Resistance of Trees against Dynamic Impacts Due to Mass Movements

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Abstract

The role of trees and forests as mitigation measures is more and more taken into account in natural hazard engineering. This requires quantification of the capacity of individual trees to dissipate the energy released by dynamic impacts, which has previously only been based on data obtained from static tree-pulling tests or from dynamic impact tests on wood samples. We predicted that these data are not representative of the maximum amount of energy that can be dissipated by living trees during dynamic impacts. To test this prediction, we carried out rockfall experiments on a forested slope in the French Alps. To calculate the rock's energy before and after impact, rockfalls were filmed digitally. The recordings of nine impacts causing instantaneous breakage of *Abies alba* Mill. trees were analyzed in detail. An exponential relationship between stem diameter at breast height (DBH) and the maximum amount of energy a tree can dissipate was highly correlated for all of our experimental data. We applied this relationship to other tree species based on published fracture energies. The relationships obtained were significantly correlated with data from other dynamic impact tests in the field. The results showed that data obtained from dynamic impact tests on wood samples underestimates the maximum amount of energy that can be dissipated by living trees during dynamic impacts. The results will help improve quantification of the protective effects of trees and forests. More accurate comparisons of the protection afforded by forests with civil engineering works will facilitate the combined use of silvicultural interventions and technical protective structures in mitigating hazardous slope processes.

Keywords: it dynamic impact test, fracture energy, rockfall, bending moment

Introduction

In mountainous areas, individual trees can save lives. They can prevent the release of snow avalanches, reduce the speed of mud flows or stop falling rocks (Brang 2001, Berger et al. 2002). Due to the lack of knowledge and data, the capacity of trees to dissipate energy is generally still neglected, especially in hazard modelling studies and in calculations for the strength of protective structure against hazards. Until recently, only some data were available from static tree-pulling tests or from dynamic impact tests on wood samples to quantify the capacity of individual trees to dissipate the energy imposed by rockfall (Dorren and Berger, 2006). We anticipated that these data are not representative for the maximum amount of energy that can be dissipated by living trees during rockfall impacts. For example, the work of Mizuyama and Narita (1988) and Nonoda et al. (2004) shows that static tests produce energy dissipation values that are on average 64% ($n = 5$) lower than dynamic impact tests, on the same tree species (*Cedrus spp.*). Therefore, we carried out real size rockfall experiments on a forested slope in the French Alps. Rockfall impacts against trees were captured on digital films, to calculate the energies of falling rocks before and after the impact as well as the energy dissipative capacity of living trees. Our overall objective was to quantify the energy dissipative capacity at rockfall impacts of the dominating tree species in rockfall protection forests in the European Alps. The specific aims were firstly to come up with a relationship between the DBH and the maximum amount of energy that can be dissipated by an *Abies alba* Mill. tree. The second aim was to evaluate whether we could transfer this relationship by using literature data on fracture energy to establish similar relationships for other tree species. The third aim was to quantify the effect of the position of the impact centre on the tree stem on the amount of energy that is actually dissipated by a tree.

pp. 237–243

Fig. 1. Photo of a Silver fir (*Abies alba*) broken by a falling rock.

Materials and methods

Real-size rockfall experiments

Our study site is situated in the Forêt Communale de Vaujany in France (lat 45°12′, long 6°3′) and has an altitude ranging from 1200 m to 1400 m above sea level. It covers an area of approximately 0.9 ha on a forested, northwest facing Alpine slope, which has a mean gradient of 38 degrees. The main tree species on the site are Silver fir (*Abies alba* — 50%), Norway spruce (*Picea abies* (L.) Karst. — 25%), beech (*Fagus sylvatica* L. — 17%) and Sycamore (*Acer pseudoplatanus* L. — 4%). Other occurring species are *Sorbus aucuparia* L., *Betula pendula* Roth, *Ulmus glabra* Huds., *Ilex aquifolium* L., *Fraxinus excelsior* L. and *Corylus avellana* L. The stand density was 290 trees per hectare. The mean DBH was 31 cm, the standard deviation was 21 cm. All used rocks had approximately the same shape (spherical), volume (0.49 m^3) and density (2800 kg m^{-3}). A Caterpillar digger was used to throw the rocks down the slope. After each single rockfall experiment, we captured the trajectory of the rock with an Impulse LR 200 laser distance meter manufactured by Laser Technology Inc (Centennial, Colorado, USA). Five digital high-speed cameras were installed along the experimental site recorded all the rockfall trajectories. They were fixed at a height of 10 m in trees that are situated 30 m away from the experimental rockfall path. We measured all the tree impacts and the resulting damages on trees (Fig. 1). We measured the size of the bark wounds, the height of the impact and the horizontal distance between the impact centre and the vertical central tree axis seen from the impact direction (Fig. 2). In total, we used 102 rocks for analysis.

