CETRA 2014

3rd International Conference on Road and Rail Infrastructure
28–30 April 2014, Split, Croatia

Road and Rail Infrastructure III

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CETRA[2014]

3rd International Conference on Road and Rail Infrastructure

28–30 April 2014, Split, Croatia

TITLE

Road and Rail Infrastructure III, Proceedings of the Conference CETRA 2014

EDITED BY

Stjepan Lakušić

ISSN

1848-9850

PUBLISHED BY

Department of Transportation
Faculty of Civil Engineering
University of Zagreb
Kačićeva 26, 10000 Zagreb, Croatia

DESIGN, LAYOUT & COVER PAGE

minimum d.o.o.
Marko Uremović · Matej Korlaet

PRINTED IN ZAGREB, CROATIA BY

“Tiskara Zelina”, April 2014

COPIES

400

Zagreb, April 2014.

Proceedings of the
3rd International Conference on Road and Rail Infrastructures – CETRA 2014
28–30 April 2014, Split, Croatia

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MULTIPLE LOAD CASE ON FLEXIBLE SHALLOW LANDSLIDE BARRIERS – MUDSLIDE AND ROCKFALL

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Abstract

Shallow landslides distinguish themselves with small failure depths or equivalently small volumes (up to 2 m or 200 m^3 respectively). They release on steep slopes during intense rainfall and runout distances are usually smaller than a hundred meters. However due to their high bulk density and speed, shallow landslides represent a serious hazard to people, buildings and infrastructures such as roads or railway lines. The potential of damage is materialised through the pressure that they exert on objects during impact. The impact pressure is dependent on the kinetics and material properties of the flow as well as the geometry of the flow-object pair. Systematic study of full-scale shallow landslides was carried out at the Veltheim test site in Switzerland. Debris mixtures with volumes of 50 m^3 were released down on 30° degrees steep and 40 m long slope on the hillside of a disused quarry. Mean front velocities between 5 and 11 m/s were measured, while ranged between 0.3 and 1.0 m. Thirty meters downstream of the release mechanism two square-shape obstacles with 12x20 cm sides were installed perpendicular to the flow. Strain-gauge sensors built in the obstacles recorded the forces experienced during the impact. In addition to the pressure measurements, distance sensors hung above the test slope measured flow depths over time and permitted the computation of flow surface velocities through a cross-correlation method. Along steep slopes often besides of shallow landslides, rockfall play an important hazard. Shallow landslide release zones are often caused by a bedrock layer underneath a loose vegetation cover. If the vegetation cover is already eroded or the bedrock layer is rising suddenly the poor rock is on the surface which leads sooner or later to rockfall problems besides the sliding hazard. Both load cases, impact pressures caused by landslides and rockfall impact can be modelled with our finite element software FARO which was originally developed for flexible rockfall barriers and after a certain research time adapted for impact pressure loads. Now suitable protection measures for both hazard can be provided to propose a save solution. Even small snow slides or snow gliding impact which act similar to shallow landslides can be retained within one barrier system.

Keywords: rockfall, shallow landslides, multiple load case, barrier, debris

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 there is a desire both from the customer and designer to combine several load cases within one protection system (Figure 1).

Figure 1 Snow net barrier loaded with rockfall (left), rockfall barrier loaded with a shallow landslide (right)

There are a number of possibilities to meet the design task of a flexible barrier suited to multiple load cases. One approach would be to conduct full scale tests for each of the expected hazard the barrier would face (i.e. rockfall, snow slides, mudslides or tree hit, shallow landslide and debris flow), however this would prove highly costly. A more measured approach is to assess the most important hazards for the design and test for these. Applicable to the case study in this paper the most severe and contrasting hazards were shallow landslides and rockfall.

In this paper rockfall and shallow landside hazards are briefly classified and the important features of their load case are discussed. The approach to testing, modeling and designing a shallow landslides barrier are then presented. Following this the results from rockfall impact testing of the specially developed shallow landslide barriers are examined. The results are then discussed in the context of the multiple load case project for which the barrier system was designed. The paper concludes with a summary of the findings highlighting the requirement to consider multiple load cases in barrier design.

2 Shallow landslide process and flexible barrier development

2.1 Shallow landslide process

Among the large family of landslides, shallow landslides or hill slope debris flows are sparsely documented and studied [1]. They distinguish themselves with small failure depths or equivalently small volumes (up to 2 m or 200 m^3 respectively). They release 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 dozens of seconds which makes observing their behavior particularly difficult. Runout distances are usually smaller than a hundred meters, while if the slide is channelised by the terrain and is able to entrain material, runout distance may be multiplied several times and the flow will be regarded as a debris flow [2].

