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DEBRIS FLOW MITIGATION BY MEANS OF FLEXIBLE BARRIERS

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ABSTRACT

Flexible barriers are usually used for rockfall mitigation. Over the years, such barriers have occasionally been hit by snow avalanches, debris and mud flows. These events proved that such barriers are able to stop and retain considerable amounts of debris material. To investigate the behaviour of these systems subjected by debris flow and avalanche impacts, various field and laboratory tests were carried out in co-ordination with universities and research institutes (USA, Japan, Germany and Austria). Furthermore, a calculation model was developed to design the barriers on the basis of specific input parameters.

Key words: debris flow, snow slide, flexible barrier, field tests, design, numerical modelling, dimensioning concept, computer simulation

INTRODUCTION

Flexible wire rope and ring net barriers showed their ability to stop and retain debris and mud flows in several according events in Europe, Japan and North America. All these barriers were installed for rockfall protection purposes and were hit by debris flows by accident. These events were the trigger to take a closer look on the mechanics of such impacts and the behaviour of flexible barriers under dynamic aeral loads.

The use and performance of flexible rockfall barriers is well researched and established and therefore tools to design these barriers and to calculate occurring forces are available and can be adapted to debris flow type impacts. Such calculations and simulations are presented in this paper. To carry out field tests is naturally much harder to do than rockfall testing. At present it is only possible to test small net panels in test flumes and to install test barriers in flow prone torrents.

Also on the load side the design of debris flow barriers is much harder to do than rockfall barrier dimensioning because there are much more input parameters which can vary a lot even during a single event. But there is sufficient data available to establish empirical relationships between the most important debris flow parameters. With these parameters and the experience

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gained from actual events it is possible to dimension debris flow barriers. It is important to consider that these relationships are quite rough and of course also site specific. Therefore input parameters should always be gained from specific data and should be used with a sufficient variation to consider the nature of debris flow hazards.

In the following essay an attempt is made to show a generic way for the design and dimensioning of flexible barrier systems based on actual case studies and on a calculation model. The calculation model uses empirical relationships between debris flow parameters and is backed up by back calculations. The resistance side of the dimensioning process is based on the experience gained by rockfall testing and the consequent testing of the capacities of the components.

CASE STUDIES AND RESEARCH

Debris Flow Event Aobandani, Japan 1998

One of the most impressive impacts of debris into a rockfall barrier happened in Aobandani, Tateyama Sabo in Japan in August 1998. A temporary rockfall barrier with a design impact energy of 1'500 kJ was installed in a riverbed to protect construction works further downstream from rockfall originating from the sidewalls of the riverbed.

According to site records the barrier was hit and filled up with debris material by three consecutive surges. The total amount of stopped material was 750 m^3. The braking elements in the retaining ropes responded between 50 and 80 % and those in the support ropes between 40 and 80 % due to the dynamics of the wave impacts. The anchoring system as well as the post-ground plate assembly showed no damage after the impact. The ring net was deformed elasto-plastically and in combination with the chain link mesh retained nearly 100 % of the debris material. The deflection of the barrier in full state was about 3 m. The barrier was dismantled after the impact and the main parts such as ring nets, posts and ground plates could be re-used for a further installation.

Fig1: Debris flow event Aobandani, Japan 1998

Debris Flow Event Seewalchen, Austria 2000

Another debris flow impact into a rockfall barrier occurred in Seewalchen in March 2000, where a system with a design impact energy of 750 kJ was hit by a 200 m^3 debris and mud avalanche also containing some trees.

The barrier was hit by two surges. Due to the relatively steep terrain above the location of the barrier trees were ripped down and stopped by the barrier as well. The braking elements in the retaining ropes responded between 60 and 80 % whereas the braking elements in the support ropes responded to a maximum of 10 % only. The deflection after the impact under full load was approx. 2 m.

Fig2: Debris flow event Seewalchen, Austria 2000

Snow Slide Event Hayato, Japan 2001

During winter 2001 a snow slide hit a 750 kJ rockfall barrier which was installed above an alpine road near Hayato, Japan for rockfall protection. The amount of sliding snow was about 400 m^3. The snow slide hit two sections and was stopped by the barrier. The energy was mainly absorbed by the brake elements in the retaining ropes of the centre post. Snow slides also show areal impact characteristics but the difference to debris and mudflows is the compressibility of the snow which has to be taken into account.

