Rockfalls and Their Hazard

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1 Introduction

Rockfalls are a type of fast mass movement common in mountain areas worldwide triggered. Natural triggers of rockfalls comprise earthquakes (Harp and Wilson 1995; Marzorati et al. 2002), freeze-thaw cycles of water (Gardner 1983; Matsuoka and Sakai 1999), melting of snow (Wieczorek and Jäger 1996) or permafrost (Gruber et al. 2004), temperature changes (Davies et al. 2001), intense rainfall (Chau et al. 2003; Cardinali et al. 2006), stress relief following deglaciation (Wieczorek and Jäger 1996), volcanic activity, and root penetration and wedging (Wieczorek and Jäger 1996). Human-induced causes of rockfalls include undercutting of rock slopes, mining activities, pipe leakage, inefficient drainage, and vibrations caused by excavations, blasting, or traffic.

An individual rockfall is a fragment of rock detached from the bedrock along new or pre-existing discontinuities (e.g., bedding, joints, fractures, cleavage, foliation, topographic surface) by creeping, sliding, toppling or falling, that falls along a cliff, proceeds down slope by bouncing and flying along ballistic trajectories, or by rolling on talus or debris slopes. When the boulder has lost enough energy in impacts or by friction, it stops on or near the foot of the slope. For primary failures, fall follows detachment immediately. For secondary rockfalls, that involve the fall of previously detached materials (e.g., by rainfall, water flow, snow avalanche, animals, vegetation, other rockfalls), the time and trigger of the fall are different from those of the detachment. A rockfall failure can involve single or multiple blocks. When multiple blocks are involved in a failure, there is little or no interaction among the individual fragments that proceed along separate trajectories. Rockfalls travel at speeds ranging from a few to tens of meters per second, and range in size from small cobbles to large boulders hundreds of cubic meters in size.

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Due to their high mobility, and despite their often relatively small size, rockfalls are a particularly destructive type of failure (Fig. 1), and in several areas, especially along roads and railways, they represent the primary cause of landslide fatalities (Evans 1997; Guzzetti et al. 2005). In mountain regions, where large areas can be subject to rockfall hazard, the morphological, lithological, structural, climatic and land cover settings controlling rockfalls vary considerably. For this reason, determining the location of the source areas, and predicting the trajectories, the invasion zones, and the travel velocities of rockfalls proves difficult, particularly over large areas.

Fig. 1 Rockfall triggered by the 6 April 2009 L'Aquila earthquake near Stiffe, central Italy

2 The Mechanics of Rockfalls

A rockfall is a combination of simple mechanical processes, including: (i) detachment (by creeping, toppling, or sliding), (ii) free falling (flying), (iii) bouncing (impact and rebound), and (iv) rolling (Guzzetti et al. 2002; Dorren 2003). Creeping is limited to the pre-failure stage of a rockfall and often goes undetected, unless specific monitoring is available. Toppling consists in the rotation outward or sideways from the slope of a single block or of multiple adjacent blocks. Sliding is limited to the initial stage of a rockfall, where it occurs over short distances. For large boulders sliding may also occur at impact, with significant loss of energy due to high friction. Free falling is the predominant type of motion of a rockfall. Driven by gravity, free fall occurs along ballistic trajectories at high and very high velocity.

In nature, where the motion of an individual rockfall fragment is most often by tumbling, i.e. “short bounces” forming a rapid sequence of short, low flying parabolas, a boulder rolling is rarely observed. Rolling occurs chiefly for sub-spherical, cylindrical or discoid blocks, when the velocity of the boulder is relatively low, on rectilinear or convex-upward slopes, with medium to low terrain gradient and limited surface roughness. Irregularities in the shape of the block or the terrain facilitate impact and bouncing, and prevent or interrupt rolling.

