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## Advanced rockfall modelling for risk mitigation: tree impact and fragmentation

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Despite their centrality to rockfall risk management, two issues are frequently overlooked: the role of forests in rockfall dynamic and the fragmentation phenomenon. To investigate the importance of these issues we have developed advanced modelling case studies in two representative sites that have been recently affected by rockfall events in the Aosta Valley Region (Western Italian Alps). In the Saint Oyen case study, about 17,500 m<sup>3</sup> of rock detached in March 2019 and reached a service road and the sport center in the lower part of the slope, passing through a mature fir forest. The presence of the forest has significantly influenced the rocks distribution along the slope, increasing the lateral dispersion of trajectories and reducing the mobility. For the design of defensive works, 3D rockfall models of three future potential risk scenarios were therefore performed by using the tree-impact algorithm of the code HY-STONE (Frattini et al., 2012). This algorithm provides the location of impacts on trees, the absorbed energy, and the deviation angle. The input parameters (i.e., the value of diameter at breast height and the forest density) were based on direct measurements of the fir forest. Compared with a traditional simulation without the protective role of forests, the results of 3D numerical modelling with tree-impact algorithm show a decrease in the number of blocks impacting the barriers (91%), no variations in the bouncing heights (for 95<sup>th</sup> percentile), and an increase in the kinetic energies due to a filter effect by the forest (85% for 95<sup>th</sup> percentile). In the Roisan case study, about 1,050 m<sup>3</sup> of rock toppled in October 2019. While the main body of the rockfall stopped in a relatively flat area close to the failure, two blocks were exceptionally able to reach the foot of the slope causing the interruption of a municipal road. An attempt to back-calibrate this event with HY-STONE showed difficulties to describe the behaviour of these isolated blocks with respects to the main landslide body. A possible explanation for this behaviour is that the detached volume fragmented soon after impacting the slope, giving rise to flying fragments with higher mobility. To test this hypothesis we accounted for fragmentation through a specific algorithm of HY-STONE that fragments the falling blocks when their energy overcomes a certain threshold and simulate the behaviour of the resulting fragments. This approach allowed to accurately replicate the rockfall event. We therefore adopted this approach for defensive-works design, simulating all the unstable volumes overhanging the municipal road. Compared with a traditional simulation, the results of 3D numerical modelling with fragmentation algorithm show an increase in the number of blocks

impacting the barriers (86%) and in the bouncing heights (96% for 95<sup>th</sup> percentile), with a decrease of the kinetic energy due to comminution (39% for 95<sup>th</sup> percentile). These two case studies demonstrate the importance of accounting for the forest or for fragmentation in the design of cost-effective defensive works.

Frattini P, Crosta GB, Agliardi F (2012) Rockfall characterization and modeling. *Landslides: types, mechanisms and modelling* 22:267-281