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Shallow landslides controlled by flexible barriers composed of high-strength steel nets

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Abstract

On steep slopes, several different gravity driven hazards (shallow landslide, rockfall, snow slides) threaten the safety of people and infrastructure. Saturated layers of soil can form into shallow landslides and flow at relatively high speeds of up to 10 m/s (35 km/h). Depending on the speed and volume of the displaced material, shallow landslides can have a destructive impact, disrupting traffic routes and cause major damage to buildings. Considering global climate change as a risk factor, with meteorologists predicting that the likelihood of extreme rainfall events will rise across the world, the potential to trigger shallow landslides is also increasing. Therefore, suitable mitigation measures need to be designed to protect lives and infrastructure against shallow landslides. Conventional protective measures consist of structures to divert the landslide – dams or reinforced walls – require a large amount of material and labor for construction.

Flexible shallow landslide barriers are alternative protection systems that have been proven to retain mudslides and shallow landslides, even in the event of multiple impacts. The barriers can be installed with a low outlay of material and man-hours, reducing costs and construction time. In addition, on steep slopes both shallow landslide and rockfall hazards occur in similar terrain and need to be considered in combination. In this contribution we discuss the challenges in designing protection measures that can cope with both shallow landslides and rockfalls, each one characterized by different load cases. Shallow landslides impact with spreading pressures that load gradually, while rockfalls impact punctually with high velocities. We discuss the findings of a few full-scale experiments investigating different load cases; a finite element simulation software FARO used in the design of flexible wire protection systems will be presented.

1 INTRODUCTION

Multiple loading on protection measures are a common topic in flexible barrier design. For example, flexible snow nets installed in steep release zone often incur rockfall impacts in summertime, and hence the need to combine several load cases within one protection system (figures 1 and 2). The design of a flexible barrier suited to multiple load cases could be accomplished by different means. One approach could be to conduct full-scale tests for each one of the expected load cases that the barrier would face (i.e. rockfall, snow slides, debris slides or tree hit, shallow slide and debris flow), however this would be hard to realize due to the costs. A more measured approach is to assess the most important hazards for the design and do the test for these. The most severe and contrasting hazards are shallow slides and rockfall, given the differences between the two phenomena. In this paper rockfall and shallow landside hazards are briefly classified, and the important features of their load cases are discussed.

Figure 1. Snow net barrier loaded with rockfall

Figure 2. Rockfall barrier loaded with a shallow landslide.

The approach to testing, modelling and designing a shallow landslides barrier are then presented. The results from rockfall impact upon a specially developed shallow slide barrier are examined. Results are then discussed in the context of the multiple load case projects for which the barrier system was designed. The paper ends with a summary of the findings, highlighting the issues to consider when designing barrier with multiple load cases.

2 SHALLOW LANDSLIDE PROCESS AND FLEXIBLE BARRIER DEVELOPMENT

2.1 Process description

Among the large family of landslides, shallow slides or hillslope debris flows are sparsely documented and studied (Rickli, 2005). They can be defined by small failure depths or small volumes (up to 2 m or 200 m^3 respectively). They occur on steep slopes during intense rainfall and despite their small size they can reach high velocities. The failure process is fast and their location mostly unpredictable. Their evolution from failure to deposition is in the order of tens of seconds which makes observing their behavior especially difficult. Runout distances are usually smaller than a hundred meters, but if the slide is channelized by the terrain and can entrain material, runout distance may be multiplied several times and the flow will be regarded as a debris flow (Bugnion, 2011).

Due to their high bulk density and speed, shallow slides represent a serious hazard to people, buildings and infrastructures such as roads or railway lines. The potential damage is realized through the pressure they exert upon objects during the impact phase. The impact pressure results from either stopping or deflecting of the flowing material by an object. The magnitude and duration of the pressure is dependent on the kinetics and material properties of the flow as well as on the configuration of the impact event. Relationships defining impact pressure as a function of the parameters are of great importance in mitigation studies, delimitating hazard zones and in the design of protection measures like reinforced buildings, retaining walls or flexible barriers (Bugnion, 2011).

