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Impacts of fracturing patterns on the rockfall susceptibility and erosion rate of stratified limestone

B. Matasci [a,*], M. Jaboyedoff [a], A. Loye [a], A. Pedrazzini [a], M.-H. Derron [a], G. Pedrozzi [b]

[a] Institute of Earth Sciences, Geosciences and Environment Faculty, University of Lausanne, Switzerland
[b] Ing. Pedrozzi & Associati SA, 6963 Pregassona, Switzerland

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ABSTRACT

The erosion of steep rock slopes is largely controlled by rockfalls, which are a relevant hazard in mountainous regions. The deposition of blocks allows us to quantify rockfall activities and analyze the fracturing pattern that is the key to understand the processes that result in rockfalls. At Monte Generoso (in southern Switzerland), we compared the calculated rockfall susceptibility with the measured rockfall activity for a thinly stratified limestone cliff area. Thus, we were able to determine the erosion rate for the past 40 years and verify the reliability of the method used to perform the rockfall susceptibility analysis. The geomorphology of the area and the fracturing pattern have been accurately analyzed and quantified in the field and using airborne laser scanning techniques. These results have been used to perform a rockfall susceptibility assessment based on the frequency of joints and the distribution of failure mechanisms. Five joint sets have been detected, and the large influence of wedge sliding is demonstrated. The emptying works carried out on a series of protective barriers and nets resulted in detailed data regarding the magnitude distribution of the blocks that fell over a period of 40 years. This information, coupled with the inventory of the present day rock slope instabilities, results in a method that can be used to correct the erosion rate. Power laws have been fit with the blocks and instability data. Then, several calibration options have been tested to consider the additional amounts of erosion due to larger and less frequent potential rockfall events. The rockfall susceptibility, calculated with the distribution of the failure mechanisms, is correlated well with the measured rockfall activity. This approach allows us to characterize the erosion processes in a steep geomorphological context to obtain new insights regarding the evolution of rock slopes.

1. Introduction

Rockfall is an important erosion process that occurs on steep rock slopes and represents an important hazard in mountainous areas (Varnes, 1978; Evans and Hungr, 1993). Rockfall activity can be evaluated from the amount of accumulated debris and the volume of blocks deposited downslope (Barsch, 1977; Becht, 1995; Matsuoka and Sakai, 1999; Moore et al., 2009; Barlow et al., 2012). Rockfall hazard assessments are used to locate source areas, measure the block sizes, calculate the probability of occurrence and define run-out paths (Selby, 1987; Evans and Hungr, 1993; Crosta and Agliardi, 2003; Frattini et al., 2008; Volkwein et al., 2011; Gigli et al., 2012). The focus of the present study is on rockfall activity and susceptibility. Several methods have been proposed in the past to assess the rockfall susceptibility of rock-walls. For example, slope steepness is a simple factor that can be used to determine the locations of areas prone to rockfall (Strahler, 1954; Crosta and Agliardi, 2003; Guzzetti et al., 2003). The relationships between steep slopes and areas susceptible to rockfall have been used to develop tools to map the most susceptible areas (Jaboyedoff and Labiouse, 2003; Frattini et al., 2008; Loye et al., 2009). Other approaches have used rating systems (Cancelli and Crosta, 1993; Rouiller et al., 1998; Vangeon et al., 2001) and historical inventories, mainly in terms of the magnitude–frequency distributions of events (Hungr et al., 1999; Dussauge-Peisser et al., 2003; Hantz et al., 2003; Brunetti et al., 2009; Barlow et al., 2012), or have been based on safety factor calculations (Hoek and Bray, 1981; Grenon and Hadjigeorgiou, 2008). Particularly, the slope mass rating system (SMR — Bieniawski, 1973; Romana, 1993; Moore et al., 2009) resulted in an interesting slope stability assessment by introducing a link between joint sets and slope orientation. In addition, other studies have demonstrated the importance of relationships between topography and joint sets for detecting rock slope instabilities (Terzaghi, 1962; Markland, 1972; Hoek and Bray, 1981; Romana, 1993; Norrish and Willie, 1996; Baillifard et al., 2003). In particular, fracture density appears to be an important factor that controls rock slope erosion because the largest talus debris deposits are located beneath highly fractured rock slope areas in some geological settings (Olyphant, 1981, 1983; Hudson and Priest, 1983; Moore et al., 2009). Various authors have used digital elevation models (DEMs) to perform rockfall susceptibility calculations by mapping joint sets and using the spatial distribution of the failure mechanisms (Gokceoglu et al., 2000; Guenther et al., 2004; Jaboyedoff et al., 2004; Brideau et al., 2011; Gigli et al., 2012; Guenther et al., 2012).

* Corresponding author. Tel.: +41 78 876 9370; fax: +41 21 692 35 35.
E-mail address: battista.matasci@gmail.com (B. Matasci).

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In the stratified limestone slope of Monte Generoso, we measured the volumes of materials that were eroded over 40 years in six catchments and accumulated behind protective structures. The sizes of the fallen blocks and the volumes of the currently unstable rock compartments were also measured. The fracturing pattern of the rock mass was characterized in the field and by using aerial LiDAR data. Subsequently, a rockfall susceptibility assessment was performed based on the fracturing density and kinematic tests (Jaboyedoff et al., 2004).

The first goal of this study is to detect the cliff areas that are most susceptible to rockfalls. The second goal is to verify the reliability of the methods used to assess rockfall susceptibility. Indeed, this site can be used to compare the rockfall susceptibility rating with the recorded volumes of blocks in the underlying protective barriers. Finally, we propose a method for correcting the erosion rate based on an inventory of unstable rock compartments and the magnitude–frequency distribution of the fallen blocks.