Due to their high bulk density and speed, shallow landslides represent a serious hazard to people, buildings and infrastructures such as roads or railway lines. The potential of damage is materialized through the pressure they exert on objects during impact. The impact pressure results from either stopping or deflecting of flowing material encountered by an object. The magnitude and duration of the pressure is dependent on the kinetics and material properties of the flow as well as the configuration of the flow-impact object. Relationships defining impact pressure as a function of the aforementioned 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 [1].

2.2 Shallow landslide barrier development

During shallow landslide testing debris mixtures up to 50 m^3 were released down a 40 m long 30° slope, which reached on average 5 – 11 m/s. It was during these experiments that a flexible wire shallow landslides barrier could be developed to withstand shallow landslide impact pressures up to 200 kN/m2 and also their limit loading capacity could be observed.
All 20 experiments which were conducted permitted a detailed characterization of the flows, in addition to deriving a relationship between flow parameters and impact pressures. Impact pressures in 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 landslide barriers. This in addition to shallow landslide flow characteristics from the 20 experiments performed it was possible to develop a fluid structure interaction barrier design model, coupling both an open FOARM flow model and a FARO finite element barrier model ([3], Figure 2). Additionally, an engineered based quasi static pressure design model for the flexible shallow landslide barriers could be developed [3].

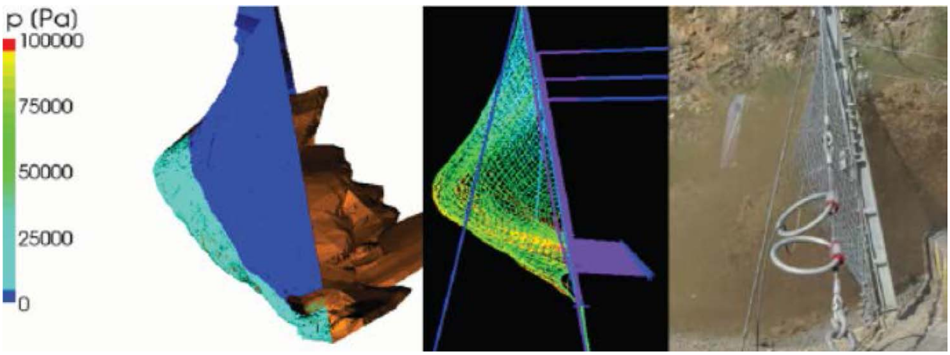

Figure 2 Modeled shallow landslide impact to the flexible barrier with coupled OPEN FOARM software (fluid code) with FARO software (Finite Element Software for barrier design) [4]

From the testing an modeling, two standard barrier systems small shallow landslide with impacts up to 100 kN/m^2 and a stronger one designed for impact pressures up to 150 kN/m^2 could be designed. 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 systems for higher pressures shallow landslides could be realized.

3 Rockfall process and flexible rockfall barriers

3.1 Rockfalls

Rockfalls are initiated by detachment of rock debris from cliffs or rock-walls with volumes between 10^{-2} and 10^2 m^3 which enter down-slope motion under the influence of gravity [5]. Rock mass instabilities resulting in rockfall are common along natural rock-cliffs and engineered rock-cuts, and can pose a sever threat to settlement and infrastructure situated beneath. The release mechanism, shape and sizes of detachable rocks are governed by failure along joint planes or discontinuities [6], and detachment is primarily driven by the weathering and erosion acting upon the rock-mass. Following release, rockfall motion consists of falling, bouncing, rolling or sliding [7], the combination of these modes of motion defines the runout path and hazard intensity of the area inundated with rockfalls [8]. Typical propagation speeds can be on the order of 25 m/s; jump 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 dimension protection structures to mitigate the hazard the pose.

3.2 Flexible rockfall barriers

Rockfall protection structures design spans simple fences to massive earthen dams capable of protecting against rockfall impacts between 100 and 50,000 kJ [9] respectively. On the spectrum of rockfall protection solutions, flexible rockfall barriers are generally designed to deal with impacts in the range of 500 – 5,000 kJ, while flexible rockfall barriers have been designed to withstand impacts up to 8,000 kJ [10]. A key aspect to their design is the flexibility built into the netting and special break elements which extend during an impact and enable the high impulsive and punctual forces of a rockfall to be absorbed over a greater distance reducing the peak forces that act on the barrier. None the less the forces involved during a rockfall are instantaneous relative to a shallow landslide impact and if a barrier is to deal with both these contrasting impacts, adaptations to the barrier system must be made.

