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Brief communication "Tree impacts into a flexible rockfall protection system"

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Abstract. In hilly terrain, on account of both timber exploitation as well as severe storms, fallen tree trunks can begin to slide, thus constituting a source of danger for people and infrastructure. Any flexible rockfall protection system that is installed under such conditions should also be designed to withstand these unique loading conditions (falling trees). A series of tests was successfully conducted with free-falling trunks. The tests showed the behaviour of a rockfall protection system, also in comparison to similar rockfall events. Numerical simulations were performed to check performance against the field tests. It could be shown that barriers can be tested and designed for tree impacts according to similar rockfall impacts.

1 Introduction

The danger of being hit by falling trees is an imminent risk in steep areas posed by forestry work, unstable tree trunks, and storms. Trees that have begun to slide can easily be shorn of all branches within a few metres of their descent and attain considerable velocities. Figure 1 (left photo) shows the impact of a tree onto a flexible rockfall barrier. Normally, the flexible rockfall protection systems available on the market are tested only for the rockfall load case according to the Swiss (Gerber, 2001) or European (EOTA, 2008) guidelines. However, barriers installed in the field are often subject to loads other than rockfall such as snow, soil, water and falling or sliding trees (see also Volkwein et al., 2009; Volkwein and Toniolo, 2011). Concerning sliding trees, tests were performed by Hamberger and Stelzer (2008) in which the trees were accelerated and impacted into a wire rope net barrier parallel to the sloping ground. It could be shown that also thin tree samples are successfully retained.

For the first time, a flexible rockfall protection system wherein the protection net consists of loosely connected rings (see also Volkwein, 2004) was tested with free-falling tree trunks in August 2005 at the rockfall protection test facility of the WSL (Gerber, 2001). The tree trunks fell vertically, one after the other, onto a rockfall protection system capable of resisting rockfall events with a kinetic impact energy of 1000 kJ.

Using the results of this test series, it is possible to evaluate whether standard or improved flexible rockfall barriers are suitable to protect from falling/sliding trees. The critical interests were the puncturing of the net and the behaviour of the net support structure. Additionally, the suitability of numerical modelling of the load case "falling trees" was also considered as to whether it is a reasonable alternative to full-scale testing.

2 Test facility and instrumentation

The rockfall test facility is located in an old quarry at Walenstadt, Switzerland, and is intended for type testing of rockfall protection systems according to Gerber (2001) and EOTA (2008). The tested barriers are mounted on a vertical rock wall; a crane having a maximum payload of 16 tonnes is positioned above the rockfall protection system. The object to be dropped can be lifted up to a height of 85 m above the level of the test area. Varying the impact velocities and/or the size (or the mass) of the falling objects, it is possible to achieve the target impact energies.

To record the impact and the energy absorption behaviour of the system, eleven load cells, designed to withstand forces up to 500 kN, were installed between the anchors and the wire ropes, each sampled with 2000 Hz. The visual documentation of the tests was achieved with two high-speed

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Fig. 1. (Left) tree impact into a rockfall protection barrier; (right) measures for preventing tree trunks from slipping through below the barrier.

Table 1. Test parameters for the three tree trunks compared to similar rockfall events into the same system and simulation of test "Tree A" (rope forces with maxima measured).

		Tree A	Tree B	Tree C	Boulder 1	Boulder 2	Simulation
Test date		26 Aug 2005	26 Aug 2005	27 Aug 2005	12 Aug 2004	18 Aug 2004	
Tree length/boulder size	[m]	10	10	15	0.9	1.1	0.6
Weight	[kg]	1600	1600	2000	1600	3200	1600
Falling height	[m]	10	20	30	32	32	
Impact velocity	[$m\,s^{-1}$]	14	20	24	25	25	14
Impact energy	[kJ]	157	314	589	512	1004	157
Impact impulse	[kNs]	22	32	48	40	80	22
Braking time	[s]	0.36	0.31	0.34	0.26	0.30	0.41
Maximum deflection	[m]	4.0	4.45	6.0	4.2	4.6	4.12
Total energy absorbed	[kJ]	220	385	705	575	1150	222
Upslope anchor rope	[kN]	64	73	114	96	135	57
Top support ropes	[kN]	205	221	228	200	230	182
Lateral anchor ropes	[kN]	156	159	153	124	131	78
Bottom support ropes	[kN]	194	184	203	198	220	183

cameras having a recording frequency of 250 images per second, installed at the same height as the point of impact. In this way, side and front views of the tests were recorded. The recorded movies allowed studying the protection system behaviour and reconstructing the chronological sequence during the braking of the impacting body by the use of the video tracking software WINAnalyze (Mikromak, 2008).

3 Test set-up

For the falling tree test, a flexible 1000 kJ rockfall protection barrier of the type Geobrugg RXI-100 was used. This system was conceived and type-tested for multiple impacts (Götz, 2006). A net made out of steel rings was installed between support ropes in such a way that it could move along the support rope like a window curtain. Support ropes were spanned over steel posts. Plastically deforming elements were integrated into the different ropes being activated and stretched at precisely defined forces. In this way, a portion of the incoming energy is dissipated and necessary flexibility of the system is enhanced. The test fence was set up as shown in Gerber (2001, p. 19). The load cells were installed both in the support ropes and in the retaining ropes.

