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Autor: Berger, Frédéric / Dorren, Luuk K. A.

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Principles of the tool Rockfor.net for quantifying the rockfall hazard below a protection forest

Frédéric Berger Cemagref Grenoble (FR)*
Luuk K.A. Dorren Cemagref Grenoble (FR)

Principles of the tool Rockfor.net for quantifying the rockfall hazard below a protection forest

There are presently no clear rules for determining optimal rockfall protection forests, taking into account forest and site characteristics as well as the size and energy of the falling rock. To provide a tool that meets these requirements and quantifies the protective capacity, we have developed Rockfor.net (www.rockfor.net). This paper explains the underlying principles as well as the calculation methods used. Furthermore, it presents case studies which provide validation.

Keywords: residual hazard, energy line, basal area, web-based tool
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* 2 rue de la Papeterie, BP 76, F-38402 Saint Martin d'Hères cedex, E-Mail frederic.berger@cemagref.fr

In mountainous areas rockfall is a natural process, but due to its spontaneous release and its extreme velocities it can pose a risk for settlements and traffic routes. In this article we define rockfall as the fall of individual rocks from a cliff face (Selby 1982), where the volume of the rock can vary from one litre to several cubic meters. Rockfall occurs at all steep rock faces due to weathering and mechanical influences (Erismann & Abele 2001). At locations where hazardous rockfall events have occurred in the past, detailed studies are often carried out for risk zoning and dimensioning civil protective structures. Although civil engineering techniques developed rapidly during recent years, the possibilities for technical protection are restricted and, above all, very costly. In the European Alps, however, there are many elements that need to be protected from rockfall, as clearly indicated by the number of rocks that are stopped in forests that are upslope of many roads and settlements. Those rocks also show that forests offer an ecologically friendly and cost efficient alternative to technical protective measures against rockfall as confirmed by Jahn (1988), Gsteiger (1993), Kienholz & Mani (1994), Schwitter (1998) and Dorren et al (2005).

The forester, who is responsible for the protection provided by forests, has to be able to quantify rapidly the state of affairs regarding the protective function in a forest stand for three reasons: firstly, because a decision has to be made upon which forests require silvicultural interventions to prevent an increase of the risk posed by rockfall. Due to the natural evolution of forest stands, the protective capacity against rockfall of a forest changes over time (Ott 1978, Brang 2001). Such curative interventions prevent running behind the facts. Secondly, a quantification of the protective potential of a forest stand allows mapping forest zones where a protective function should be assigned. Thirdly, it is needed to target more detailed site investigations on local rockfall hazards as well as targeting future investments in rockfall protection using mixed civil engineering – forest management techniques.

A rapid assessment implies the calculation of the protective capacity of a forest stand using a small dataset, formalised in a user-friendly tool. The input data should give a global representation of reality and should be easy to acquire; for example, at the scale of the slope or the forest stand. Until now, an adequate tool that meets these requirements does not exist.

There are, however, guidelines for rockfall protection forests that give an idea about the required stand densities and diameters (e.g., Wasser & Frehner 1996). More recent guidelines relate required stand characteristics to the dominating rock size (e.g., Frehner et al 2005, Gauquelin et al 2006). The latter is a very important parameter, as smaller rocks have a lower impact probability, but also a low kinetic energy. Larger rocks have a higher impact probability and much more kinetic energy. In addition, the size of a rock significantly influences its modes of motion (Gerber 1998). Tools that do take the effect of the size of the falling rock into account are 2D and 3D rockfall trajectory simulation models (e.g., Zinggeler 1990, Spang & Sönser 1995, Le Hir 2005, Dorren et al 2006). However, these models require expert knowledge on modelling and on the acquisition of model parameter values in the field. As such, they are not user-friendly for forest practitioners.

One of the first concepts for quantifying the protective capacity of forests against rockfall that took the rock size into account was the «Mean Tree Free Distance» (MTFD) of Gsteiger (1993), later adapted by Perret et al (2004), Brauner et al (2005) and Dorren et al (2005). The MTFD refers to the average distance a rock travels between two tree contacts. This distance is calculated on the basis of the size of the rock, the stand density for a given planimetric area and the mean tree diameter at breast height (DBH) in that given area. Therefore, the MTFD is always expressed as a planimetric distance. Gsteiger (1993) assumed that forest stands whose MTFD exceeds 40 m cannot effectively slow down or stop falling rocks. This, however, depends on the mean slope gradient of the terrain covered by the protection forest and, more importantly, on the energy the rock develops. What is therefore very much needed is a tool that takes the slope gradient and the rock energy into account. A simple field measurement that compensates for the slope gradient is the basal area measured with a relascope (Bitterlich 1984). In addition Dorren et al (2005) state that it is a certain surface of a tree that intercepts a falling rock rather than the tree diameter. These arguments both support the development of a tool that is based on the basal area.