Before each rockfall experiment we measured the volume of the rock. All rocks had approximately the same shape (spherical), volume (0.49 m^3) and density (2800 kg m^{-3}). With this information we could determine the mass of the rock and therefore the translational kinetic energy ($E_{\text{k-trans}}$), as well as the rotational energy (E_{rot}), at any given point in its trajectory, given that the rock was clearly visible on the movie images. The total kinetic energy ($E_{\text{k-tot}}$) (J) was calculated with:

$$E_{k-tot} = E_{k-trans} + E_{rot} = 0.5 * m * \nu^2 + 0.5 * I * \omega^2 \tag{1}$$

where m is the mass of the rock (kg), ν is the translational velocity (m s^{-1}), I = moment of inertia for a sphere (0.4 * m * radius^2) (kg m^2), ω = angular velocity (rad s^{-1}). We obtained the maximum amount of energy that can be dissipated by a tree by calculating the difference between the kinetic energy of a rock before and after an impact that resulted in stem breakage. Here, we used the total kinetic energy as well as only the translational kinetic energy in order to assess whether the effect of the rotational energy could be neglected, which would minimise the uncertainty in our results.

Nine impacts that caused instantaneous breakage of *Abies alba* trees enabled us to establish a function that describes the relationship between the DBH and the maximum amount of energy in J that can be dissipated

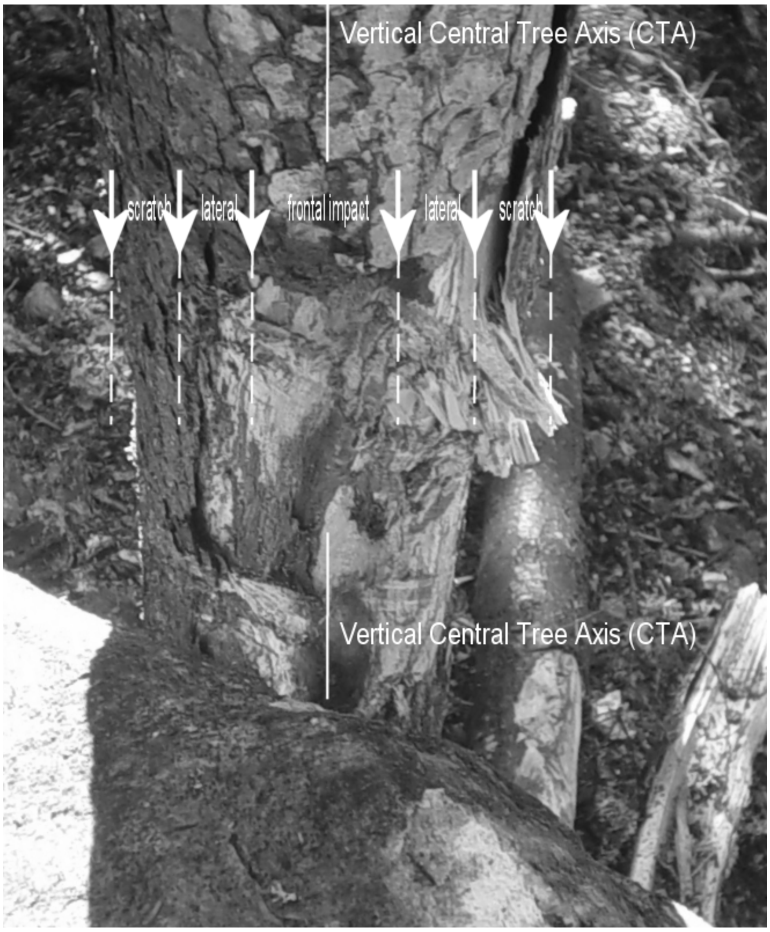

Fig. 2. The three main impact types (frontal, lateral, scratch) according to the horizontal distance between the impact centre and the vertical central tree axis (CTA) seen from the impact direction.