The impacting bodies, i.e. the tree trunks, were chosen to exert an actual load for the imminent danger of falling trees, resulting in a significant loading of the barrier system. This resulted in tree lengths between 10 and 15 m with masses of 1600–2000 kg at an impact velocity of 14–24 $m\,s^{-1}$. The trunks were shorn of all branches in order to obtain a concentrated load on the protection net. For the same reason, the

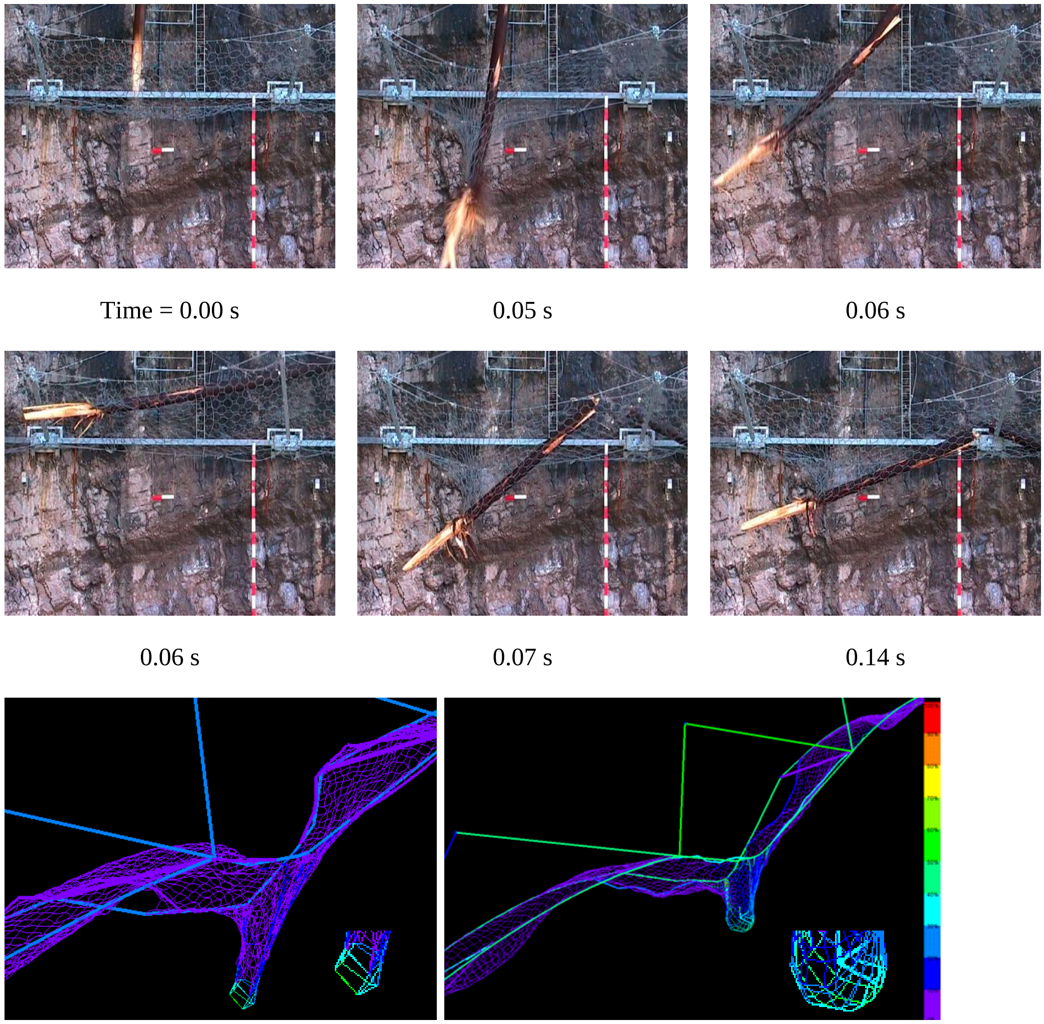

Fig. 2. (Upper and middle part) frame sequence extracted from recorded high speed video of test C – 610 kJ; (lower part) simulated rockfall protection system loaded by a falling tree (Test A on the left) and a design rockfall event with 1000 kJ (on the right) together with a magnified detail of the impact locations. The colour spectrum shows the degree of utilization of the single components ranging from 0 % (blue) to 100 % (red). Piercing of tree trunk front face not modeled in simulation.

front sections of the trunks were narrowed. The untreated sections had a diameter of up to 60 cm. The details of the individual trees and testing conditions can be found in Table 1.

The test sequence consisted of three individual tests. Both the weight of the tree trunks as well as the height from which they fell were increased incrementally from test to test. The velocities given in Table 1 are those attained by the tree trunks as they first made contact with the net.