In summary, despite the MTFD concept and the available guidelines, there are presently no clear quantitative rules for determining the required combination of stand density and basal area, regardless of being translated into a mean DBH. This required combination should depend on the dominating rock size, its kinetic energy (to a high degree determined by the slope gradient), the length of the forested slope and the tree species present in a forest stand. To provide a tool that quantifies rapidly the protective capacity of a forest stand against rockfall, which takes into account the above mentioned parameters, we developed Rockfor.net. In this paper our first aim is to explain the underlying principles, our second is to describe the used calculation methods and our third aim is to present case studies that served for validating the tool.

Materials and methods

Real-size rockfall experiments

To calibrate the parameters used in the different calculations carried out by Rockfor.net, we carried out real-size rockfall experiments in the Forêt Communale de Vaujany in the French Alps (lat 45°12', long 6°3'). The site (Figure 1) that has been analysed in detail for this study has an altitude ranging from ~1200 m to ~1400 m above sea level and a mean slope gradient of 38°. We released 57 individual rocks with a mean diameter of 1 m from a forest road straight down the slope, using a Caterpillar hydraulic excavator. The mean rock volume was 0.52 m^3 (min. = 0.15 m^3; max. = 1.51 m^3; stddev. = 0.32 m^3, n = 57) and the mean rock mass was 1466 kg. Additional details on the experimental protocol are presented by Dorren et al (2005). The area investigated in detail for this study covers a triangle with a base of 106 m and a height of 300 m. This corresponds to a lateral deviation from the steepest down slope descent of 10° to both sides, which covers the maximum lateral deviation of the rocks released during the experiments. The mean stand density in this area is 294 trees/ha. The total basal area measured was 31.6 m^2/ha, which gives a mean DBH of 36.9 cm. The main tree species in this area are silver fir (*Abies alba* – 57%), Norway spruce (*Picea abies* – 13%), European beech (*Fagus sylvatica* – 23%) and sycamore (*Acer pseudoplatanus* – 7%).

Basic concept of Rockfor.net

The underlying idea of the tool Rockfor.net is that the existing forest is considered as a sequence of open rockfall nets that consist of a row of trees (Figure 2). These rows are hereafter referred to as curtains. Rockfor.net begins by calculating the to-

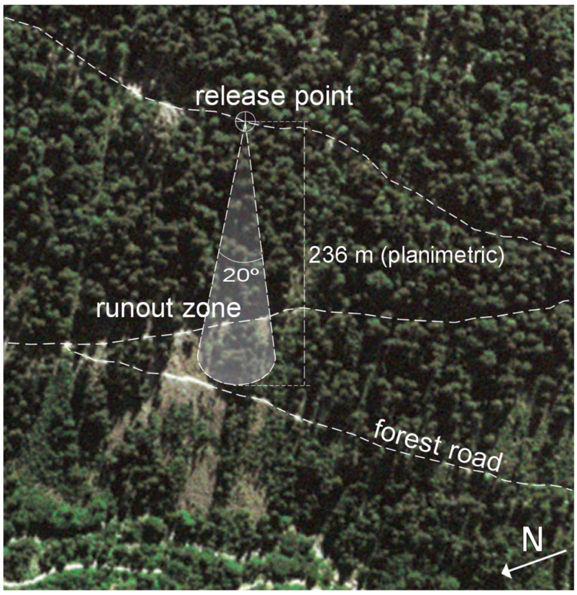

Fig 1 *Overview of the test site in Vaujany (France).*

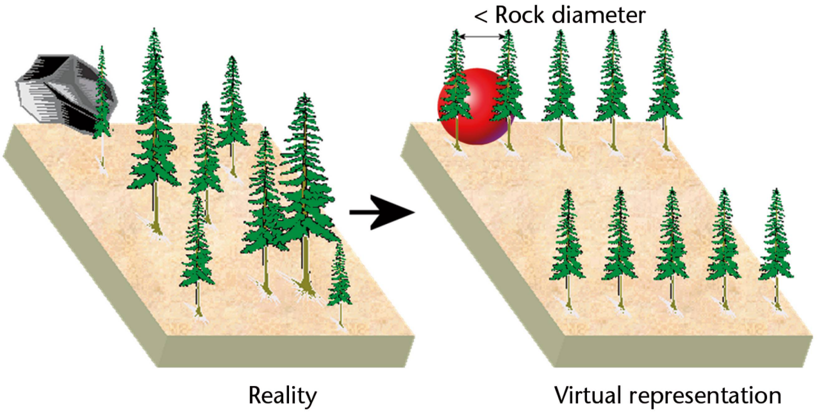

Fig 2 *Explanation of the principle for expressing a real forest structure in a sequence of virtual rockfall protective tree rows (curtains).*

tal energy developed by a falling rock, as calculated with the energy line principle. Then it calculates the energy dissipative capacity of each curtain and the number of curtains required for dissipating the total energy of the rock. Subsequently, the required number of curtains is converted in a required basal area using the mean DBH. Finally, Rockfor.net calculates the basal area that is theoretically encountered by the rock when it falls through the given forest. The protective role of the forest against rockfall can subsequently be quantified by comparing the required basal area with the theoretically encountered basal area. All these steps, as well as the calibration of the parameters needed for the calculations performed in these steps, will be explained in detail in the following sections.