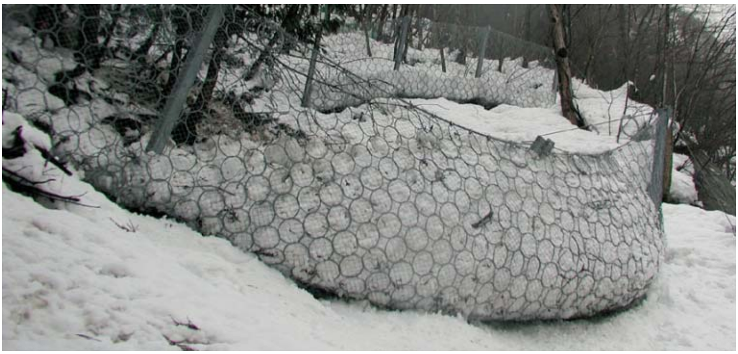

Fig3: Snow slide event Hayato, Japan 2001

Test flume H. J. Andrews Experimental Forrest, Oregon

Induced by a barrier located along the California State Route 41 which was hit by debris material in winter 1994-95 a test program was launched to investigate the behaviour of flexible barriers in a professional approach. Field testing was carried out under the support of the US Geological Survey (USGS) at the Experimental Debris Flow Flume near Blue River, Oregon. A total number of 6 tests with different barrier setups were carried out in the summer of 1996.

A full set of surveying and monitoring equipment including piezometers, lasers, ultrasonic flow depth meters and load cells were used to monitor the flows and the forces occurring in the most critical parts of the barrier. The flow itself and the behaviour of the barrier were documented by video cameras and the flow deposit was surveyed after the impact.

Fig4: Test flume H. J. Andrews Experimental Forrest, Oregon

Tab. 3: Summary of test results

Test No.	**1**	**2**	**3**	**4**	**5**	**6**
Debris volume [m3]	9.8	9.6	10.3	10.4	10.4	10.1
Impact velocity [m/s]	No signal	9.0	6.5	8.0	6.0	5.0
Deflection of net panel [m]	No signal	1.46	0.30	1.93	0.40	1.50
Consecutive flow onto deposit of test No.	No signal		2		4	
Max. force tie-back cable [kN]	No signal	16	13.5	9	6	4
dT from impact to max. force [s]	No signal	2.5	1.5	0.5	1.5	0.5

From the design point of view, the most important result from the USGS test series was that ring nets performed better compared to wire rope nets. The main advantages of ring net panels are:

- higher flexibility
- higher energy absorption capacity
- better load distribution to the superstructure
- ring links tougher than wire rope net clamps

Fig5: Ring net after test

DESIGN AND BENEFITS

Design Principles and Mode of Action

The Geobrugg flexible protection system against debris flow is based on the approved and from independent institutes certified flexible protection system against rockfall. Due to the areal load of debris flows some adaptations have to be implemented:

- stronger support and retaining ropes (or more of them), brake elements with higher capacities and ring net with lower capacity due to the areal load
- stronger anchorage
- protection of the top support ropes against abrasion
- protection system adjustable to different torrents

Figure 6 shows a principle drawing of the system. For small torrents a version without posts is proposed.

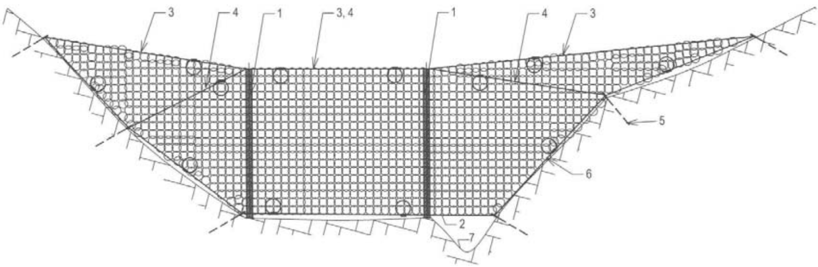

Fig6: Principle drawing of a flexible debris flow protection barrier (1-posts, 2-bottom support rope, 3,4-top support ropes, 5-cable anchors, 6-border ropes, 7-aperture for normal discharge)

Due to the permeable construction of the ring net barrier an impacting granular debris flow is drained as a result of the retention of coarse material and the passing of water and fine particles. Due to this dewatering effect a certain length of the debris flow is stopped (the so called effective length / mass) which then stops the rest of the flow.