4 Rockfall test on standard shallow landslide barriers

To address the differences in load case, 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. Tests up to its maximum design capacity of the components were never performed (see Figure 3). 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 that a few structural system modifications would be necessary.

Figure 3 500 kJ rockfall impact into a standard SL 150 shallow landslide barrier

Comparing rope forces of 500 kJ rockfall impact with forces measured during the shallow landslide impacts the most important differences are the following:

- impact of rockfall is highly impulsive visible on the recorded rope forces with 200-300 ms compared to slide impact which last over 4-5 s;
- peak rope forces similar for both load cases in the support cables;
- peak rope forces in the retaining cables are, however, higher for shallow landslides because each retaining cable due to the accumulated static load of material that piles up behind the barrier as it fills to the full height;
- pressure force in the posts are higher for shallow landslide impacts compared to rockfall impact. We could see plastic deformation at post base plate after area loaded landslide impact. No plastic deformation at the post foundation was visible at the rockfall tests.

These important results have been crucial in making the barrier adaptations for multiple load case rockfall to shallow landslide barriers. 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.

5 Project Balisberg – Multiple load case designed rockfall barrier

The Balisberg project was commissioned by the Swiss railway and presented a multiple hazard case involving shallow landslides and rockfalls which threatened the safety of the railway line. We were charged with the task of developing 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 shallow landslide and rockfall in which the intensity, return period and inundated area were delineated (Figures 4 and 5). Both hazard maps give a similar intensity and probability of return period.

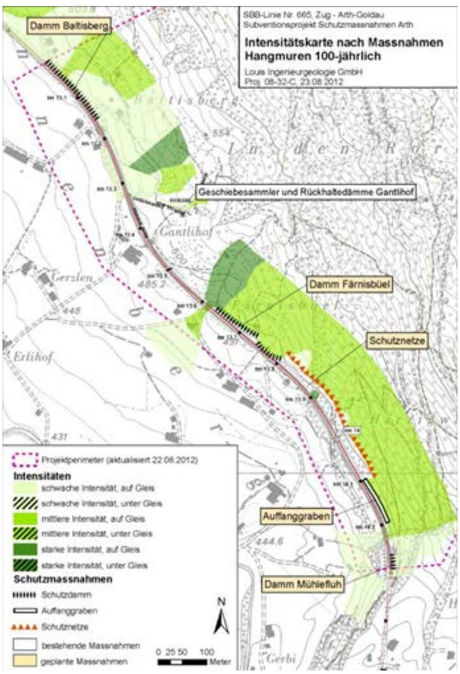

Figure 4 100 year return period intensity map of shallow landside shows for the area of projected nets a middle intensity

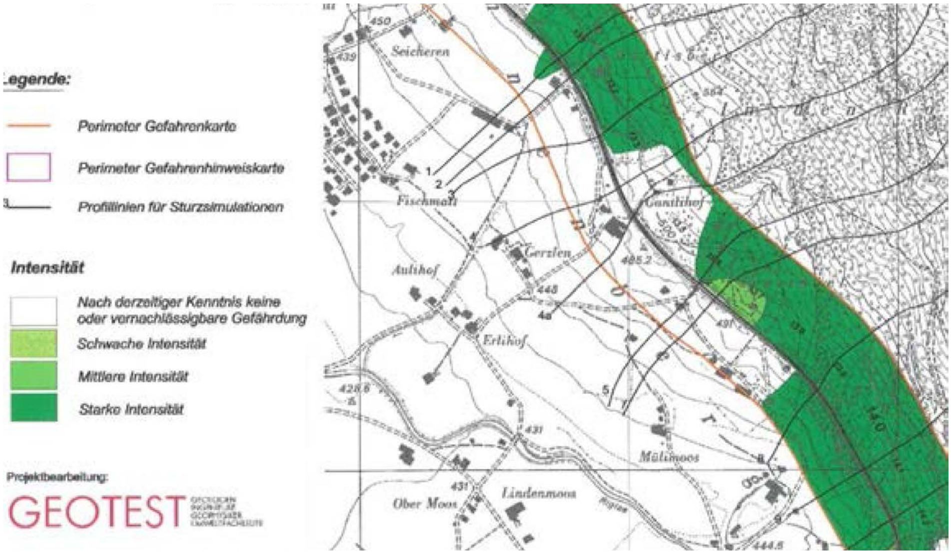

Figure 5 Intensity map of rockfall for 100 year return period shows at the area of projected nets a high intensity

Middle shallow landslide intensity means slight break failure depth M between 0.5 ‹ M ‹ 2 m and flow height h up to 1 m. From the landslide working group suggestion AGN [11] impact pressures up to 60 kN/m² have to be considered for middle intensity. The rockfall hazard map gives rockfall energies with high intensity which means energies larger than 300 kJ (see Table 1). From rockfall field investigation and simulation results the design energy results in 2'000 kJ for the net impact.