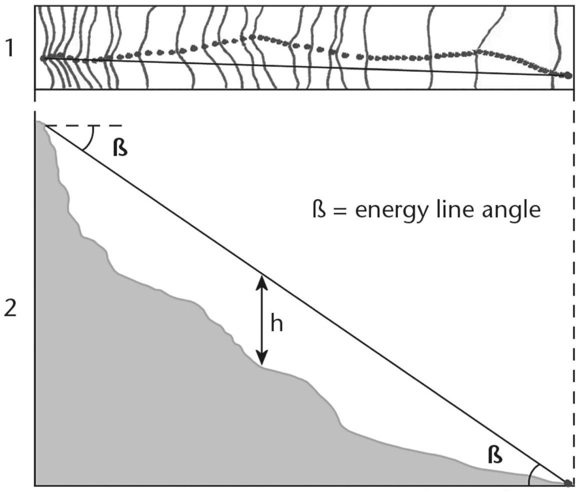

Fig 3 *Explanation of the energy line principle. Scheme 1 gives a helicopter view of a slope with the rebound positions of a rockfall event; Scheme 2 shows a cross-section of the slope with the energy line of the rockfall event.*

Energy line principle

Energy loss during rebounds cannot be taken into account in a simplified tool like Rockfor.net. Therefore, the total amount of energy that has to be dissipated is calculated with the energy line angle principle as described by Heim (1932), Toppe (1987), Gerber (1998), and Meissl (1998). The energy line principle assumes that the kinetic energy of a falling rock at a given point equals the potential energy (E_{pot}) at that given point, following

$$E_{pot} = m * g * h \qquad (1)$$

where m is the mass of the rock (kg), g is the acceleration due to gravity (9.81 m/s) and h is the height difference between the energy line and the terrain at a given point in m (Figure 3).

The energy line angle used in the tool Rockfor.net is 31°, which is the angle observed during the real-size rockfall experiments on a non-forested slope of 38° described by Dorren et al (2005) rounded down to the nearest integer. The restriction imposed by Rockfor.net is that the maximum velocity that can be attained by the rock (V_{max}), which is also calculated by the energy line following

$$V_{max} = \sqrt{2 * g * h} \qquad (2)$$

cannot be higher than 0.64 * slope gradient (°) if the total basal area (G) of the forest is at least 10 m². Here V_{max} is given in m/s. If G is lower, or if a forest cover is absent, the maximum velocity of the rock is assumed to be 0.8 * slope gradient. The values 0.64 and 0.8 are derived from the velocities observed during the real-size experiments. The maximum velocity on the forested part was 24.3 m/s and on the non-forested part it was 30.4 m/s. Consequently, we assumed a linear relationship between the slope gradient and the maximum velocity. The condition of a minimal G of 10 m² is based on observations made by Doche (1997), who found that forests with a lower G have almost no mitigating effect on rockfall. The total amount of energy to be dissipated by the forest (E_{totd}) is calculated by Rockfor.net following

$$E_{totd} = 0.5 * m * V_{max}^2 + m * g * 0.25 * Fh \qquad (3)$$

where m is the rock mass in kg, V_{max} is given in m/s, Fh is the height of the cliff or rock face and E_{totd} is given in J. The first part in equation 3 calculates the translational kinetic energy of the rock and the second part calculates an additional potential energy. Here it is assumed that 75% of the initial fall energy is dissipated during the first impact on the slope surface (Broilli 1974, Evans & Hungr 1993). The remaining 25% is considered to transform into additional kinetic energy due to rotation, which has to be dissipated by the forest as well. To evaluate the energy line principle, we compared the velocity given by the energy line principle with the absolute maximum velocity and the mean maximum velocity of all the rocks released during the experiments, which were calculated from digital films (Dorren et al 2005).

Encountered basal area

After each rock was released at the test site, we surveyed its trajectory from the release to the stopping point using an Impulse LR 200 laser distance meter manufactured by Laser Technology Inc (Centennial, Colorado, USA). If trees were impacted, we measured the basal area of the impacted tree that overlapped with the impacting rock (Figure 4). For each rock we summed to total encountered basal area (g_{en_real}) from its starting to its stopping point. Subsequently, we established a relationship between the real planimetric distance travelled and the g_{en_real} using linear regression. Next, we calculated g_{en_theo}, which is the basal area that a rock theoretically encounters after travelling a given distance through a forest with a given total basal area. This can be calculated following

$$g_{en\_theo} = (d * R_{diam}) * G / 10\,000 \tag{4}$$

where g_{en_theo} is given in m^2, d is the travelling distance of the rock (m), R_{diam} is the diameter of the falling rock (m) and G is the total basal area of the forest (m^2/ha).

To confirm the suitability of the theoretically encountered basal area (g_{en_theo}), we tested whether a significant difference exists between the linear relationship established on the basis of g_{en_real} and the g_{en_theo}, assuming a normal distribution of the estimator ($\alpha = 0.05$). In addition, we used a bootstrap analysis in which we applied 10000 linear regressions to a dataset that was re-sampled with replacement from the original g_{en_real} data. It can then be analysed if the slope of the g_{en_theo} falls within the 95% percentile confidence interval of the regression slope distribution generated by the bootstrap.