The energy of the debris flow is mainly absorbed by the brake elements. The task of the ring net is to carry the load to the support ropes. The ring net has a proven capacity to absorb punctual impacts and has therefore ideal features for debris flow impacts because most of the large blocks in a granular debris flow are transported at the front of the flow. Experiences further show that the links between rings are much stronger than the clip connections of wire rope nets.

Range of Application and Benefits
For the location of a barrier a torrent section as straight as possible should be chosen. The inclination should be as small as possible to reduce the impact velocity and to enlarge the retention capacity. The location should further be well accessible to ensure an immediate inspection and a cleaning of the barrier if necessary. The bed at the barrier location has to be stable enough to withstand the occurring loads; otherwise additional protective measures have to be carried out.

The barriers should be checked regularly and cleaned and repaired if necessary immediately after an event. Experiences show that the cleaning of a barrier is easily practicable. Engaged brake elements have to be replaced. This is the only repair effort to be done even after big events. If the barrier is intended to remain filled with debris, static loads and corrosion have to be considered.

The range of application of the flexible protection system against debris flow is limited by a maximum volume of about 1'000 m^3 and a maximum flow velocity of about 5 to 6 m/s. For larger loads special net barrier designs with a very strong cable support and concrete abutments have to be considered (the so called Tabata Barrier stopped nearly 3'000 m^3 of debris in an event in August 2003 in Tateyama, Japan).

The main advantage of a flexible barrier compared to massive steel or concrete structures is the light weight which allows an easy and fast installation of the system. Only little foundation work has to be carried out and less material has to be carried to the barrier location which is mainly favourable in places where the access is poor. Debris flow protection projects show that flexible barriers are up to 50% more cost-efficient than solutions consisting of massive structures. Flexible barriers are further much more transparent and fit better into the landscape.

FLOW MODELLING AND BACK CALCULATIONS

Debris Flow Parameters

Natural phenomena which are located between landslide/rockfall and bed load transportation in water flows are called debris flows. They mostly occur as a result of heavy rainfall but can also be triggered by other events such as melting snow or dam failure. The pre-conditions for the appearance of debris flows are mainly steep slopes, sufficient material which is easy to mobilise and sufficient water to trigger the flow.

Under a mechanical point of view debris flows can be divided in two main types:

- **Mud flows**, which mainly consist of water and fine material, which is more or less uniformly distributed.
- **Granular debris flows**, which consist of water, fine and coarse material. The larger components are mostly accumulated at the front of the flow and play an important role in the overall flow behaviour of a granular debris flow.

Fig7: Front of a granular debris flow, Leuk-Susten 2000 (source WSL)

Observations of debris flows show that they mostly occur in surges. The number of surges is varying between two and seven while in most of the cases three surges are counted. In all observed debris flows the first surge was the largest one. The observations show further that the velocity and the consistency of the surges may vary from surge to surge. Therefore it is important to use load parameters always with a sufficient variation.

The first step is the estimation of a possible debris flow volume V_{DF}. A lot of different formulas are proposed in the literature, but they are all not very reliable. Therefore observations and experiences at the location of the project should be considered. A further method is to execute a geomorphologic assessment of the sediment potential (Rickenmann 1999). The volume for flexible protection system is in a range of 100 m^3 to 1'000m^3.

Several studies proved that the peak discharge of a debris flow is correlated to its volume. There are different relations for granular debris flows and mud flows. Mizuyama et al. propose for a granular debris flow (debris avalanche) the following empirical relationship between peak discharge and debris flow volume:

$$Q_p = 0.135\, V_{DF}^{0.78} \qquad (1)$$

Equation (2) represents the according relationship for mud flows:

$$Q_p = 0.0188\ V_{DF}^{0.79} \tag{2}$$

By using the peak discharge it is possible to estimate the average flow velocity v at the front of the flow. Rickenmann proposes a regime condition for the relation between velocity, peak discharge and slope inclination (friction considered). S refers to the gradient of the torrent.

$$v = 2.1\ Q_p^{0.33}\ S^{0.33} \tag{3}$$

Japanese guidelines suggest a Manning-Strickler equation to determine the average flow velocity (PWRI 1988). The parameter n_d refers to a pseudo-manning value which is typically between 0.05 $s/m^{1/3}$ and 0.18 $s/m^{1/3}$, while the values for granular debris flows lay between 0.1 $s/m^{1/3}$ and 0.18 $s/m^{1/3}$.

$$v = (1/n_d)\ h^{0.67}\ S^{0.5} \tag{4}$$

The flow depth h is calculated by using the cross section and the peak discharge. It is recommended to use both equations (3) and (4) and compare the results.