Impact is the most complex, uncertain and poorly understood phase of a rockfall. At impact, energy is lost and the direction of motion of the rockfall changes. Impact can vary from (almost) completely elastic to (almost) entirely inelastic, depending on the mechanical properties of the terrain and of the block, the impact angle, and the block shape, mass and velocity (Azzoni and de Freitas 1995; Chau et al. 2002). Upon impact, a block can break into multiple fragments that proceed along separate trajectories. In forests, collisions against trees can deflect or stop rocks (Stokes et al. 2005; Ciabocco et al. 2009; Lundström et al. 2009).

3 Rockfall Modelling and Hazard Assessment

In principle, a rockfall is a simple geomorphological process to model. Knowing the release point, the topography of the slope, the energy lost at each impact point and where a block is rolling, it should be possible to predict the location, velocity and distance to the ground of the falling block at any point along its trajectory. Reality is different, and a rockfall represents an example of a relatively simple mechanical system whose behaviour cannot be predicted exactly, even if the initial conditions and the driving forces are known. This limits our ability to ascertain rockfall hazard.

A good predictor of rockfall occurrence in an area is the evidence of previous rockfalls. Identifying and mapping rockfalls and their associated geomorphologic forms (e.g., talus slopes) provide valuable information to determine rockfall hazard. Assessing rockfall hazard involves determining: (i) where rockfalls can occur, including the identification of the detachment (source) areas, the travel zones, and the deposition areas, (ii) the magnitude of the expected rockfalls, including the number, volume, velocity and energy of the falling blocks, and (iii) when, or how frequently, rockfalls are expected in an area, for different triggers.

To determine where a rockfall can develop, one has to locate the potential source areas of the rockfalls. When studying a single slope or an individual rockfall, the location and characterization of the unstable blocks is made in the field, through geological, geomorphological and structural mapping. For larger areas, the potential detachment zones are identified using geomorphological techniques (e.g., field observation and mapping, interpretation of aerial photographs), and GIS modelling (Frattini et al. 2008; Günther and Thiel 2009).

Where the location of the potential source areas of rockfalls is known, the travel paths and the depositional areas are ascertained through numerical modeling. Evidence for past rockfalls is valuable information to validate the numerical modeling. Software has been designed to model the rockfall trajectories adopting kinematical ("lumped mass"), dynamic and hybrid schemes (Guzzetti et al. 2002; Dorren 2003; Dorren et al. 2006). Most of the computer codes adopt a two-dimensional approach, and simulate a rockfall along pre-defined topographic profiles. To cover a large area, multiple simulations must be prepared and the results interpolated to obtain a spatially-continuous model of the rockfall process. Guzzetti et al. (2002), Crosta and Agliardi (2004) and Stoffel et al. (2006), among others, tested three-dimensional rockfall simulation software. Some of these codes have been demonstrated to perform well in small (Stoffel et al. 2006; Wieczorek et al. 2008; Agliardi et al. 2009), large (Guzzetti et al. 2003, 2004; Frattini et al. 2008), and very large (Guzzetti et al. 2002) areas, and were used successfully to ascertain hazard (e.g., Guzzetti et al. 2003, 2004; Frattini et al. 2008). Figure 2 shows the result of a spatially distributed rockfall simulation obtained using an improved version of the 3D-modelling software STONE (Guzzetti et al. 2002).

Rockfall magnitude, a proxy for destructiveness, is a function of the energy of the individual rock blocks along the falling trajectories. Adopting a simple physical model to describe a rockfall, at any given point along the trajectory the kinetic energy depends on the velocity and mass of the falling block. Velocity depends chiefly on the falling height and the gravitational acceleration. Mass depends on the volume and the bulk density of the block. The rock density is determined based on the rock type, and the falling height is obtained from topographic maps or computed from a digital representation of the topography (Guzzetti et al. 2002; Dorren et al. 2006).

Measuring the volume of an individual block, or of a few blocks, in the field is a relatively simple operation. Determining the volume of several (a few hundred to several thousands) rockfalls over a large area is impractical, and rarely performed (e.g., Wieczorek et al. 1992; Wieczorek and Snyder 2004; Luckman 2008). This limits the ability to determine rockfall hazard over large areas. To overcome this limitation, investigators have examined the statistics of rockfall volumes. Analysis of catalogues of rockfall volumes has revealed that the probability (or frequency) density of rockfall volumes exhibits a typical negative power law scaling behaviour (Brunetti et al. 2009).