Energy dissipation per curtain

A key parameter of Rockfor.net is the ratio of the amount of energy that is actually dissipated by one curtain to the maximum amount of energy that could be dissipated by one curtain. For further convenience this parameter is called $d_{Ecfactor}$, which is actually a measure for the efficacy of each curtain.

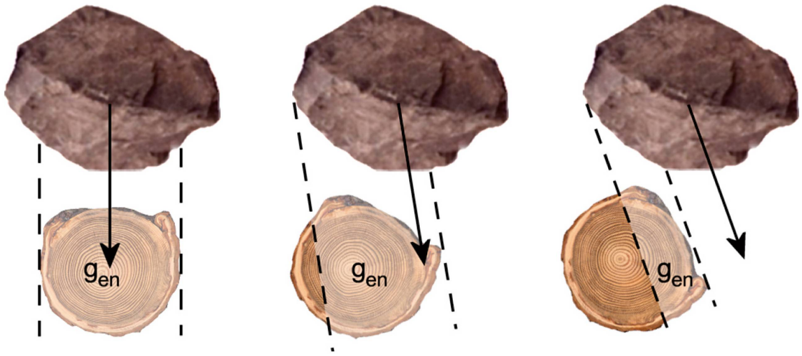

Fig 4 Basal area of the impacted tree that overlapped with the impacting rock (g_{en}).
Photo of stem disc by Michelle Bollschweiler (Dendrolab, Univ. Fribourg).

Our approach for obtaining a value for this key parameter was to calculate the g_{en_theo} at the exit of the forest upslope of the middle forest road, depicted in Figure 1, which is 175 m planimetric, or 222 m measured over the slope. Hereby, we assumed that the g_{en_theo} is representative for the observed g_{en_real}. Then, on the basis of the g_{en_theo}, we calculated the mean number of tree impacts following

$$Nr\_tree\_impacts = (g_{en\_theo} * 4) / (\pi * (DBHm)^2) \tag{5}$$

where DBHm is the mean diameter at breast height in the forest expressed in m. With the amount of energy that should have been dissipated by the forest at the point where all the rocks stopped and the calculated mean number of tree impacts, the amount of energy that is dissipated by each curtain can be calculated.

At the exit of the forest upslope of the middle forest road at the test site in Vaujany, 66% of all rocks were stopped (see also Figure 8). This means that the number of curtains required to stop all rocks (Nr_required_curtains) can be calculated with

$$Nr\_required\_curtains = Nr\_tree\_impacts * (100/66) \tag{6}$$

The virtually constructed curtains are all constituted of standardised trees. A standardised tree means that its species is a weighted mix of all occurring species in the forest (see explanation below) and that its DBH is equal to the mean DBH in the forest as derived from the G. The maximum amount of energy that could have been dissipated by one standardised tree is supposed to be given by

$$max\_E\_diss = FE\_ratio * 38.7 * DBH^{2.31} \tag{7}$$

where max_E_diss is the maximum amount of energy that can be dissipated by one standardised tree given in J, FE_ratio is the fracture energy ratio of a given tree species to *Abies alba*. DBH is the mean stem diameter at breast height (cm). Details behind this equation are described by Dorren & Berger (2006). For example, according to Dorren & Berger (2006), the FE_ratio of *Picea abies* to *Abies alba* is 0.9. By using a FE_ratio of 1, equation 7 represents the maximum energy that can be dissipated by an *Abies alba* as a function of its diameter.

If more than one tree species occur in the forest stand, a weighted average of the FE_ratio can be calculated using the species distribution in the forest. For example, if the forest consists of 80% *Abies alba* and 20% *Picea abies*, the standardised tree has a FE_ratio of 80% * 1 + 20% * 0.9 = 0.98. By that, the energy dissipative capacity of the standardised tree is determined by a «weighted mix of all occurring species».

Multiplying this amount with the number of curtains required to stop all rocks then provides the total amount of energy dissipated by the forest. Finally, the $dE_{cfactor}$ can be calculated following

$$dE_{cfactor} = E_{totd} / (Nr\_required\_curtains * max\_E\_diss) \qquad (8)$$

Results

Energy line and rockfall velocity

The comparison of the velocity given by the energy line principle, using an angle of 31° with those velocities observed during the experiments (Figure 5) shows that the energy line principle slightly underestimates the absolute maximum velocity (curve a in Figure 5) and overestimates the mean maximum velocity of all the released rocks (curve c). The curve of the absolute maximum velocity (curve a) shows the upper boundary of all maximum velocities observed. The observed velocity of a sample rock (curve d), which was the rock that attained the highest velocity, shows that the energy line principle (curve b) well represents the maximum velocities of the sample rock over the distance travelled.