The density of the material is based on empirical values and is about d = 1'800 to 2'300 kg/m^3.

Energies and Forces

As a result of the dewatering of the debris flow during the impact on a permeable barrier not the whole mass of the flow has to be stopped but only an effective length or mass. The effective mass M is determined as follows: It is assumed that only that part of the flow is acting dynamically which fills up the barrier with debris between the time of contact and the time of the maximum deflection of the barrier. In the Oregon tests with volumes of 10 m^3 T_{imp} was about 1 s. Real debris flows are expected to be much larger and therefore the braking time will also last longer. T_{imp} is estimated to be between 1s and 4 s.

The effective mass is consequently calculated as follows:

$$M = d\ Q_p\ T_{imp} \tag{5}$$

The expected energy of the debris flow is determined by using the law of the kinetic energy.

$$E_{KIN} = 0.5\ M\ v^2 \tag{6}$$

Thus the kinetic energy in the range of flexible barriers is between 100 kJ and 3'000 kJ. It is important to note that the dimensioning energy may not be compared with design energies of rockfall protection systems. The reasons for this are given in table 1:

Tab1: Comparison of rockfall and debris flow impacts on flexible barriers

	Rockfall	**Debris flow**	**Influence of a debris flow on a flexible barrier compared to a rockfall**
Load	Punctual	aerial	positive due to smaller local loads
Impact time	0.2 - 0.5 s	1 - 4 s	positive due to smoother deceleration
Type of impact	Single impact	In surges	negative due to static loads in the system after the first impact
Braking distance	5 - 8 m	2 - 3 m	negative due to higher dynamic forces

In order to dimension the barrier the energy is transformed to a quasi-static force. In doing so a linear deceleration is assumed. The comparison with the measurements in Oregon and their back calculations justify this approach. By using equation (6) and Newton's second law (F=ma) it can be stated that the quasi-static force F is equal to the doubled energy E divided by the braking distance f.

$$F_{QS} = (M\,v^2) / f = (2\,E_{KIN}) / f \qquad (7)$$

Equation (7) predicts that with higher energies higher forces and with larger braking distances smaller forces can be expected which both seems to be plausible.

The deflection f of the barrier varies in height and width. It is assumed that there is an average deflection all over the barrier. With maximum deflection of 2.5 m to 3.5 m the average deflection d is about 2 m - 3 m. The result of this is that the quasi-static force varies between 100 and 2'000 kN.

Back calculation Aobandani

It is assumed that the debris volume per surge is 250 m^3 and from this a peak discharge of 10 m^3/s is calculated. To consider uncertainties and the fact that the surges are usually not distributed equally a peak discharge of 20 m^3/s is also considered for the calculations.

Table 4 – Range of debris flow parameters for Aobandoni

Qp [m^3/s]	**S**	**B [m]**	**h [m]**	**v [m/s]**	**B [m]**	**h [m]**	**v [m/s]**
10	0.4	5	0.60	4.5	8	0.38	3.3
10	0.6	5	0.53	5.0	8	0.33	3.7
20	0.4	5	0.96	6.1	8	0.60	4.5
20	0.6	5	0.84	6.9	8	0.52	5.0

Where B is the width of the flow channel and h is the flow depth. To be able to calculate impact energies the further following assumption have been made. The time as needed for the full deflection of the net due to the impact is assumed to be T_{imp} = 1 s as a minimum and T_{imp} = 4 s as a maximum. The specific weight of the flow mass is assumed to be 2'300 kg/m^3.

Table 5 – Estimated impact energies for Aobandoni

Qp [m^3/s]	**v [m/s]**	**T_{imp} min. [s]**	**T_{imp} max. [s]**	**M min. [kg]**	**M max. [kg]**	**E min. [kJ]**	**E max. [kJ]**
10	3.5	1	4	23'000	92'000	140	560
10	5.0	1	4	23'000	92'000	290	1150
20	4.5	1	4	46'000	184'000	470	1860
20	6.5	1	4	46'000	184'000	970	3900

Back calculation Seewalchen

The same approach as for Aobandoni is made considering two 100 m^3 surges impacting into the barrier. The so calculated peak discharge is 5 m^3/s.