(max. E. diss.) by an *Abies alba* tree. To relate this obtained relationship for *Abies alba* to other dominating tree species in rockfall protection forests in the Alps, we used literature data on fracture energy values of different wood samples (Table 1). The validation of these transferred relationships is described in detail in Dorren and Berger (2006).

During the experiments we registered and measured 235 impacts on tree stems. Thirty-two impacts on trees (16 on *Abies alba* trees, 14 on *Fagus sylvatica* trees, 1 on an *Acer pseudoplatanus* tree, and 1 on a *Picea abies* tree) that were well captured on the digital films allowed establishing a relationship between the energy dissipated by the tree and the horizontal distance between the impact centre and the vertical central tree axis (CTA), as seen from the impact direction (see Fig. 2). The other 203 impacts could not be used, because the impact was hidden behind other trees on the digital films. According to the distance between the impact centre and the CTA, we defined three main impact types: frontal, lateral and scratch (Fig. 2). For each impact type we determined the occurrence frequency and the efficacy regarding stopping a falling rock.

Results

Figure 3 shows the relationship between the maximum amount of energy that can be dissipated by a tree given its species and its diameter at breast height (DBH). The *Abies alba* line shown in this figure is the best-fit function ($R2 = 0.92$, $P < 0.001$, $ME = -14.1\%$, $RMSE = 39.0\%$) based on measurement of energy loss during the breakage of different 9 due to rockfall impacts. It shows that the amount of energy that can be dissipated by a living tree increases exponentially with its DBH.

Figure 4 shows additional DBH — max. E. diss. relationships that are based on field and laboratory impact tests on *Fagus sylvatica samples* described by Couvreur (1982) and Sell (1987). The laboratory based relationships (the lines called sample) are similar in the sense that both provide much lower energy dissipation values than the ones we obtained for *Fagus sylvatica* (average difference -61%).

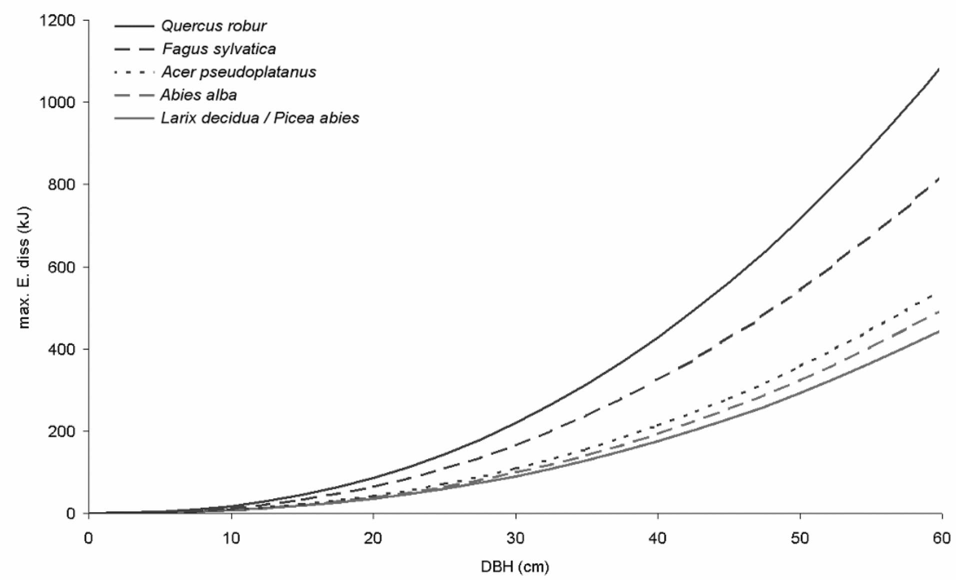

Fig. 3. The relationship between the maximum amount of energy that can be dissipated by a tree given its species and its diameter at breast height (DBH).