Using the energy line for calculating the amount of energy to be dissipated by the forest after 236 m planimetric distance, taking into account the V_{max} restriction of 24.3 m/s on a slope of 38°, an initial fall height of 0 m, and a rock mass of 1466 kg, the energy to be dissipated equals to 433 565 J.

Encountered basal area

An analysis of the residues showed that there was one outlier in the data (Figure 7), which was discarded in further analyses. These showed that there is a linear relationship between the g_{en_real} and the real planimetric distance travelled (y = 0.003x, R^2 = 0.73, p < 0.0001, n = 56), which is presented in Figure 7. There is also a good correspondence between the linear regression of g_{en_real} and the theoretical model g_{en_theo} (Root Mean Squared Error = 0.13, n = 56). The statistical test showed that there is no significant difference between the two (p = 0.46, α = 0.05). In addition, the bootstrap analysis showed that the slope of the g_{en_theo} falls within the 95% percentile confidence interval of the generated regression slope distribution.

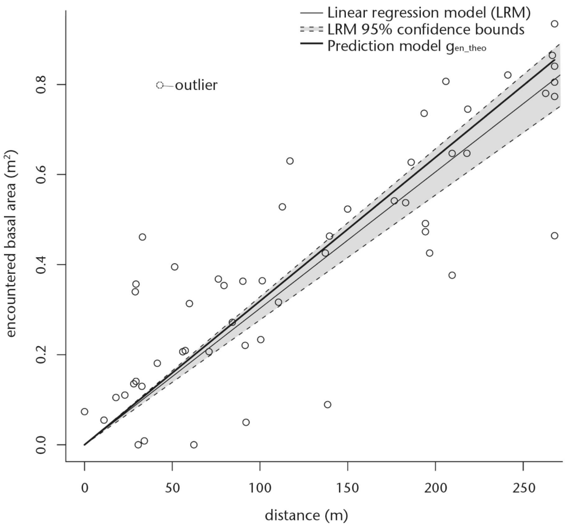

Fig 6 *The cumulated real encountered basal area (g_{en_real}) from its starting to its stopping point versus the real planimetric distance travelled from the release point for each rock (depicted as black circles). The figure further presents the linear regression of g_{en_real} with the 95% confidence bounds and the predicted basal area encountered by the falling rocks.*

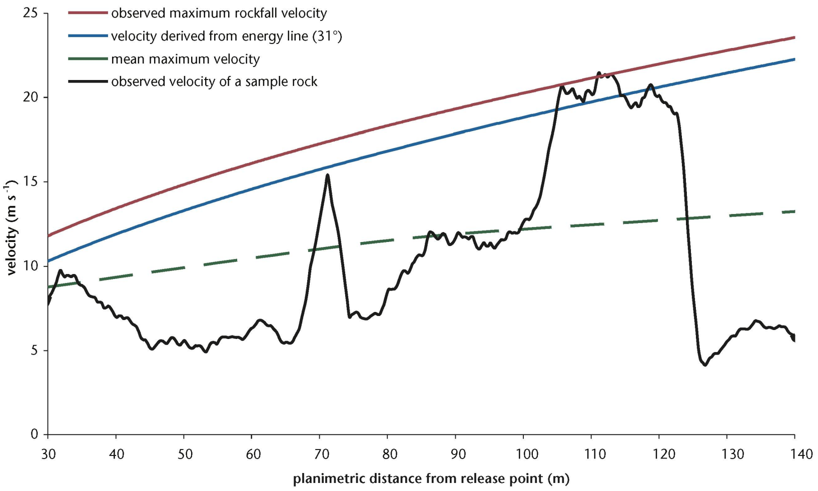

Fig 5 *Observed and predicted rockfall velocities using the energy line principle with an angle of 31°.*

Energy dissipation per curtain

The cumulated basal area that a rock theoretically encounters (g_{en_theo}) at the exit of the forest upslope of the middle forest road is 0.55 m². The real encountered basal area, calculated with the fitted linear relationship between the distance from the release point and the encountered basal area observed during the experiments, is 0.58 m². The

g_{en_theo} of 0.55 m² equals to 5.15 tree impacts or curtains. If after 5.15 curtains 66% of the rocks are stopped, the total number or curtains required to stop all rocks equals to 7.81 (equation 6). The total amount of energy that will be dissipated by the forest equals 7.81 multiplied by the amount of energy that can be dissipated by one curtain, which are all constituted of standardised trees. The maximum amount of energy that could have been dissipated by one standardised tree with a FE_ratio of 1.15 (*Abies alba* 57% * 1 + *Picea abies* 13% * 0.9 + *Fagus sylvatica* 23% * 1.7 + *Acer pseudoplatanus* 7% * 1.1) is 186 166 J (values are published by Dorren & Berger 2006). Therefore, the final $dE_{curtain\_factor}$ can be cal-

