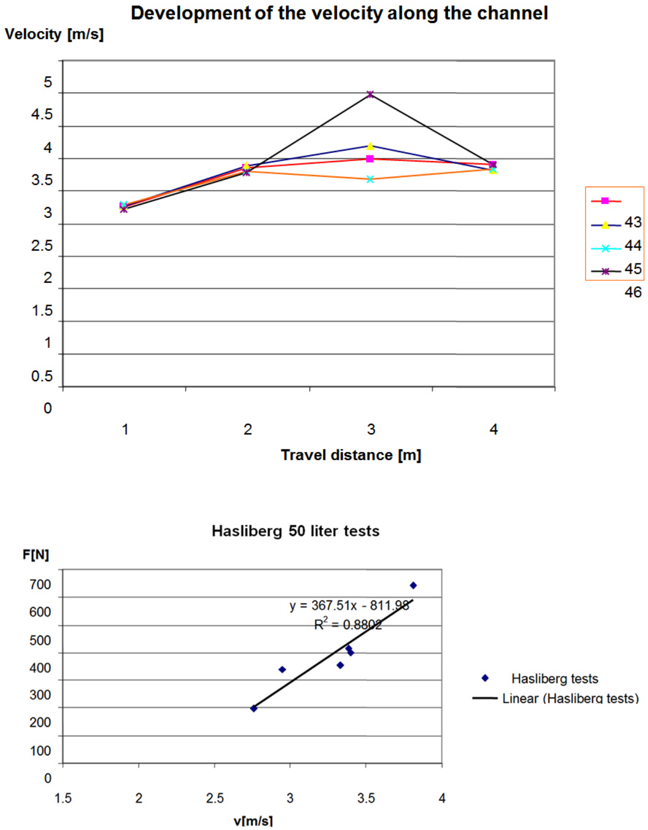

Figure 8. (a) Velocity profile along the channel length and **(b)** impact forces of the tests over the impact velocities.

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