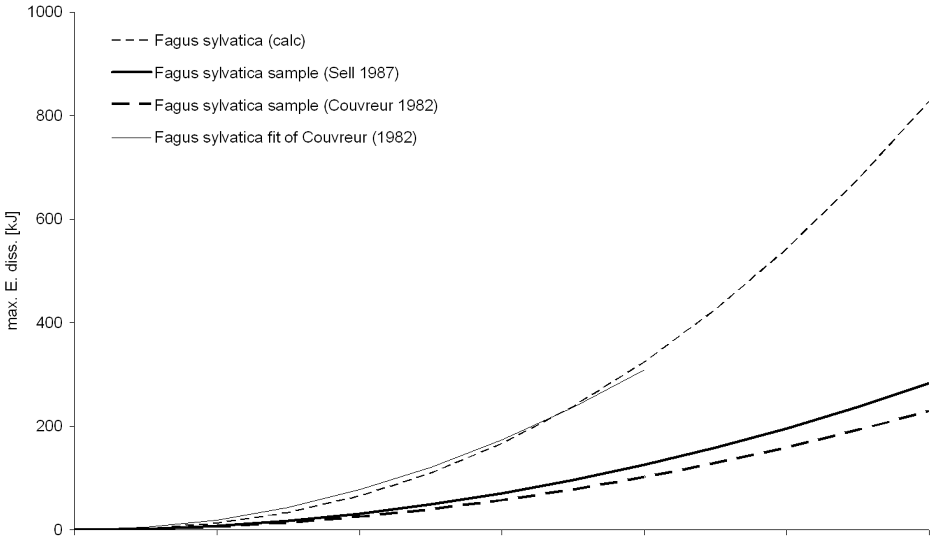

Fig. 4. The relationship between the maximum amount of energy that can be dissipated by a *Fagus sylvatica* tree and its DBH: *Fagus sylvatica* is the relationship calculated on the basis of our field data for *Abies alba* and the ratio presented in table 1; *Fagus sylvatica* fit of Couvreur (1982) is based on data obtained by his dynamic impact tests in the field; *Fagus sylvatica* sample (Sell 1987) and *Fagus sylvatica* sample (Couvreur 1982) are relationships calculated on the basis of dynamic impact tests on wood samples in the laboratory;

Table 1. Minimum, mean and maximum fracture energy of different wood samples as obtained by Couvreur (1982) and Rupé (1991) and the mean ratios to *Abies alba* and *Fagus sylvatica.*

Tree species	Fracture energy (J cm^{-2})			Ratio to	Ratio to
	Min.	Mean	Max.	Abies alba	*Fagus sylvatica*
Cedrus spp.	3.3	3.3	3.3	0.7	0.4
Picea abies (L.) Karst.	4.0	4.4	4.8	0.9	0.5
Larix decidua Mill.	4.0	4.4	4.8	0.9	0.5
Abies alba Mill.	4.3	4.9	5.5	1.0	0.6
Pinus nigra Arn.	5.5	5.5	5.5	1.1	0.7
Pinus sylvestris L.	5.5	5.5	5.5	1.1	0.7
Acer pseudoplatanus L.	5.5	5.5	5.5	1.1	0.7
Fraxinus excelsior L.	7.3	7.3	7.3	1.5	0.9
Fagus sylvatica L.	7.5	8.1	8.8	1.7	1.0
Quercus robur L.	8.8	10.6	12.5	2.2	1.3
Robinia pseudoacacia L.	11.5	13.4	15.3	2.7	1.6

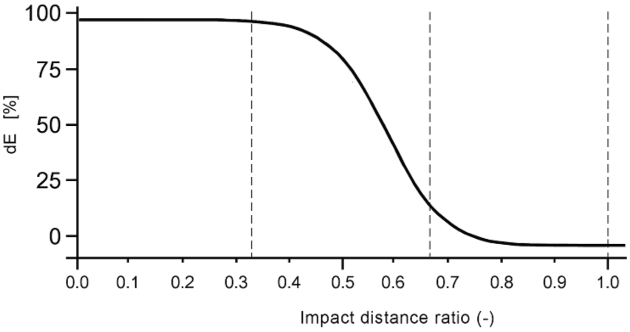

Fig. 5. The sigmoidal relationship between the horizontal impact distance ratio (see text for explanation) and the fraction of the maximum amount of energy that is dissipated by a tree.