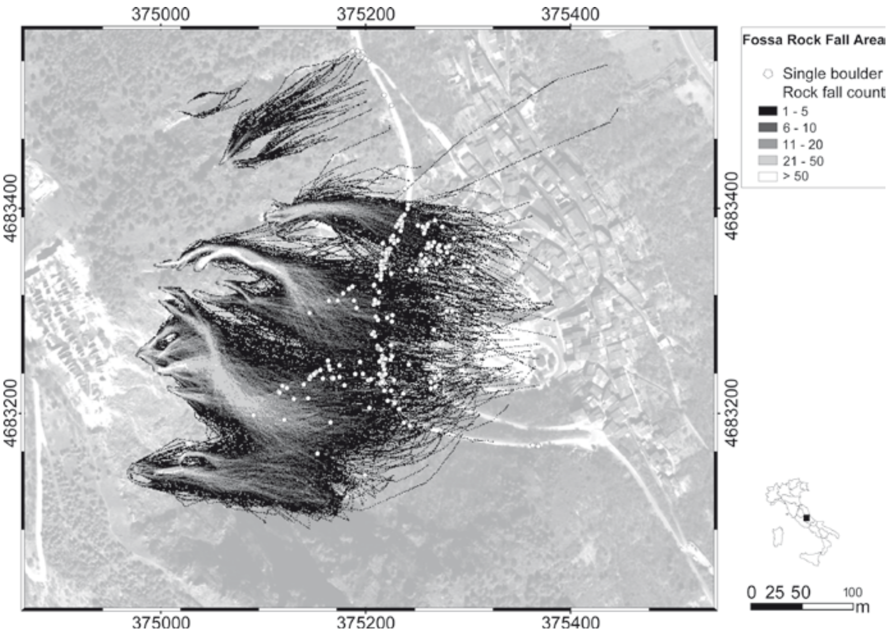

Fig. 2 Multiple rockfalls triggered by the 6 April 2009 L'Aquila earthquake at Fossa, central Italy. Rockfall source areas and individual boulders were mapped in the field studying aerial photographs and very high resolution satellite images taken shortly after the earthquake. Numerical modelling of rockfall was performed using a modified version of the code STONE (Guzzetti et al. 2002)

Establishing when or how frequently rockfalls occur is difficult. When a rockfall takes place depends on the time of the trigger (e.g., an earthquake); but daily and seasonal conditions play a role (Luckman 1976; Douglas 1980; Gardner 1983; Stoffel et al. 2005a). For a single rockfall, and assuming a simple geometry for the unstable block, the time of failure can be predicted with reasonable accuracy, where adequate monitoring is available (Zvelebil and Moser 2001). Determining how often rockfalls occur in an area is more problematic. Rockfall frequency in area depends on multiple factors, including the rate of rockfall activity and the frequency of the triggers, which are difficult to know precisely. To determine the probability of rockfall occurrence one can exploit information on past rockfall events, but constructing complete, uncensored, and accurate time series of rockfalls, covering a significant period, is difficult and time consuming.

Catalogues of rockfall events are compiled searching historical records, and through direct observation and field mapping. Wieczorek et al. (1992) prepared a catalogue of 519 rockfalls and rock slides, in the period between 1857 and early 2004, for the Yosemite Valley, California. Guzzetti et al. (2003) exploited this information to study the rate of rockfall occurrence, and to determine the annual frequency of the failures. Hantz et al. (2003) exploited a catalogue of 33 rockfalls in the 66-year period 1935–2000 to determine the probability of rockfall failures along 120 km of escarpments in the Grenoble area, France. Luckman (2008) measured the volume of blocks deposited along an abandoned road in Jasper National Park, Alberta, in the 40-year period 1961–2000, and determined average rockfall accumulation rates. Other investigators have exploited dating techniques, including lichenometry (Luckman and Fiske 1995; McCarroll et al. 1998) and dendrochronology (Stoffel et al. 2005b; Perret et al. 2006; Stoffel 2006; Schneuwly and Stoffel 2008a, b; Moya et al. 2010, this volume) to reconstruct the history and rate of activity of rockfalls. The advantage of this approach consists in the possibility of constructing spatial-temporal catalogues spanning multiple centuries (Stoffel et al. 2005b; Perret et al. 2006; Stoffel 2006). As a drawback, the temporal resolution of the analysis is coarser.

