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Assessment of periglacial slope stability for the 1988 Tschierva rock avalanche (Piz Morteratsch, Switzerland)

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ABSTRACT

The Tschierva rock avalanche occurred on October 29, 1988 in the area of the Piz Morteratsch, Switzerland. Releasing a total volume of ~300,000 m^3, the avalanche ran out over 1 km destroying a hiking trail before stopping on the Tschierva Glacier. We analyze the setting of this periglacial slope failure, combining geomechanical and cryosphere investigations to identify the primary factors contributing to the rock avalanche. An approach to slope stability assessment is presented that copes with existing data limitations in an inaccessible alpine terrain. Results from the analyses of morphology, geology, glaciation history, permafrost, hydrology, and meteorological data allowed preliminary inferences to be made regarding the influence of these factors on slope stability. Conceptual kinematic and numerical slope stability modeling critically analyzed the role of kinematic degrees of freedom, glacier retreat, and water infiltration from above the detachment zone. Results highlight the strong influence of discontinuity orientation with respect to the slope face, the role of a fault zone with increased joint density, and long-term progressive development of persistent discontinuities induced by glacier retreat and groundwater loading cycles in leading to the rock avalanche. The role of permafrost could not be clearly assessed, however observations and analyses indicate that permafrost had no dominant influence on the slope failure. Extraordinary precipitation prior to the event is suggested to have played a role in triggering the rock avalanche, especially in combination with observed superficial ice that could have sealed the rock face generating high water pressures. Our results emphasize the importance of analyzing multiple contributing factors when assessing alpine rock slope failures, with careful consideration of data limitations prevailing in such areas.

1. Introduction

Large rock slope failures (rock slides and rock avalanches) in steep alpine terrain present a significant geological hazard in many high mountain areas throughout the world. An increased number of periglacial slope failures have been identified in recent decades (e.g. Evans and Clague, 1988, 1994; Dramis et al., 1995; Barla et al., 2000; McSaveney, 2002; Haeberli et al., 2004; Cola, 2005; Geertsema et al., 2006; Cox and Allen, 2009; Huggel, 2009), that combined with growing infrastructure and access to alpine regions creates considerable exposure to rock slope hazards. However, assessment of these events is often limited by data availability, an incomplete understanding of the underlying processes, and the long return period of large slope failures. Ongoing climate change can introduce further complication, as changes in glacier and permafrost distribution may shift hazard zones and modify controlling processes.

The stability of alpine rock walls is governed by a number of factors including: the long-term geomorphic evolution of the slope, the topographic and geological setting, geotechnical properties of the rock mass, hydrogeology, glacial history, and permafrost distribution (Fischer and Huggel, 2008). Changes in one or more of these factors, in some cases in combination with external forcings such as earthquakes or heavy precipitation, may reduce stability and lead to failure (e.g. Whalley, 1974; Wieczorek, 1996; Ballantyne, 2002; Keefer, 2002; Huggel et al., 2010).

Relevant geotechnical parameters controlling rock slope behavior include large-scale structures (faults and fracture zones), intact rock strength and deformability, and the geometry and strength characteristics of discontinuities (Terzaghi, 1962; Hoek and Bray, 1981; Ballantyne, 2002; Moore et al., 2009). Changes in these geomechanical properties can be induced by changing boundary conditions of the slope (e.g. glacial debuttressing) and subsequent stress redistribution, near-surface physical and chemical weathering, or cyclic loading (e.g. thermal- or hydro-mechanical), which can drive progressive propagation of fractures through intact rock connecting non-persistent discontinuities (Griffith, 1920; Einstein et al., 1983; Eberhardt et al., 2004; Prudencio and Van Sint Jan, 2007). Such accumulated damage acts

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over the long-term to reduce rock mass strength and condition slope failure.

Temporal changes in the distribution of glaciers and permafrost can have a large impact on the rock wall stress field, groundwater setting, and geotechnical properties, and play a primary role controlling slope stability in alpine landscapes (Evans and Clague, 1993; Augustinus, 1995; Haeberli et al., 1997; Wegmann et al., 1998; Davies et al., 2001; Harris et al., 2001; Ballantyne, 2002). Glaciers and permafrost can be, in turn, extremely sensitive to climate change (e.g. Harris et al., 2003, 2009; Zemp et al., 2006; IPCC, 2007), and are thus two important variables affecting rock wall stability. The role of permafrost in rock slope destabilization is still a young field of research, but recent studies on the thermal conditions of detachment zones attest to the influence of changes in the rock wall thermal regime (e.g. Noetzli et al., 2003; Allen et al., 2009). Similarly, a number of recent rock slope failures are thought to be related to glacier retreat and changes in permafrost distribution (Bottino et al., 2002); for example the 2.5 million m^3 Punta Thurwieser (Italy) rock avalanche in 2004 (Cola, 2005), the 2–3 million m^3 Brenva rock avalanche (Mont Blanc, Italy) in 1997 (Barla et al., 2000), and a number of smaller events during the hot European summer of 2003 (Gruber et al., 2004). Groundwater occurrence and distribution, major factors governing rock slope stability, may in some cases also be closely connected to glacier and permafrost distribution (e.g. Tart, 1996; Gruber and Haeberli, 2007).