2.2 Barrier development

During full-scale shallow landslide testing debris mixtures up to 50 m^3 were released down a 40 m long 30° slope, which reached on average 5 to 11 m/s. It was during these experiments that a flexible shallow landslide barrier could be developed to withstand impact pressures up to 200 kN/m^2, also their limit loading capacity could be observed (figure 3).

The 20 experiments conducted permitted a detailed characterization of the flows; it was also possible to define a relationship between flow parameters and impact pressures. Impact pressures of the flow were measured with two square obstacles (12 by 20 cm) fitted with strain gauges placed approximately 10 m before the impact with the barrier. Flow heights and surface velocities were measured with laser distance sensors hung above the flow. From the load cells installed in the barrier's support ropes it was possible to measure the rope forces required to develop a standard design for shallow slide barriers (WSL report 10-17, 2010).

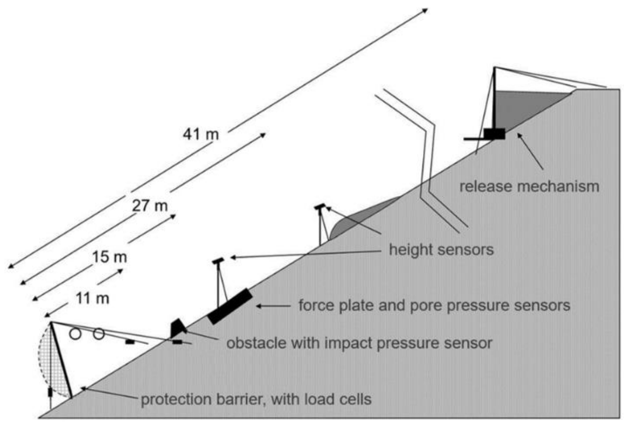

Figure 3. Experiment setup. Test channel in the cement quarry, Veltheim (Switzerland)

The knowledge of the mentioned parameters and of the characteristics of the shallow slide flow (from all 20 experiments performed) allowed developing a fluid structure interaction barrier design model, coupling both an open FOARM flow model and a FARO finite element barrier model (Bötticher, 2012; figure 4). Moreover, an engineering based quasi static pressure design model for the flexible shallow landslide barriers could be developed (Bugnion, 2012).

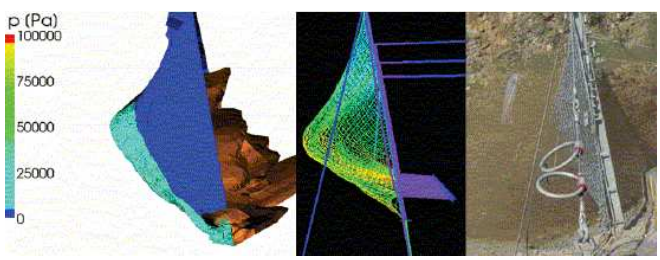

Figure 4. Modelled shallow slide impact on the flexible barrier with coupled OPEN FOARM software (fluid code) and modelled with FARO software (Finite Element Software for barrier design).

From the test and model results (figures 5 and 6) it was possible to design two standard barrier models: the light one is capable to withstand pressures up to 100 kN/m^2, the stronger one up to 150 kN/m^2. Higher impact pressures up to 200 kN/m^2 could be achieved only once due to the limitations of the test facility. However, with the aid of the calibrated computer simulation model a design system for higher pressures shallow slides could be realized.