Table 6 – Range of debris flow parameters for Seewalchen

Qp [m^3/s]	**S**	**B [m]**	**h [m]**	**v [m/s]**	**B [m]**	**h [m]**	**v [m/s]**
5	0.53	5	0.34	3.5	8	0.21	2.6
5	0.73	5	0.31	3.9	8	0.19	2.8
10	0.53	5	0.55	4.9	8	0.34	3.6
10	0.73	5	0.49	5.3	8	0.31	3.9

Table 7 – Estimated impact energies for Seewalchen

Qp [m^3/s]	v [m/s]	T_{imp} min. [s]	T_{imp} max. [s]	M min. [kg]	M max. [kg]	E min. [kJ]	E max. [kJ]
5	3.0	1	4	11'500	46'000	50	210
5	4.0	1	4	11'500	46'000	90	370
10	3.5	1	4	23'000	92'000	140	560
10	5.0	1	4	23'000	92'000	290	1150

The back calculations show that only the highest assumptions lead to the design impact energies of the respective barriers namely 1'500 kJ for Aobandoni and 750 kJ for Seewalchen. This is in accordance with the observations made on site showing that the barriers have not been loaded to the limit. Therefore the highest assumptions can be considered as worst case scenario for the two case studies and would be a conservative approach regarding the design for debris mitigation structures for the respective locations.

DIMENSIONING CONCEPT AND COMPUTER SIMULATIONS

Load

As mentioned before debris flows mostly do not occur in a single impact but in surges. Therefore only the first surge is a dynamic load on the barrier whereas the following surges are a combination of dynamic and static loads due to the steady filling up of the barrier. Naturally this also affects the stiffness of the whole system.

To assess the influence of this uncertainty, simulations were carried out to calculate the energies and forces of a debris flow impacting a flexible barrier with a given volume but with varying the number of surges from only one to five. The above introduced debris flow parameters were used as well as the following relationships:

- **Debris Volume V**: Experiences predict that the first surge is the largest and the following ones become smaller from surge to surge. It is therefore defined that the volume is cut in half from surge to surge.
- **Braking distance f:** The total deflection d is supposed to be independent of the number of surges. It is split according to the volumes of the different surges. Thus it is assumed that the braking distance increases linearly with increasing volume. The effect of increasing system stiffness is considered later.
- **Impact time T_{imp}:** The impact time T_{imp} is defined as the time between first contact of the flow with the barrier and maximum deflection of the barrier. It is kept constant for all surges. This assumption is on the safe side because the impact time would be shorter with smaller volumes and consequently also the effective mass would be smaller.
- **Gradient S:** The tests in Oregon showed that after an impact the depth of the accumulated material is decreasing upstream the barrier. Experiences confirm this observation; Rickenmann proposes a reduction of the gradient by 1/3. As a result of the decreasing gradient, the impact velocity of the surges is also decreasing from surge to surge.
- **System stiffness:** Tests with ring net panels show that the forces from impact to impact become higher although the kinetic energy remains the same. This is a result of the decreasing deformability and the increasing system stiffness.

- **Static loads:** The first surge which hits the system only acts dynamically, but all following surges are a combination of dynamic and static loads. The static loads can be calculated by using the material properties and the active earth pressure.

By using the results of these simulations a **Design Debris Flow** can be established:
The analysis of the total energies indicates that the highest energy can be expected if there is a debris flow with only one surge. This is independent of the variation of the flow parameters. It is therefore recommended to calculate the energy for the expected flow volume by considering only one surge and to bring it into the dimensioning process with the factor 1.0.

The analysis of the maximum force on the system indicates that it is more or less constant for the chosen border conditions independent of the number of surges. A sensitivity analysis with variation of all parameters by +/- 25 % shows that the maximum force with several surges is at most 40 % higher than the maximum energy with only one surge. It is therefore recommended to calculate the maximum force with the expected flow volume for the case with only one surge (without any static loads) and then to multiply it with the factor 1.5 to consider the effect of more or less surges.

The model further shows that the dynamic component is exceeding the static loads and represents the relevant case (except in long-term applications). For totally different conditions or if there are more precise values needed, the load of the debris flow can be modelled for a specific case following the surge-model.

Resistance
The maximum retention capacity of the barrier depends on the topographic situation and the height of the system. Experiences indicate that the gradient of the deposit behind the barrier corresponds to 2/3 of the original gradient of the torrent (Rickenmann 2001). The remaining barrier height is about 3/4 of the original height and thus the minimum required barrier height can be determined. If the design height gets too high, a flatter and/or wider barrier location has to be chosen.