In this study we examine the 1988 Tschierva rock avalanche (Engadin, Swiss Alps), an example of a periglacial rock slope failure. The objective is to analyze a range of factors influencing slope stability using approaches from several disciplines. A number of recent alpine rock avalanches have been investigated in varying detail (e.g. Barla and Barla, 2001; Bottino et al., 2002; Noetzli et al., 2003; Oppikofer et al., 2008), but generally consider only a limited range of influencing factors. In this study, we combine geomechanical and cryosphere investigations, using analysis techniques from both fields. Kinematic and numerical modeling was used to evaluate different assumptions, such as the role of discontinuity orientation, glacier retreat, and groundwater conditions. Our study contributes to developing an analytical approach for slope stability assessment in alpine environments, where access and site-specific data are typically limited. The outcome is particularly relevant in view of the suggested effects of recent climate change on rock slope stability in these regions, and anticipated future changes.

2. Study site and 1988 rock avalanche

The Tschierva rock avalanche occurred on October 29, 1988, shortly before midnight (local time). A volume of 250,000–300,000 m^3 of crystalline rock detached from ~3180 m a.s.l. on a steep west-facing slope of Piz Morteratsch (eastern Swiss Alps; Figs. 1 and 2). Volume estimates are based on the deposit area and thickness (Schweizer, 1990), and the extent of the detachment zone (current study). The failed rock mass incorporated additional material from below the detachment area and ran out on to the Tschierva glacier, coming to rest at around 2700 m a.s.l. The runout length was approximately 1000 m and the drop height 480 m, corresponding to a Fahrböschung (travel angle) of 26°. The rock avalanche crossed and destroyed a hiking trail during its runout.

The detachment zone extends over an area of roughly 7000–8000 m^2, in a triangular shape about 150 m wide at the base at 3050 m a.s.l and with one apex reaching a ridge at 3180 m a.s.l. (Fig. 1). The detachment surface is stepped in the form of three benches (Fig. 3). The deposit is clearly delineated atop otherwise relatively clean glacial ice and contains large boulders up to 200 m^3. The thickness of the deposit was estimated to be 1–3 m immediately after the rock avalanche (Schweizer, 1990). An increased frequency of small rockfalls was noted in the area during the months prior to the rock avalanche (personal communication A. Amstutz), while during field work in the summer and fall of 2006, occasional small rockfalls were also observed.

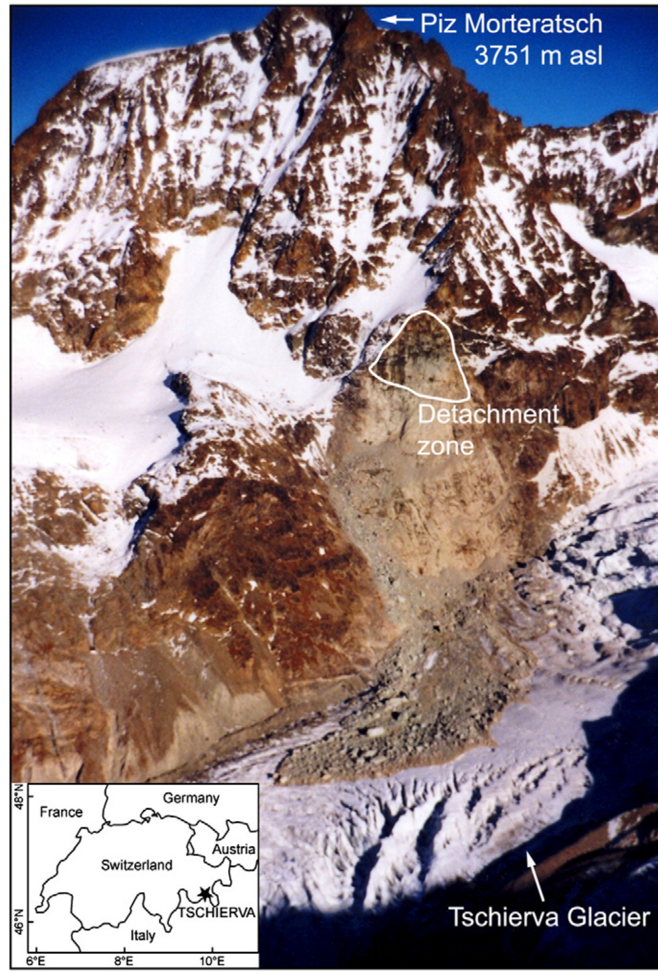

Fig. 1. Western flank of the Piz Morteratsch and Tschierva Glacier. The detachment zone of the 1988 rock avalanche (outlined) and the deposit resting on the glacier are visible in the middle of the photograph (Photograph: A. Amstutz, 1988).

3. Analysis of potentially contributing factors

Although the Engadin region shows occasional earthquake activity, inspection of the Swiss Earthquake Catalogue (Swiss Seismological Service, 2002) showed no significant (M_w>1.5) seismic events on the day of the failure. Thus an earthquake can be excluded as a trigger of the Tschierva rock avalanche. In addition, no events were catalogued that could be interpreted as seismicity resulting from the rock avalanche itself, and continuous seismic data are not available for further analysis.

Other potential factors contributing to reduce slope stability at the Tschierva detachment site include topography and morphology, geological and rock mass properties, the hydrological setting, glacial history, permafrost distribution, and meteorological disturbances. These factors are described sequentially below in support of a simplified analysis intended to highlight possible influences.

3.1. Topography and morphology

The area around the Piz Morteratsch ranges in altitude from 2500 to 4000 m a.s.l. Regional landforms display a strong influence of Late Pleistocene and Holocene glaciers. Only the highest peaks in the area protruded above the Last Glacial Maximum (LGM) ice level, around 21,000 yr BP, while the lower flanks were sculpted and partially steepened through erosion by valley glaciers. Minor debris cover on Tschierva glacier, aside from the deposit of the investigated rock avalanche, suggests that few large mass movements have occurred in