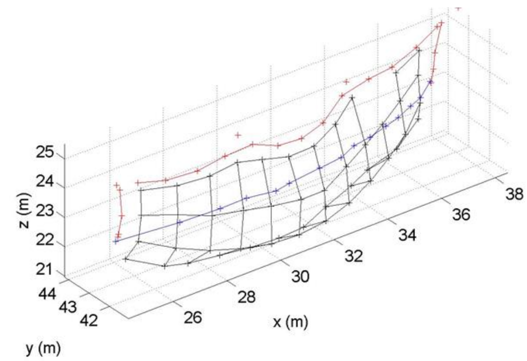

Figure 5. Simulation of load distribution during impacts

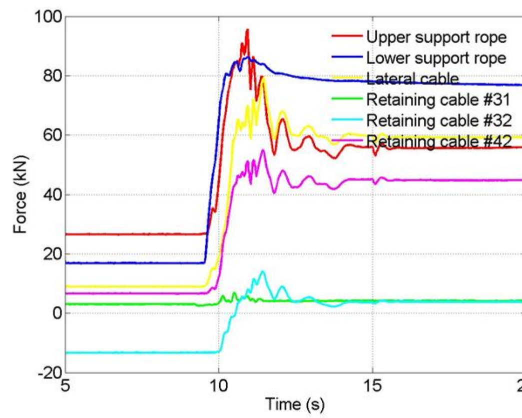

Figure 6. Load combination during impact (dynamic and static), influence into ropes.

From the measurement of the impact pressure during the different release, a back-calculation analysis can be made and the dynamic impact coefficients (c_w) that characterize the expression can be obtained, by which the impact pressure is determined in the field test (figure 7).

$P_1 = c_w \cdot \rho \cdot v^2$

where:
P_1: impact pressure, [N]
c_w: dynamic impact coefficient (0,7-1,0)
$\rho \cdot$ material density [kg/m3]
v: velocity, [m/s]

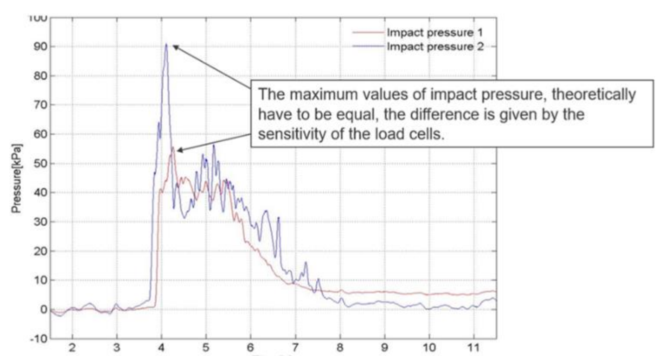

Figure 7. Impact pressure measurement at the test site.

Subsequently, the force in the cable can be calculated by which the load q is distributed in [N/m] (Palkowski 1990). F_{rope} refers to the force cable in the direction of the cable's axis (figure 8).

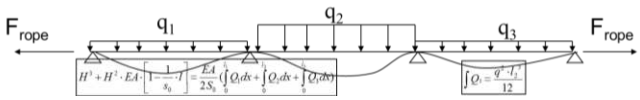

Figure 8. Analytical solution from the cable equation

2.3 Application example 1: Infrastructure protection.

Following heavy rainfall, on September 8, 2009, a shallow slide - the second in quick succession - struck the A83 (figures 9 and 10), a key through road in northwest Scotland, near the "Rest and be thankful" viewpoint.

A total of 440 m^3 of mud and debris accumulated on the road surface, which equates to about 1000 t, which forced the responsible authorities to close traffic for several days.

Figure 9. A83 road general view, after the 2009 event

With the area susceptible to shallow slides that are impossible to prevent, a suitable protective measure was needed to protect road users and ensure that the road could remain open in the event of another landslide.

Figure 10. After the landslide, the A83 road was fully blocked.

A SL-150 shallow landslide barrier, about 80 m long and 4 m high, was installed, complete with a SPIDER® spiral rope net and a secondary mesh with a mesh opening width of 50 mm (figure 11).

Figure 11. View of the road, after the installation of the barrier.

As a combined measure, an additional VX debris flow barrier, 15 m long and 4 m high, fitted with ROCCO® ring nets, was installed in an adjacent gully to prevent material seepage from flooding beneath the road. The design concept for muddy debris flows fits to the expected flow parameters (Bugnion, 2011).

At the slope of "Rest and be Thankful" several old landslide channels are obvious. The grass cover becomes thinner after each event increasing the erosion processes during normal surface flow. Therefore, during high intensity rainfalls shallow slides and debris flows are likely to occur again. As expected, this phenomenon is recurrent in this area. On December 5, 2015, once again, after heavy rains, there was sliding of the near surface layer of the slope materials. In this incident 150 m^3 of material mobilized and impacted the landslide barrier, which behaved satisfactorily as shown in the following picture (figure 12).