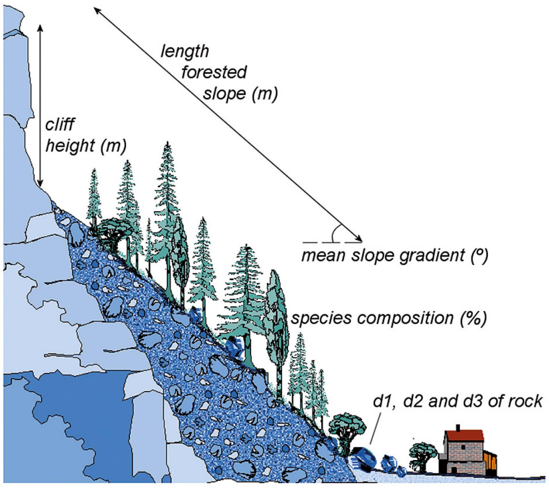

Fig 7 Scheme showing the input parameters required for the web tool Rockfor.net.

culated by dividing the total energy given by the energy line, being 433 565 J, by 186 166 J * 7.81 curtains, which provides 0.3. This value thus equals the efficacy of each curtain, or each impact.

Conceptualisation and creation of the tool

Rockfor.net quantifies the protective role of a forest against rockfall by comparing the energy that can be dissipated by a forest with the total energy developed by a falling rock. To do this, energies are expressed in encountered basal area. We assume that the difference between the theoretical basal area to be encountered to ($G_{required}$) stop all rocks and the available basal area ($G_{available}$) is indicative for the residual rockfall hazard, i.e., the number of rocks that surpass the forested zone on a given slope. Rockfor.net calculates the Probable Rockfall Hazard (PRH) below a forested slope following

$$PRH = 100 - (G_{available} * 100 / G_{required}) \qquad (9)$$

where PRH is given in percentage

$$G_{required} = Nr\_req\_curtains * \pi * 0.25 * DBH^2 \qquad (10)$$

$$Nr\_req\_curtains = E_{totd} / (max\_E\_diss * dEc_{factor}) \qquad (11)$$

$$G_{available} = ((Rock\_diameter * Slope\_length) / 10\,000) * G \qquad (12)$$

where DBH is given in m, Rock_diameter is the mean rock diameter in m and Slope_length is the length of the forested slope (m).

We fixed the minimum PRH that is given by Rockfor.net at 1%, because 100% protection is virtually impossible. To calculate the PRH, the input data presented in Figure 7 are required.

In addition to the PRH, Rockfor.net provides the required stand density and the required mean DBH in order to obtain a PRH of 1%. The required mean DBH_r is calculated following

$$DBH_r = \left(\frac{E_{totd} * Curtain_{dist}}{Slope\_length * FE\_ratio * dE_{factor} * 38.7} \right)^{\frac{1}{2.31}} \qquad (13)$$

where $Curtain_{dist}$ is the distance between two curtains, which we fixed at 30 m, a compromise between the maximum gap length in rockfall protection forests presented by Gsteiger (1993), Frehner et al (2005), Dorren et al (2005), and Gauquelin et al (2006).

The required stand density can then be calculated following

$$Rq\_stand\_density = (4 * G_{required}) / (\pi * DBH_r^2 / 10\,000) \qquad (14)$$

To provide minimum and maximum values for the mean DBH and the density of the target stand, the free and publicly available Internet version of Rockfor.net (www.Rockfor.net), which is developed in PHP (www.php.net), calculates the required DBH and required stand density by varying the input rock diameter with ± 5%. As such, the PRH given is a result of the mean PRH calculated for the input rock diameter + 5% and the input rock diameter – 5%.

Using the parameter values presented in the previous sections and applying Rockfor.net to our test site in Vaujany, and using the input values presented in Table 1 results in a PRH of 34% after 175 m planimetric distance (middle forest road) and 11% after 236 m planimetric distance (point where all the rocks stopped).

General description	Site characteristics			Forest characteristics					Rock characteristics		Rockfall hazard	
Location	Fall height (m)	Slope gradient (°)	Length non-forested slope (m)	Length forested slope (m)	Density (stems/ha)	G (m^2/ha)	DBH (cm)	Species composition	Mean diam. (m)	Type & shape	**Observed rockfall hazard (%)**	**PRH with Rockfor.net (%)**
Vaujany	0	38	0	222 299	294	31.6	36.9	Abies alb. 57% Picea ab. 13% Fagus syl. 23% Acer ps. 7%	1	Granite, sphere	**34** **0**	**34** **11**

