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Magnitude–frequency relation for rockfall scars using a Terrestrial Laser Scanner

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ABSTRACT

The analysis of the three-dimensional rockfall scar geometry provides clues for the understanding of the failure mechanisms acting on cliffs, of the conditioning factors, and on the frequency of the events. In this paper, a supervised step-by-step methodology is presented for establishing the statistical magnitude–frequency relation of rockfall scar volumes, using a point cloud from Terrestrial Laser Scanner (TLS) data. The methodology includes a procedure for identifying discontinuity surfaces, calculating the areas of those which are exposed, and the height of rockfall scars. In the estimation of the rockfall scar volume a key issue is the consideration of the minimum spacing of the discontinuity sets to differentiate between step-path surfaces and undulated ones. Having obtained the distributions of both the basal area and height of the scar across the slope, the volume of the rockfall scars is calculated stochastically by multiplication of these two parameters by means of a Monte Carlo simulation. Both distributions of the basal area and of the rockfall scar volume are found to be power-law, with the exponent b ranging from 0.9 to 1.2. The relation obtained might be used as a first approach of rockfall magnitude–frequency curves in large cliffs.

1. Introduction

Cliffs are morphological features frequently found in shorelines and mountain ranges. They form steep rock faces that recede continually by erosion and slope instability as most active degradation processes. In alpine environments rockfalls are the predominant evolutionary mechanism of cliffs (Whalley et al., 1983; Flageollet and Weber, 1996). Rockfalls are masses of any size detached from a steep rock face that descend rapidly mostly through the air by free fall, sliding, bouncing or rolling (Varnes, 1978; Cruden and Varnes, 1996).

Lithology, stratigraphy and structure exert strong control on the geometry and the temporal evolution of cliffs (Hampton et al., 2004). The study of rock face features allows the understanding of the mechanisms that cause cliff degradation and instability. Surface characteristics of joints daylighting in the rock outcrop affect their shear strength (Patton, 1966; Barton, 1976) while the spatial arrangement of both the slope face and the discontinuities configures the failure mode. The latter are typically included as input parameters for kinematical and stability analyses of rock slopes (Hoek and Bray, 1981; Goodman, 1989). The potential for future instability of cliffs may be also assessed and rated based on several measurable parameters observable in rock mass exposures such as the rock strength, geologic structure, joint spacing, weathering stage, among others (Pierson et al., 1990; Rouiller et al., 1998; Budetta, 2004; Jaboyedoff et al., 2004b). The reader is referred to Pantelidis (2011) for a recent review of the most used rock mass instability indexes.

Traditional surveying methods employed for the characterization of the rock mass discontinuities, their location, orientation, persistence, and spacing, include scan-line or cell mapping methods (Priest and Hudson, 1981; Priest, 1993). Manual field discontinuity surveys are however time consuming and they are often affected by systematic and human errors (Ewan et al., 1983; Herda, 1999). Furthermore, steep and often unstable profile of the rock face often renders data acquisition both unsafe and unfeasible (Sturzenegger and Stead, 2009).

In the last decade, Terrestrial Laser Scanner (TLS) applications have become a common surveying technique for characterization of the rock mass exposures. Explicit information on the performance of TLS can be found in Slob and Hack (2004), Slob et al. (2005) and Shi et al. (2009). Its increasing use is due to its capability to provide quickly and easily, digital data of high accuracy and precision. TLS may capture information from inacessible outcrops, and acquire large data sets which can be readily treated. The main applications for the assessment of the instability of a rock face may be summarized in the following (Kemeny and Turner, 2008; Jaboyedoff et al., 2010): the reconstruction of the topography and generation of DEM (Abellan et al., 2006; Agarwal et al., 2006); the identification and characterization of discontinuity sets and of their spacing (Feng and Röshoff, 2004; Jaboyedoff et al., 2004b,

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2008; Slob et al., 2005; Gaich et al., 2006; Poropat, 2006; Coggan et al., 2007; Lato et al., 2009; Sturzenegger and Stead, 2009); the determination of the size and spatial distribution of potentially unstable rock mass volumes (Jaboyedoff et al., 2009; Sturzenegger et al., 2011); the detection and measurement of rock face displacements (Rosser et al., 2007; Oppikofer et al., 2008; Abellan et al., 2009; Oppikofer et al., 2009); obtaining the spatial distribution and magnitude of rockfalls events (Abellan et al., 2006; Rosser et al., 2007; Lim et al., 2010); and monitoring of cliff erosion and quantification of the retreat rate (Rosser et al., 2005; Abellan et al., 2011; Young et al., 2011).

The observation of geometrical features of the rock face caused by the detachment of rock masses may provide clues for the understanding of the instability mechanisms affecting the rock mass, their conditioning parameters, and the temporal evolution of the slope profile. TLS has been used to identify and locate recent rockfall scars and missing rock volumes from the cliff faces based on the analysis of sequential scans (Abellan et al., 2006; Oppikofer et al., 2009; Lim et al., 2010; Kenner et al., 2011). The density distribution of rockfall scars is a measure of the rockfall activity and may be used for estimating cliff recession rates. In particular, the number of both rockfall scars and potentially movable blocks has been taken as a qualitative measure of the frequency of rockfalls (Copons and Vilaplana, 2008).