Figure 12. The impacted SL-150 H4 barrier after the December 2015 event

2.4 Application example 2: Direct protection.

The region of Gütsch at the city of Luzern has a history of several landslides in the last century. In 1908 even 4 fatalities occurred. The last event in 2008 even reached the buildings of Baselstrasse. The inclination of the terrain is relatively steep, more than 30°, in the region. The current hazard map of the area called “Gütsch” shows a moderate risk for landslides.

The hazard map shows clearly a moderate danger level for shallow landslides at Gütsch area behind the buildings of Baselstrasse in the City of Luzern. Law of hazard mapping in Switzerland says if modifications occur existing buildings in blue risk zone (moderate risk) of hazard maps additional protection measures must be performed to reduce risk and be declared as lower hazard risk. For this reason, the geology office of Keller + Lorenz recommended the implementation of the new flexible landslide barriers developed by Geobrugg (WSL report 10-17, 2010). This system is also tested for rockfall impacts of 500 kJ (Geobrugg AG, 2019).

The Gütsch project is the first use of this new protection system against shallow slides as direct property protection in Switzerland (figure 13). Adaptation of hazard maps after protection measures will be done according to the Protect Report (Planet report, 2008). First studies of the influence of flexible shallow slide barriers to hazard mapping were given in Wendeler 2011.

A big advantage of the flexible barriers is the fast and easy installation, low space requirements and the transparent appearance compared to conventional protection measures against shallow slides such as deviation dams or concrete walls. Mitigation measures applied directly to structures normally ends up in thick concrete walls and no openings to the expected impacted side of the house (Wegleitung, 2005). Most of the homeowners do not want to rebuild their house because of the hazard map adaptation. In such a case a flexible barrier between the house and hazard might be a preferred solution. The expected life span of these barriers in moderate corrosion classes, without any impact is approximately 30 years like flexible rockfall barriers. If the barrier gets impacted within this life period some maintenance work must be executed like opening the barrier system, digging out the material and replacement of the energy absorbing devices.

The decisive design pressure of the expected shallow slide according to Wegleitung 2005 was 120 kN/m^2 where a SL-150 barrier with a total height of 3.5 m was suitable with a tested design pressure of 150 kN/m^2.

3 ROCKFALL CONTROL PROCESS AND FLEXIBLE BARRIERS

3.1 Rockfalls

Rockfalls start by the detachment of rock debris from cliffs or rock-walls with volumes between 1 and 100 m^3 which begin down-slope motion under the influence of gravity (Rochet, 1987). Rock mass instabilities resulting in rockfall are common along natural rock-cliffs and engineered rock-cuts and can pose a severe threat to lives and infrastructure situated beneath. The release mechanism, shape and sizes of detachable rocks are governed by failure along joint planes or discontinuities (Jaboyedoff, 2011), and detachment is primarily driven by the weathering and erosion acting upon the rock-mass. After the release, rockfall motion consists of falling, bouncing, rolling or sliding (Dorren, 2003). The combination of these modes of motion defines the runout path and hazard intensity of the area subject to rockfalls (Baillifard, 2003). Typical propagation speeds can be on the order of 20-30 m/s; trajectory heights can reach 20 m or more. This is significant because it gives rockfalls substantial damage potential and it is understandable why steps are taken to predict their runout dynamics and to dimension protection structures to mitigate the hazard they pose.

Figure 13. Shallow landslide barrier in Luzern Gütsch Switzerland as direct property protection.

3.2 Flexible rockfall barriers

Rockfall protection structure design spans from simple fences to massive earthen dams capable of protecting against rockfall impacts between 100 and 50,000 kJ (ASTRA, 1998) respectively. On the spectrum of rockfall protection solutions, flexible rockfall barriers are generally designed to deal with impacts in the range of 100 to 5000 kJ, although flexible rockfall barriers have been designed (Geobrugg, 2019) to withstand impacts up to 10.000 kJ (figure 14).