2. Study site

2.1. Geomorphological setting

The investigation was carried out on the western side of Monte Generoso, which is located in the canton of Ticino (southern Switzerland) above the village of Capolago and an important motorway that links Italy with Northern Europe (Fig. 1).

The slope consists of two rockwalls situated one above the other and divided by a steep talus slope covered with sparse forest. The upper cliff, where our investigation focused, is divided into six “V-shaped” catchments with different depths according to the occurrence of persistent brittle structures. Small areas with more gentle slopes covered with debris exist locally inside the catchments. Several channels incise the talus slope deposits in the area below the lower cliff. In this geomorphologic setting, erosion is controlled by the fracturing pattern of the rockwall that results in rockfalls. Transportation, especially for the finer grain size fraction, is related to intermittent water flow, leading to debris-flows that occasionally reach the motorway.

2.2. Geological setting

Monte Generoso is composed of sedimentary rocks from the south-alpine realm of the Alpine belt. The main lithologies are Liassic (Carixian–Hettangian) and belong to the lower Orobische nappe (Bernoulli, 1964; Bertotti, 1991). These lithologies consist of stratified siliceous limestone intercalated with thin marly limestone beds. The typical thickness of the siliceous limestone layers is approximately 20 to 30 cm, with maximum values reaching 1.5 m. Weaker foliated marly limestone beds that are 5 to 20 cm thick separate these strong layers. Generally, the rock is heavily fractured and slightly weathered.

2.3. Barrier characteristics

The motorway and part of the village of Capolago are potentially affected by rockfall hazards. Hence, the Swiss Federal Road Office (FEDRO) installed several protective barriers and fences at the end of the 1960s below the upper cliff. The barriers are composed of concrete bases, iron or concrete pillars and horizontal wood timbers (Fig. 2a). The barriers are 3 m tall and 2 to 3 m wide, which allows each to store

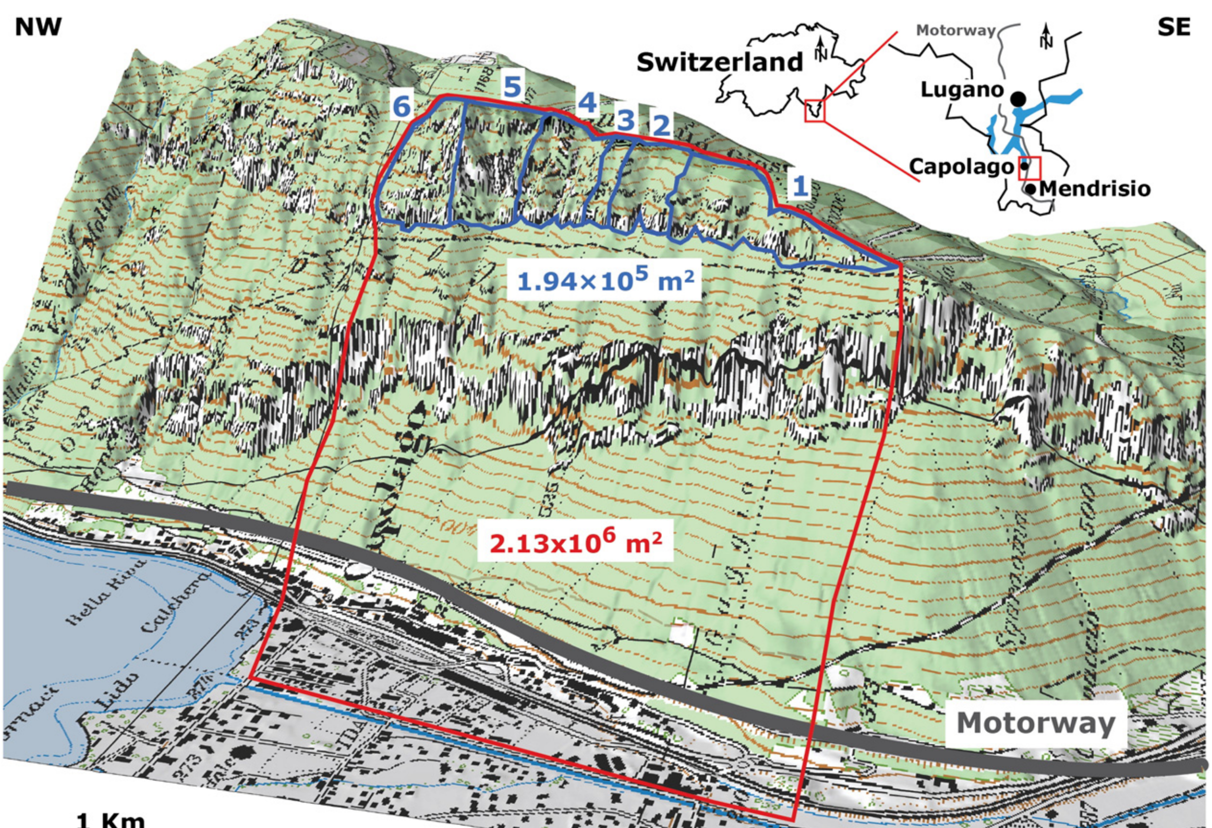

Fig. 1. The Monte Generoso area in Switzerland (1:25,000 topographic map and DEM from Swisstopo). The perimeters of the six studied catchments are shown in blue. The red perimeter represents the entire slope, including the talus slope and the plain. The total planar areas of the six catchments and the red perimeter are 1.94×10^5 m^2 and 2.13×10^6 m^2, respectively.