Afterwards the distribution of the impact force over the barrier height and width has to be determined. Because the barrier is filled up with material quite quickly it is assumed that the impact force is constant over the barrier height. The distribution over the barrier width is assumed according to the torrent geometry.

By comparing the energy absorption capacity of the system (brake elements) and the expected impact energy the geometry of the deformed system can be analysed (by considering the expected elongation of the brake rings). Now it is possible to calculate the expected forces in the components which are compared with the capacities of the elements by considering common safety factors. The elements to be considered are:

- Support wire ropes (axial load)
- Retaining wire ropes (axial load, forces acting on rope)
- Cable anchors with flexible head (axial load, installation angle)
- Border wire ropes (axial load)
- Universal columns (axial load, forces acting on columns)
- Ring net (load in net plane)

The analysis of static loads (weight of the debris) by using active earth pressure showed that they are less than the high dynamic forces. Therefore the static loads are not relevant. If there is a very steep slope the static loads may exceed the active earth pressure. In such a case the static loads have to be determined by using common geotechnical approaches. Due to the lack of long-term experiences with flexible debris flow barriers, they should be checked regularly and after an event they should be cleaned and maintained immediately.

The forces acting on the retaining ropes and the posts can be estimated by using the fluid dynamic resistance of the element in the flow. Experiences show that these forces normally are not critical and even if the rope or the post is hit by a large block these elements do not fail. The connection post-ground plate is fitted with a shear pin which breaks before the post fails and the system remains effective.

In contrast to rockfall barriers debris flow protection systems are located in torrents where it is normally not possible to level the ground. Thus it has to be considered that the assembly (i.e. the angles) of the retaining ropes are very dependent on the topographic situation. Figure 8 shows an example from Japan. This barrier was further fitted with an additional ground plate in the centre of the middle section to adapt the barrier optimally to the situation.

Fig8: Debris flow barrier Tobinosu, Japan

Computer Simulations

Within the scope of a KTI project (Swiss Commission for Technology and Innovation) a computer program was developed by Volkwein to simulate the impacts of rocks into flexible ring net barriers. The project was executed in collaboration with the ETH Zurich (Federal Institute of Technology) and the WSL Birmensdorf (Research Institute for Forest, Snow and Landscape). The program is called FARO (falling rocks) and was calibrated by using the data resulting from static pull tests of single elements and 1:1 system trials.

With this simulation program it is possible to simulate the behaviour of flexible barriers under dynamic aeral loads. In doing so the occurring peak forces can be calculated as well as the bearing behaviour of the whole system can be visualized. Figure 9 illustrates an impact of a debris flow into a flexible system. It is assumed that the debris flow only hits the centre section and hits the barrier first in the bottom part and then fills up the whole system.

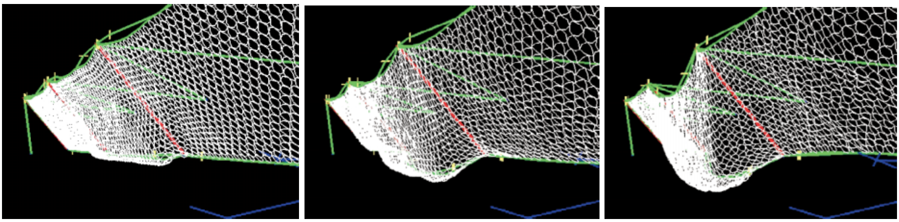

Fig9: Impact of a debris flow into a flexible barrier (simulated with FARO)

CONCLUSIONS AND OUTLOOK

The calculations and the computer simulations as well show that debris flows with a volume of up to 1'000 m^3 can be stopped by using flexible ring net barriers. For such cases they are a real alternative to rigid systems due to their large deformation capacity which is ideal to stop dynamic impacts. Due to the light construction of flexible barriers they are easy to install and cost-efficient. The barriers are transparent and fit better into the landscape than massive concrete or steel structures.

Several practical experiences from tests in Oregon and from real events confirm the calculations and further show empirically the bearing behaviour of flexible barriers and their capability to protect people and infrastructure against such natural hazards. Due to the lack of long-term experience flexible barriers should be checked regularly and should be cleaned out immediately after an event.

The hazard "debris flow" is still insufficiently researched. More work has to be done on this subject to get more reliable data on input parameters. The interaction between the front of the flow and flexible structures is another important subject which should be better researched. Furthermore debris flow parameters are very hard to predict because they vary from situation to situation and it is even possible that a flow changes its velocity and consistency from surge to surge. Therefore it is always important to consider sufficient variations on the load side.

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