4 Research Needs and the Potential Contribution of Tree-Ring Analysis

In mountain regions, expansion of settlements and infrastructure over dangerous areas is increasing the impact of natural hazards, including rockfalls. In several countries, this has fostered rockfall investigations. Rockfalls are studied primarily: (i) to predict where destructive events may happen, and to design adequate defensive measures ("engineering" approach), and (ii) to understand the factors and circumstances that control rockfalls and their rate of occurrence, including the temporal and geographical variations ("geomorphological" approach). Evidently, the two approaches are synergic.

From an engineering perspective, sophisticated technologies are used to design, test, construct and deploy highly efficient defensive structures to protect specific assets. In this field, research is mostly technological, and involves the innovative design and testing of new structures and new materials. Innovation is also required to improve rockfall modelling through advanced computer codes, and a better understanding of the mechanics of a rockfall; chiefly the loss of energy and fragmentation upon impact. Efforts should also be made to study the protective function of forests, and to design appropriate land management strategies.

From a geomorphological point of view, the challenge is to determine the combined geographical and temporal evolution of rockfalls. Over large areas, this has implications for sediment fluxes and erosion/accumulation studies, and for hazard assessment. To study the geographical and temporal patterns of rockfalls, historical information on past events is of paramount importance. There is a need for local, regional, national and even continental efforts to search, collect, and organize information on historical rockfall events and their consequences. Further, an agreement has to be reached on how to analyse the time series of rockfall events. When investigating a time series of natural events, the assumption is made that the series is "stationary" i.e., the rate of the process does not change significantly with time. Where a trend exists, it is assumed that the trend is known. However, a series may be stationary (or not), depending on the length of the series. Further, in mountain areas, due to climate, environmental and socio-economical variations, the time series may be not stationary, hampering the ability to determine reliable statistics for the time series. This has implications for hazard and risk assessment, and for policy making.

The consequences of damaging natural events – including rockfalls – depend on: (i) the location, density, frequency and magnitude of the events (i.e., the hazard), and (ii) the density, relevance and fragility of the elements exposed to risk (i.e., the vulnerability). For rockfalls, efforts should be made to disentangle the two components, particularly where human impact on the environment is significant or longstanding, and to design appropriate reduction (for hazard) and strengthening (for vulnerability) strategies.

Dendrogeomorphology, the application of tree-ring dating techniques to investigate geomorphological processes (Solomina 2002), has recently emerged as a powerful tool to study rockfalls (Stoffel 2006). Where applicable, tree-ring analysis can contribute significantly to: (i) identify and date historical failure events (e.g., Stoffel et al. 2005b), (ii) reconstruct long time series of rockfall events (Stoffel et al. 2005b; Perret et al. 2006; Moya et al. 2010, this volume), (iii) determine the rates and the spatial distribution of rockfall activity (Stoffel et al. 2005b; Perret et al. 2006; Luckman 2008; Schneuwly and Stoffel 2008a), (iv) investigate the seasonal variation of rockfall occurrences (Stoffel et al. 2005a; Schneuwly and Stoffel 2008b), (v) provide long-term statistics for the geometry of rockfall trajectories in an area (Schneuwly and Stoffel 2008a), and (vi) determine the impact probability of rockfalls on trees (Moya et al. 2010, this volume), fostering our understanding of the protective role of forests (Ciabocco et al. 2009; Lundström et al. 2009). There is a clear need for similar – and other – studies, as tree-ring analysis can help advance significantly our understanding of the rockfall process, and can contribute to the production of improved rockfall hazard assessments.

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