Analysis of the translational kinetic energy before and after 32 impacts on different tree species showed that the fraction of the max. E. diss. that will dissipated by a tree depends on the horizontal impact distance ratio. This is the distance between the impact centre and the vertical central tree axis divided by the radius of the tree.

Our results show that it can be calculated with the following sigmoidal function (Fig. 5):

$$dE = -0.046 + \frac{0.98 + 0.046}{1 + 10^{(0.58-((Ci-CTA)/0.5*DBH)*-8.007}} \tag{2}$$

where dE is the fraction of the max. E. diss. (%) that will be dissipated at the impact, Ci − CTA is the horizontal distance between the impact centre and the vertical central tree axis seen from the impact direction (m), DBH is given in m. This function is highly correlated to the experimentally obtained data ($R^2 = 0.98, P < 0.001, ME = 4.8\%, RMSE = 26.5\%, n = 32$).

Discussion and conclusions

The overall objective of this study was to quantify the energy dissipative capacity at rockfall impacts of the dominating tree species in rockfall protection forests in the European Alps. The first main result is the empirical demonstration of the relationship between the DBH of *Abies alba* trees and the maximum amount of energy they can dissipate (max. E. diss.) at a rockfall impact. We found an exponential relationship between the DBH and max. E. diss, which highly correlates with our experimental data.

In the case of a rockfall impact, the kinetic energy of the rock causes displacement and deformation of the tree stem as well as the root-soil system. If the tree is anchored well enough in the soil to prevent uprooting and if the stem does not fracture or break, a sinusoidal shockwave is transferred through the stem to the tree crown. Thereby most coniferous trees start swaying and, depending on how closely the tree crown is surrounded by other tree crowns that stabilise the crown, they loose their top. The root-soil system, the stem and the tree crown all thus play an important role in dissipating the impact energy. The volume of a tree increases exponentially with the DBH, and with it also the crown size and the size of the root system (e.g., Morgan and Cannell 1994, Peltola et al. 2000). This probably explains why the energy dissipative capacity increases exponentially with increasing DBH.

To establish the relation between the DBH and the max. E. diss. we only used the translational kinetic energy instead of the total kinetic energy before and after impacts. This resulted on average in max. E. diss. values that are slightly too high (on average 0.2%), but it minimised uncertainty due to errors in the angular velocity measurements.

The second main result of this study is that the basic exponential relationship between the DBH and max. E. diss. for *Abies alba* can be transferred to other tree species by using literature data on fracture energies. On the basis of the results presented here and in Dorren and Berger (2006) we believe that it is possible to transfer the relationship obtained for *Abies alba* to other tree species by using literature data on fracture energies. Therefore, we now use this method to obtain relationships between DBH and max. E. diss. for different tree species in our simulation models. Moreover, at present, no other data are available.

The data also confirm that broadleaved trees are generally more resistant to breakage, which we also observed during the experiments. Nevertheless, the relationships for the tree species other than *Abies alba*, *Fagus sylvatica* and *Picea abies* still have to be validated by additional impact tests. Dynamic impact tests on wood samples are not suitable for this, as this study showed that they produce lower energy dissipation values than dynamic impact tests on living trees.

The last main result of this study is the quantification of the change in energy dissipation due to the horizontal position of the centre of the rockfall impact on the tree stem. An attempt to estimate the fraction of the max. E. diss. that will be dissipated by a tree at an impact, related to the horizontal distance between the impact centre and the vertical central tree axis has been made by Dorren and Seijmonsbergen (2003) and by Dorren et al. (2004). This was not based on experimental data, but it was merely a hypothetical relationship developed for their simulation model. The relationship obtained in this study highly correlates with the experimentally gained data and is therefore valuable for rockfall and protection forest research. Finally, the results obtained in this study enable us to better understand the functioning of single trees facing rockfall impacts and impacts by comparable mass movements in general. This improves the quantification of the protective effect of forests and trees against dynamic impacts. As such, we can better compare protection forests with civil engineering works and promote the combined use of silvicultural interventions and technical protective structures where possible.

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