***Tab 1** Input and output for the test site of Vaujany (PRH = Probable Rockfall Hazard).*

General description	Site characteristics			Forest characteristics					Rock characteristics		Rockfall hazard	
Location	Fall height (m)	Slope gradient (°)	Length non-forested slope (m)	Length forested slope (m)	Density (stems/ha)	G (m^2/ha)	DBH (cm)	Species composition	Mean diam. (m)	Type & shape	Observed rockfall hazard (%)	PRH with Rockfor.net (%)
Savournon (FR) 05/04/2006	49	28	0	525	1534	29.6	16	Quercus sp. 5% Fagus syl. 95%	2.84	Limestone, rectangular	66	85
St. Martin le Vinoux (FR) 06/08/1987, (Bigot 2006)	20	35	0	270	800	16.1	16	Quercus sp. 80% Pinus ni. 20%	1	Limestone, rectangular	75	78
Lumbin (FR) 07/01/2002	50	32	0	707	1080	23.3	17	Quercus sp. 5% Acer ps. 62% Robinia ps. 8%	2.35	Limestone, rectangular	100	88
Le Fontanil (FR) 1998, (inventory; Crenn 1999)	30	32.8	0	148	2750	34.8	13	Quercus sp. 65% Fagus syl. 25% Acer ps. 10%	1.25	Limestone, rectangular	25	26
Diemtigtal (CH) 2001, (inventory; Stoffel et al 2006)	50–350	40	0	90	523	20.1	22	Picea ab. 97% Acer ps. 3% (estimated)	0.15	Limestone, rectangular	<5	4 (mean)
Vailly (FR) 1997, (experiment; Doche 1997)	0	38	0	140	485	38.7	28	Picea ab. 48% Abies alb. 16% Acer ps. 21% Fagus syl. 15%	0.87	Granite, sphere	34	35
Balzers (LI) 1987, (experiment; Jahn 1988)	0	35.5	0	161	3400	–	13	Fagus syl. 50% Picea ab. 25% Pin. sylv. 25%	0.28	Limestone, sphere	0	1

Tab 2 *Observed data, input parameters used for Rockfor.net and results of validation cases (PRH = Probable Rockfall Hazard).*

Validation

To evaluate the performance of Rockfor.net we validated the developed tool with either: 1) past rockfall events, 2) rockfall forest inventories during which the stop positions of previously fallen rocks in forests were mapped or 3) data coming from rockfall experiments other than those carried out at our test site in Vaujany. All the validation cases are summarised in Table 2, which presents a general description of the source of the data, the data observed in the terrain, the input parameters used for validating Rockfor.net and the real and calculated PRH.

Discussion

The explanation of the underlying principles of the tool Rockfor.net showed that it is strongly based on the basal area. This is well justified by the linear relationship between the encountered basal area (g_{en_real}) and the stopping distance and, therefore, indirectly with the dissipated energy of the rocks released during our experiments. The correlation between g_{en_real} and g_{en_theo} provided a good basis for predicting and quantifying the protective function of a forest against rockfall. Although the parameter values of Rockfor.net are only based on the observations at one single site, it can be concluded that the tool performs well at other sites, as shown by the validation cases. The maximum error observed in the validation cases is 19% with a Root Mean Squared Error of 9.3%. More importantly, Rockfor.net predicted satisfactorily for the validation sites whether more or less all rocks would be stopped by the forest or about 25%, 50% or more than 75% of the rocks would pass the forested zone. Consequently, we believe that the basic principles of Rockfor.net can be considered valid.

Additional strong points are that the user of the tool does not need to calibrate the tool. Only site related, global input data are required and no excessive details are required. Furthermore, the tool provides specific details on the required mean diameters and the stand density at a given site in relation to the rock size, the rockfall energy and forest characteristics.

Improvements can be made regarding the calibration and the validation of the tool. Additional real size rockfall experiments at another site would allow us to re-calibrate the tool with an additional dataset. As such, we could test the robustness of the parameter values that are currently used. An important parameter used is the $dE_{curtain\_factor}$, which is currently set to 0.3. In fact, this value comes close to the probability that a rock will impact a tree frontally (P=33%), which leads to the highest energy dissipation (Dorren & Berger 2006). It would be interesting to find out whether this value changes significantly when calibrating this parameter using data from other sites.

Additional validation would allow us to test the robustness of the tool as a whole. Currently, various assumptions are included in the tool. One example is the maximum velocity restriction imposed to the energy line calculation and the underlying conditions. Another example is the assumption that the linear relationship between the g_{en_real} and the stopping distance is valid for all forest types. As for the cumulative number of rocks stopped in relation to the distance from the release point, a logarithmic function could be appropriate (Figure 8). Such a function, rather than a linear one, would increase the protective capacity of a forest stand more rapidly over the travelled distance. To better describe this function, which is of key importance for the tool Rockfor.net, additional data is needed.

Stopping reasons other than tree impacts, such as surface roughness or flat areas, are not accounted for in Rockfor.net. Due to its set-up this is impossible. However, especially smaller rocks tend to stop due to terrain features like a high surface roughness than to tree impacts. The fact that the effect of flat areas are not included explains why Rockfor.net calculated a residual rockfall hazard of 11% at the point where all the rocks actually stopped at our test site. In reality, these rocks stopped on the middle forest road (Figure 8), which is known to be a very effective protective measure (Dorren et al 2005).

Rockfor.net is currently only adapted for one typical terrain type: a cliff with a relatively straight slope covered by a rather homogeneous forest. Terrain variations, due to rock outcrops and small rock faces, or variations in the forest cover caused by local rockfall or avalanche couloirs cannot be taken into account.

Nevertheless, a basic tool is currently available that gives quite detailed information on rockfall protection forest while demanding little effort from the user. In addition, it allows the user to compare the protective capacity against rockfall of different forest stands. It provides promising first results and seems to be a valuable help for managing forests that should protect against rockfall. The tool is open for further development and validation.