The distribution of the rockfall scars on the cliff face is an indicator of the rockfall activity over the last hundreds or thousands of years. In this paper, we present a methodology to obtain a statistical distribution of the volumes of rockfall scars from a cliff using a point cloud captured by a TLS. We combine recently developed methods for filtering and segmentation of the point cloud to extract planar surfaces, identify the main joint sets present in the rock face, calculate the area of the exposed discontinuity surfaces, and the volume of the detached rock masses. This is a supervised procedure including a few semi-automated steps that can be applied to a large rock wall exposure. We also implement our own method to refine and validate the plane orientations used to define the joint sets.

2. Estimating volumes of rockfall events and rockfall scars

A rockfall scar is a rupture surface on a vertical cliff resulting from one or several rockfall events. Its state of freshness is often an indication of the scar age. Colors of the scars generated by recent rockfalls are bright. In temperate and alpine environments, scars tend to darken shortly after their generation, so some time after the occurrence of the rockfall event, the scar color starts vanishing and eventually it could be hardly differentiated from those existing previously.

The volume of rockfall events occurring between successive TLS scans can be easily measured. Accurate estimate of the volume of the detached rock mass can be obtained by subtracting DEMs or by computing the volume between point clouds prepared before and after the rock fall event (Abellan et al., 2011; Deline et al., 2011). When the original topography is not available or has not enough resolution, volumes of rockfall events of a known age have been calculated by reconstructing the pre-existing topography over a TLS-scan generated DEM with the support of photographs taken before the detachment of the rock mass (Ravanel and Deline, 2008). Oppikofer et al. (2009) were able to detect scars on the slope face that are formed by the sliding planes involved. The pre-rockfall event topography was reconstructed by fitting planes around the scars using the commercial software Polyworks V.10 and the Sloping Local Base Level SLBL method (Jaboyedoff et al., 2004a). In this case, rockfall volume distribution was established for a limited number of scars.

Uncertainties in the computed volume come primarily from the resolution and errors associated to the TLS equipment, selected methodology, distance to the target area, and to the generation of the DEM (Mikos et al., 2005; Abellan et al., 2009; Dunning et al., 2010; Jaboyedoff et al., 2010). However, when the pre-rockfall topography of the slope is lacking, main uncertainties in volume computation derive from the assumptions made for its reconstruction and the nature of the rockfall events. Measurement of the rockfall scar volume does not yield the volume of the rockfall events that generated the scar although both volumes are related to some extent. Rockfall scars are the result of the detachment of rock masses from the rock face in either one or multiple events. The detachment of an initial rock mass may induce further instability in the slope and the rockfall scar may enlarge and retrogress by successive failures. Eyewitness accounts describing historical rockfalls indicate that minor detachments may be noticed before and after a main event (Deline et al., 2011). A paradigmatic example is the Randa rockfall of 1991 (Noverraz and Bonnard, 1992; Sartori et al., 2003). On April 18 a rockfall was produced by breaking up of about 22 mio m^3 from the rock face over a period of several hours. The day after, a mass of about 100,000 cm^3 of rock fell again. Finally, another large rockfall of about 7 mio m^3 occurred on May 9. Frequent minor rockfalls were noticed several weeks before and after the main failures.

Sequential scans taken at either monthly or annual intervals (Lim et al., 2010; Abellan et al., 2011; Young et al., 2011) are able to provide accurate distributions of rockfall scar volumes. Most of them are probably the result of single rockfall events but the possibility that some scars could be the result of several consecutive rock mass detachments cannot be completely disregarded. Consequently, rockfall scar volumes must be considered as an upper envelop of the rockfall volumes that have originated them.

In this work we present a procedure to calculate the rockfall scar volumes distribution in a large cliff face. To calculate the size of the detached rock masses from the scars we must consider the pre-existing topography. Here, it has been assumed that the cliff recedes following a slope equilibrium model (De Lange and Moon, 2005) which is parallel to the initial slope profile. According to this, large failures changing significantly the original profile such as a step path rock mass failure are not considered. The volume of the rockfall scar is thus approximated by the volume of the prism whose faces are the basal discontinuity surface of the scar and two other intersecting discontinuity planes that quite often behave as tension cracks (Fig. 1). The basic assumption in the considered case is that detachment of rock volumes from the slope face is mostly governed by the existing discontinuity sets and that rockfall scars on cliffs are formed by intersecting discontinuities. The detachment is produced by the initial displacement of a rock block resting on the basal surface by either sliding (planar failure) or toppling until it is detached from the rock wall. The volumes corresponding to the scars are calculated probabilistically by multiplying a random sample of the basal sliding area of the detached rock mass and scar height distributions, using a Monte Carlo simulation. The details of the methodology followed are given in the next section.

3. Methods

The methodology to obtain the volume distribution of the existing scars on the outcrop from a TLS point cloud involves 6 main steps, which are resumed in Fig. 2.

It consists in a supervised procedure, including some automated sub-steps (1, 3 and 4). Being a step-by-step procedure, it favours the reproducibility of the results, and consequently their objectivity and reliability.

3.1. Step 1: plane fitting at each point and calculation of normal vectors and of the plane's attributes

After obtaining the point cloud of a slope using a TLS, the first step of the proposed procedure aims at the visualization of it and the acquirement of preliminary information for the dip and dip direction of the topographic surface at each point. To enable accurate surface