4 Results and discussion

The tested rockfall protection system resisted the series of impacts without damage, successfully stopping the falling trees. The image sequence in Fig. 2 shows, as an example, the typical behaviour of the system and of the falling trees during the test with Tree C. This shows that the first contact between trunk and net is followed by a deformation of the net. Following the initial impact a rebound effect sets in, during which the tree trunk rebounds to the initial level of the net. After this the tree trunk comes to rest inside the net.

The deformational response of the tested system to the impact of the falling tree trunk is retrieved from the video analysis. From the data obtained, the braking time of the tree trunks, the braking distance, and the totally absorbed energy are calculated (Table 1). The braking time is the time interval from the first contact between the tree trunk and the net, up to the maximum deflection. The braking distance of the system refers to the maximum deflection of the net during the braking process. The maximum measured rope forces are grouped and also shown in Table 1.

In general, the process of energy dissipation (absorption) through the system can be described as follows: Immediately after the tree trunk contacts the protection system, the forces are transferred to all the supporting and upslope anchor ropes. The top support ropes are subjected to the highest forces. Once the tree trunk has been stopped completely by the rockfall protection system, a rebound effect can be observed. The total system behaves in a partly elastic manner and reacts with a marked relaxation phase following the first impact. A considerable part of the energy has already been absorbed by the protection system. At least two such cycles follow this phase of relaxation.

Corresponding to the increasing falling height, the impact energy rises from 157 kJ to 589 kJ (Table 1) by the factor 3.7 between Tests A and C. The increase of braking distance (= maximum deflection) from 4.0 to 6.0 m shows a factor 1.5 (Table 1), which results in a total energy absorption changing from 220 to 705 kJ (factor 3.2). The only half increase of the braking distance compared to the impact energies demonstrates that the deformation capacity of the barrier is quite large for smaller impact energies, but converges to a maximum deformation when reaching the design energy level.

Because the braking times remain relatively constant (0.31 s vs. 0.36 s), it may also be concluded that additional or increasing energy will result in increased forces within the barrier system because no additional distribution over time is possible. This can be observed for the upslope ropes (64 vs. 114 kN, Table 1). However, the support and lateral anchor rope forces seem to be more or less constant. Especially for the lateral anchor ropes, it is striking that they always experienced almost the same load, irrespective of the energies of impact. This has one main reason. The maximum system load of 589 kJ amounts to just 59 % of the system's design energy of 1000 kJ. The braking elements integrated into the support ropes have a load-deflection behaviour that exhibits a more or less constant resistance until approximately 80–90 % of its maximum deflection. Therefore, the brake elements are loaded within a range that keeps the forces in the support ropes constant. The load in the lateral anchor ropes directly depends on the support rope load and therefore also remains constant. Without any integrated brake elements, the upslope anchor ropes are attached more or less directly to the net system, and from this it can be concluded that a large part of the additional energy is transferred to the upslope anchor ropes.

The system deflection depends on the event. As expected, the system is subjected to a smaller stress in the first test than in the last. The increase of the deflection curve between Tests A and C amounts to about 2 m (Table 1). The maximum deflection of the system in Test A occurred later than in B and C. This is because of the excess plastic deformation of the overall system after Test A and the higher impact velocities in Tests B and C. Since the system remained unchanged during the tests, all the components experienced almost the entire possible amount of three-dimensional deformation. If the falling body is stopped now, the maximum deflection will be reached earlier, since it is now only the elastic deformation that needs to be overcome.

5 Computational simulation

Above results were used to verify numerical simulation performed using the software FARO (Volkwein, 2004). The software has been designed to deal with large spherical concrete boulders with a more or less smooth surface. Thus, the tree tests were an ideal opportunity to obtain field results for lower impact energies than the barrier design energy and to test the suitability of the software also against different impactors.

The computationally simulated event was Test A, and the barrier state at its maximum deflection is given in Fig. 2 (lower part) together with the degree of utilization of the single components. The numerical results show a usability of the software (Table 1), having – apart from lateral ropes – a general discrepancy of less than 11 % compared to the field test. Looking at the impact location, one can see that the loading rate of the net is much higher compared to the overall system loading rate if the impactor is small. For the maximum load test (1000 kJ) using a boulder with a larger front face than that of the tree (Fig. 2, lower right), the degree of utilization of the ring net does not differ as much from the degree of the other components as it does for the tree test. This effect is also described in more detail in Volkwein et al. (2005) and Cazzani et al. (2002).

6 Conclusions

The system passed all field tests. No maintenance or repair measures were undertaken in between the individual tests. That leads to the conclusion that such flexible rockfall barriers with ring nets are suitable to catch trees with energies close to their rockfall capacity rating. The response of the support system for the net is very similar to rockfall with the same energy level. The main difference is the higher concentrated load in the net that occurs with falling trees at the impact location. It was even observed that the trees are protruding through it.

Furthermore, it can be stated that vertical rockfall test sites like the Walenstadt facility are suitable for executing tests with falling trees. It is possible to execute such tests with energies of 600 kJ or even more in a well-defined and repeatable manner.

However, if barriers in the field have to be designed against trees, prevention of tree trunks from slipping underneath the system also has to be considered. For this case, the net could be extended at the base and fastened to the ground as shown in Fig. 1 (right photo).

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