Conclusions and outlook

We conclude that the basic principles of Rockfor.net can be considered as valid. Therefore, the forester currently has a tool that allows the rapid quantification of the protective function of a forest against rockfall. Priority should be given to additional validation of the tool. Further research focuses on the linkage of Rockfor.net with dynamic forest growth models, in order to test different silvicultural interventions in forest stands and their effect on the future protective capacity.

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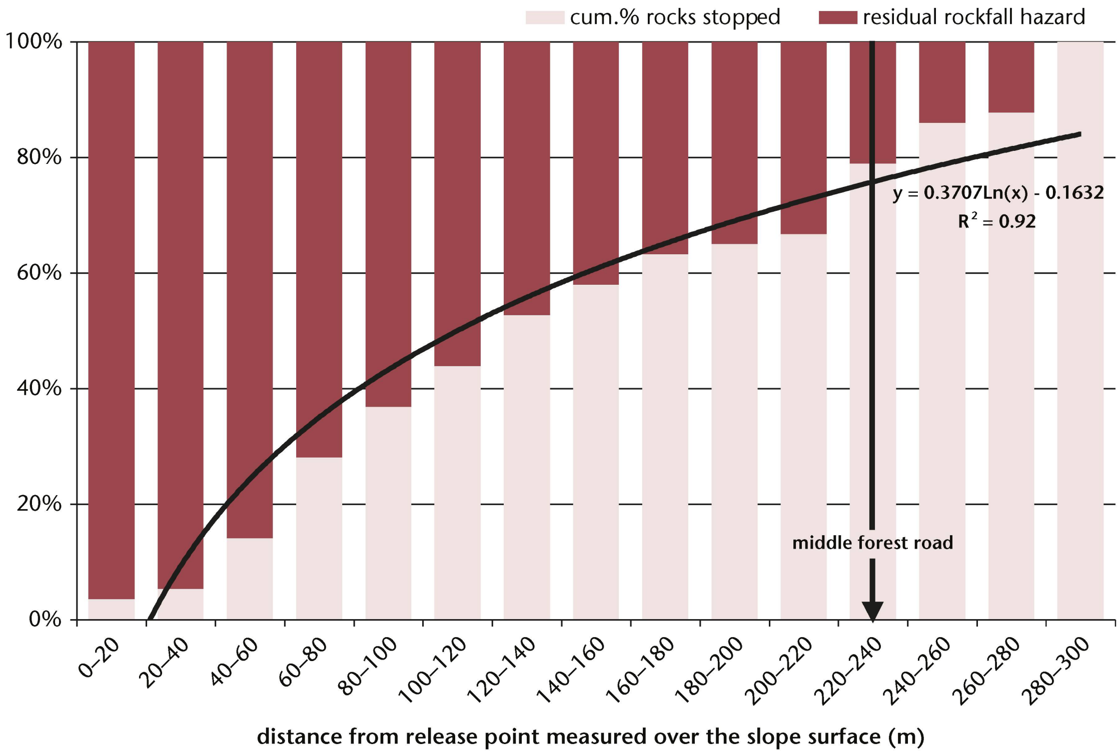
Fig 8 *Cumulative percentage of rocks stopped and the residual rockfall hazard, i.e., the percentage of rocks that surpass a given point, versus the distance from the release point as observed during the real-size experiments. A logarithmic function is fitted to the cumulative percentage of stopped rocks, which is depicted as a black curve ($R^2 = 0.92$). The dashed white line shows the linear relationship that is currently used by Rockfor.net ($R^2 = 0.98$).*



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Funktionsweise der Software Rockfor.net zur Bestimmung der Steinschlaggefahr unterhalb eines Schutzwaldes

Zur Zeit bestehen keine klaren Regeln zur Bestimmung der optimalen Kriterien von Steinschlagschutzwäldern, welche auch die Wald- und Geländeeigenschaften und die Grösse und Energie der stürzenden Felsen einbeziehen. Die Software Rockfor.net (www.rockfor.net) berücksichtigt diese Anforderungen und ermöglicht es, die Schutzwirkung des Waldes zu quantifizieren. Der Aufsatz erklärt die zugrunde liegenden Prinzipien und Berechnungsmethoden und präsentiert die Fallstudien, mit welchen die Software validiert wurde.

Mode de fonctionnement du logiciel Rockfor.net permettant de déterminer le danger de chutes de pierres en aval d'une forêt protectrice

Il n'existe actuellement aucune règle claire pour définir les caractéristiques optimales des forêts de protection contre les chutes de pierres en incluant les caractéristiques de la forêt et de la topographie, de même que la grandeur et l'énergie des blocs dévalant la pente. Le logiciel Rockfor.net (www.rockfor.net) répond à ces exigences et permet de quantifier l'effet protecteur de la forêt. Le présent article présente les principes et modes de calcul à la base du logiciel, ainsi que les exemples qui ont servi à le tester.