Figure 14. RXE-10000 barrier (height 9m) located in Mölltal, Austria (December 16, 2019)

A key aspect to rockfall barrier design is the flexibility built into the netting and special dissipation elements which extend during an impact. These characteristics enable the high impulse and punctual forces of a rockfall to be absorbed over a bigger distance reducing the peak forces which act on the barrier (Geobrugg, 2012). None the less the forces involved during a rockfall are instantaneous if compared to a shallow landslide impact, and if a barrier must deal with both these contrasting impact dynamics, adaptations to the barrier system must be made.

3.3 Rockfall test on standard shallow landslide barrier

To address the differences in load cases, the shallow landslides barrier system developed during the testing in Veltheim was tested under the punctual impact load case of rockfall at the Dynamic Test Centre in Vauffelin, Switzerland. The test setup consisted of a 500 kJ horizontal rock impact into the standard SL-150 barrier (impact pressure strength of 150 kN/m^2). The shallow landslide barrier was able to absorb the 500 kJ impact and remained well within its serviceable condition (Geobrugg, 2012; figure 15). Tests up to its maximum design capacity of the components were never performed.

However, it is expected that the standard system can absorb rockfall energies between 1000 -1500 kJ with limited damages. It was observed that for higher rockfall impact energies, some structural system modifications would be necessary. It is possible to compare the rope forces of 500 kJ rockfall impact with forces measured during the shallow landslide impacts. From these comparisons the most important differences being:

- Impact of rockfall is highly impulsive, this is visible on the recorded rope forces which shows a duration of 200 to 300 ms which is to be compared to shallow slide impact which last over 4 to 5 s;
- Peak rope forces are similar for both load cases in the support cables;
- Peak rope forces in the upslope retaining cables are, however, higher for shallow slides for each retaining cable, due to the accumulated static load of material contained behind the barrier as it fills to the full height.
- Pressure forces in the posts are higher for shallow slide impacts compared to the tested rockfall impact. Plastic deformation could be observed at post ground plate after a shallow slide impact. No plastic deformation at the post foundation was visible after the rockfall tests.

Figure 15. EOTA standard block 1600 kg, with 500 kJ energy impact into a standard SL-150 shallow landslide barrier.

These important results have been critical to adapt the barrier for multiple load cases: both rockfall and shallow slide were considered. The details of the design adaptations are discussed in the following section on the Balisberg project which was the main motivation to perform testing on the barrier for both hazard cases.

4 PROJECT BALISBERG – MULTIPLE LOAD CASE DESIGNED ROCKFALL BARRIER

The Balisberg project was commissioned by the Swiss Railway and presented a multiple hazards case involving shallow slides and rockfalls which threatened the safety of the railway line. The engineering designers were charged with the task to develop a flexible barrier system to withstand both hazard cases, according to the hazard assessment provided by a third-party engineering office. Hazard maps were provided for both shallow slide and rockfall, defining the intensity, return period and subject areas (figure 16 and 17). Both hazard maps give a similar intensity and probability of return period (Wendeler, 2011).

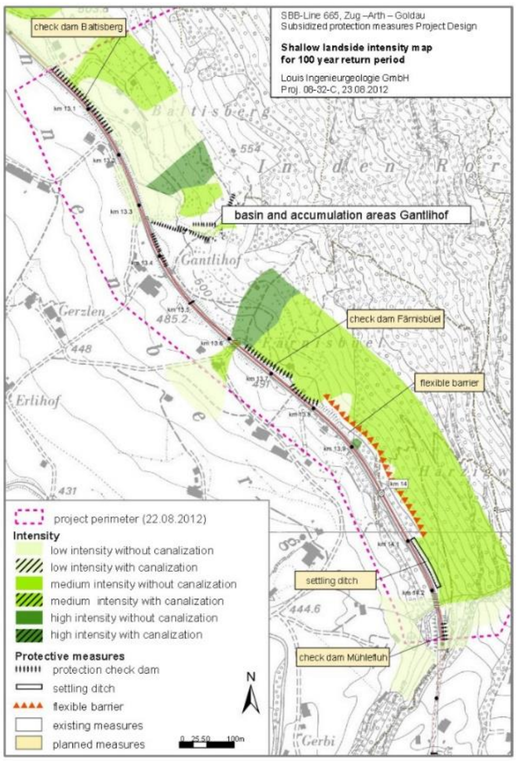

Figure 16. Shallow landside intensity map for 100 year return period, at Balisberg area.