Table 1 Intensity classification of rockfall and shallow landslide hazard maps in Switzerland acc. to AGN [11].

Process	Weak intensity	Middle intensity	High intensity
Rockfall	E ‹ 30 kJ	30 ‹ E ‹ 300 kJ	E › 300 kJ
Shallow landslide	M ‹ 0.5 m	0.5 m ‹ M ‹ 2 m h ‹ 1 m	M › 2 m h › 1 m
M = failure depth; h = deposition height of the material; E = Rockfall energy			

5.1 Numerical simulation and barrier adaptation

The required barrier system to meet the hazard case was a combination of a standard SL 100 (design pressure of 100 kN/m²) system, which would fit for the landslide impact with design pressure of 60 kN/m², and a rockfall barrier designed for energies up to 2'000 kJ. This required that the barrier design be verified for this particular load case 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.
The approach was to take a standard RXI-200 rockfall barrier certified under the Swiss rockfall testing guideline [12] for impacts up to 2'000 kJ to fulfill the rockfall requirements acc. to the rockfall design energy, and expose it to the impact pressures of the expected shallow landslide using FARO (Figure 6.) numerical simulation models. Fig. 6 shows the first impact pressure of the landslide with 60 kN/m² dynamic impact over a flow height of 1 m acc. to the hazard map. On the right side the complete filled up barrier is modeled loaded by the hydrostatic pressure of the mud material over the barrier height of 4 m.

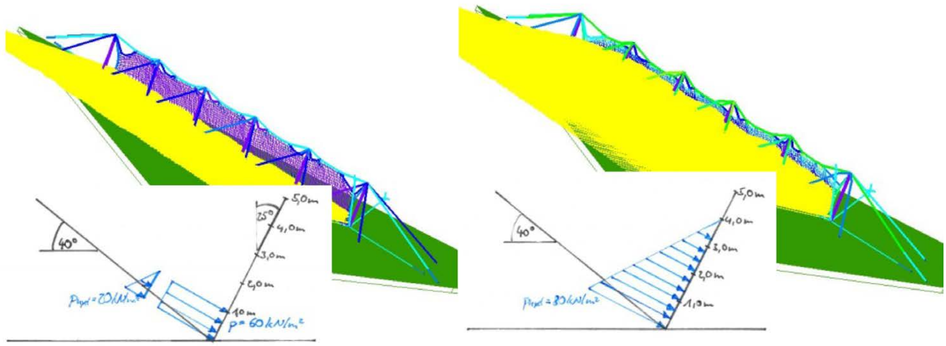

Figure 6 First load case for rockfall barrier dynamic impact pressure of 60 kN/m2 acting over flow height of 1 m (left) and second load case of hydrostatic pressure acting over filling height of 4 m (right)

Full details of the results of the simulation are given in internal design report for SBB [13]. Most important adaptations to the rockfall barrier meeting the addition shallow landslides load were to strengthen the retaining ropes and their anchors, in addition to strengthening the lateral and vertical ropes and selecting a stronger post profile and foundation. All these required adaptation according to the simulation results did not alter the functional capacity of the tested rockfall barrier [14]. That was and important design criteria that had to be proven in the simulations.

6 Conclusion

Through this work it has been proven that flexible wire protection barriers can be designed for greatly differing impact load cases of shallow landslides and rockfalls and has clearly illustrated the case for their requirement. Within the paper two procedures to combine rockfall load with shallow landslide impact pressure have been explained in detail. The first method was based on full scale tests of a shallow landslides 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 have to be strengthened to withstand the accumulative pressure loads of shallow landslides. It was found that the area loads of shallow landslides lead to higher forces to the posts due to the spreading behavior of the impact load across all barrier fields. Consequently also higher forces goes to the retaining ropes because of higher slope parallel force component resulting from impact pressure of landslides. Rockfall as highly dynamic impact results in shorter force transmission to the ropes in milliseconds compared to impact loads of shallow landslide filling which can last several seconds. These results can be also transferred to rockfall barriers impacted by creeping snow or small snow slide impacts [15].

Summarized each load case from a different natural hazard has to be considered separately in the calculation but similarities between spread out area loads like snow pressures and landslide and debris flow pressures are obvious for the general loading behavior but of course pressure values vary.

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