Middle shallow slide intensity means slide failure depth (m) between 0.5 < m < 2.0 m and flow height (h) up to 1.0 m. From the landslide working group suggestion AGN (Bolliger, 2004) impact pressures up to 60 kN/m^2 must be considered for middle intensity.

The rockfall hazard map gives rockfall energies with high intensity - larger than 300 kJ (see table 1). From rockfall field investigation and simulation results design energy of 2000 kJ was found.

Table 1. Intensity classification of rockfall and shallow slide hazard maps in Switzerland acc. to AGN (Bolliger, 2004).

Process	Unit	Weak	Middle	High
Rockfall$^{(1)}$	kJ	E<30	30<E<300	E>300
Shallow landslide$^{(2)}$	m	m<0.5	0.5<m<2.0 h<1.0	m>2.0 h>1.0

$^{(1)}$E= Rockfall energy

$^{(2)}$m = failure depth and h=deposition height of the material

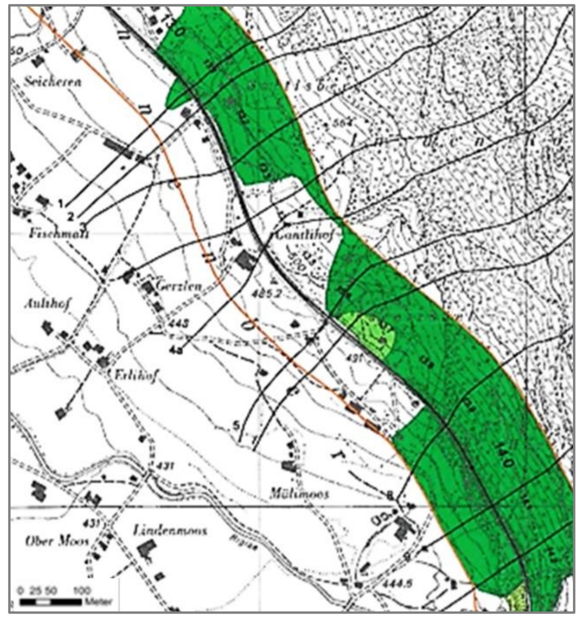

Figure 17. High intensity rockfalls, for a 100 year return period, at Balisberg area.

4.1 Numerical simulation and barrier adaptation

The required barrier system to meet the landslide hazard case was a SL-100 (design pressure of 100 kN/m^2) system, which would be sufficient for the anticipated landslide impact with a design resistance pressure of 60 kN/m^2, and for the rockfall hazard a standard rockfall barrier designed for energies up to 2000 kJ.

To meet both the landslide and rockfall design criteria it was required that a rockfall barrier to be verified for the landslide load case (Wendeler, 2016), since these were not the conditions tested during the full-scale experiments. The numerical models developed during the full-scale testing facilitated the verification and adaptation of the barrier design (Wendeler, 2016).

The approach was to consider a RXI-200 rockfall barrier, certified under the Swiss rockfall testing guideline (Gerber, 2001) for impacts up to 2000 kJ to fulfil the rockfall design energy requirements, and expose it to the impact pressures of the expected shallow slide using FARO numerical simulation model (Wendeler and Neuman, 2013; figure 4). Figure 18 shows the first impact pressure of the landslide with 60 kN/m^2 dynamic impact over a flow height of 1 m accordingly to the hazard map.

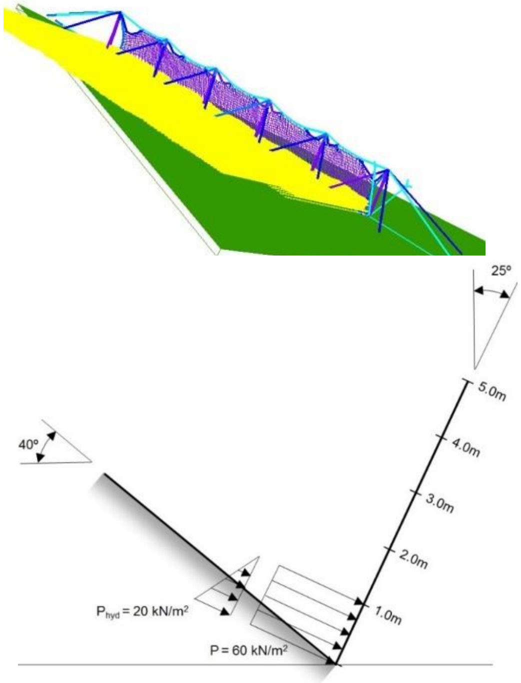

Figure 18. First load case for rockfall barrier dynamic impact pressure of 60 kN/m^2 acting overflow height of 1 m.

Figure 19 shows the filled system where the load is distributed over the affected net area and acts on the net nodes. Assumed simplified direction of the impact is rectangular to the barrier for all load cases.

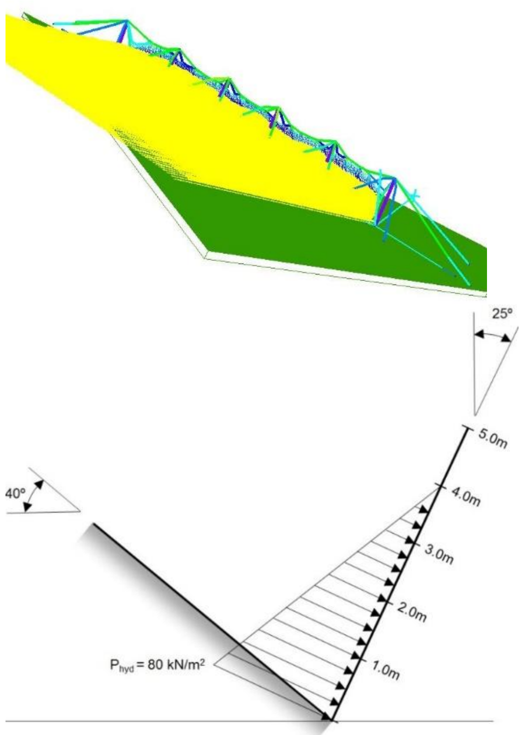

Figure 19. Second load case of hydrostatic pressure acting over filling height of 4 m.

The FARO simulation results required the standard RXI-200 rockfall barrier posts and ropes to be adapted for the landslide impact pressures. All these required adaptations did not alter the functional rockfall capacity of the tested rockfall barrier (WSL report 04-07, 2004). That was an important design criterion that had to be proven in the simulations.

5 CONCLUSIONS

Through this work it has been proven that flexible protection barriers can be designed for different impact load cases such as shallow slides and rockfalls and has clearly illustrated the case for their requirement. Inside the paper two procedures to combine rockfall load with shallow slide impact pressure have been explained in detail. The first method was based on full-scale tests of a shallow landslide barrier system which was additionally exposed to rockfall impacts. This demonstrated how the retaining, lateral, and vertical ropes, along with the posts and post foundations of a standard rockfall barrier must be strengthened to withstand the accumulative pressure loads of shallow slides. It was found that the distributed loads of shallow slides lead to higher forces to the posts due to the spreading behaviour of the impact across all barrier fields. Consequently, higher forces are applied to the retaining ropes from the larger slope parallel force component resulting from the slide impact pressure. Highly dynamic rockfall impact results in shorter force transmission to the ropes in milliseconds compared to impact loads of shallow landslide filling events which can last several seconds. The modelling results of the distributed landslide impact loads can be also transferred to rockfall barriers impacted by creeping snow or small snow slide impacts (Margeth, 2006).

In summary, each load case from a different natural hazard must be considered separately in the calculation but similarities between distributed loads like snow pressures, landslide, and debris flow pressures are obvious for the general loading behaviour, but of course with different magnitudes of impact pressure.

The rockfalls, shallow landslide and debris flow activity cannot be avoided. They are recurring hazard that threatens the integrity of the roadways, railways, buildings and lives. However, with the suggested mitigation measures the current situation can be improved. The barrier systems installed upslope of the path prevent debris accumulation in culverts which will avoid debris material flowing over the road and eroding the slope beneath.

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