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Evolution of gravity-driven rock slope failure and associated fracturing: Geological analysis and numerical modelling

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ABSTRACT

An accurate analysis of fracture and cleavage anisotropies along two landslides in the Argentera massif (French Southern Alps) was performed in order to relate the fracturing mode to the rock slope failure state. The mature La Clapière landslide and the incipient Isola Landslide were investigated. In both cases, the gneissic rock schistosity was found sub-horizontal in the vicinity of the landslides at shallow depths, while it was sub-vertical elsewhere at the massif's scale. In addition to the well known regional tectonic fracture sets, we identified in both cases a new family of vertical valley parallel (VP) fractures. The VP fractures were only observed on the lower part of slopes affected by landslides where schistosity was found sub-horizontal. The VP fractures are clearly related to the decrease in schistosity dip and correspond to 'fold extrado'-like joints. The proximity of the schistosity folds and the associated VP joints to the landslides suggests that they are gravity-driven. The presented 2-D finite-difference models of the slope destabilisation in the La Clapière site shade light on possible mechanisms of the indicated gravity-induced processes. A progressive degradation of the material strength was imposed in these models to simulate the weathering effect which led to inelastic deformation/damage at the lower part of slope. This was followed by the formation of dense sub-vertical deformation bands and then by the initiation of a landslide in the area corresponding to the actual position of the La Clapière landslide. It is suggested that the gravity-induced damage in the lower part of slope increases the permeability and thereby accelerates the weathering that causes a more rapid strength reduction. The latter results in the tilting/folding of pre-existing fabrics and the related VP fracturing. The La Clapière landslide is initiated in the upper part of this zone.
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1. Introduction

Gravitational slope failure is known to be influenced by several factors among which the structural heterogeneities and alteration/weathering processes are assumed to play a dominant role. Both physical and chemical weathering and alteration are caused by temperature changes and fluid circulations within the fractures and pores (Hall and André, 2001; Hoek and Brown, 1997; Migon and Lidmar-Bergstroem, 2002). Slope movements develop largely through the propagation and interaction of pre-existing fractures of tectonic origin (Bois and Bouissou, 2010; Bois et al., 2008; Kaneko et al., 1997; Scavia, 1995) and the development of new gravity-induced fractures (Bachmann et al., 2009; Petley, 1996). The relative influence of the listed factors is still misunderstood, which requires further investigations. In this work we performed a geological analysis and numerical modelling of the Argentera massif (French Southern Alps) along the Tinée valley. The eastern side of the valley is subjected to active landsliding and is composed of weathered metamorphic units affected by tectonic fracture sets related to the Oligocene–Miocene thrust tectonics (Gunzburger and Laumonier, 2002). In order to analyze the evolution of fracturing during gravitational rock slope failure we carried out an accurate analysis of fractures and cleavage anisotropies along the slope (from the toe to the crest) around two landslides, the mature La Clapière landslide active for about sixty years (Casson et al., 2005; Follacci, 1987, 1999; Guglielmi et al., 2002) and the initiating Isola landslide. In both cases, the schistosity was found sub-horizontal in the vicinity of the landslides at shallow depth and sub-vertical elsewhere. In addition to the well known tectonic fracture sets, we documented in both cases a new family of vertical, valley parallel (VP) fractures. The latter are 'fold extrado'-like joints associated with a progressive tilting of schistosity. The proximity of this schistosity folding and the VP jointing to the landslides suggests that they are gravity-induced.

The presented finite-difference models support this conclusion. The principal factor defining the gravity-driven destabilization of the model was a gradual reduction of the cohesion simulating effects of alteration/weathering. This corresponds to a time softening of the material and not to a strain softening applied in some other studies (Eberhardt et al., 2004; Hajiabdolmajid and Kaiser, 2002). The modelling approach is similar to that reported in Chemenda et al. (2009), where we investigated a large-scale (relatively low-resolution) gravity induced deformation pattern and related landsliding in the La Clapière area. A simple Hooke–Mohr–Coulomb constitutive model was used

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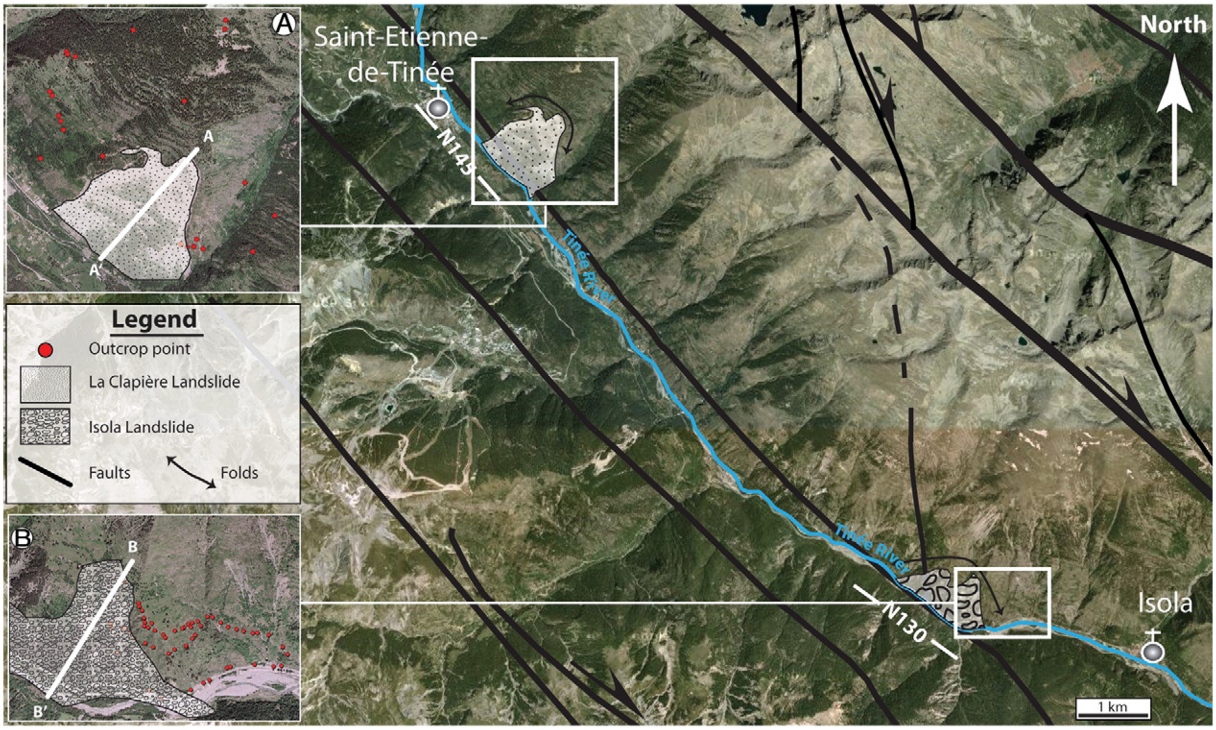

Fig. 1. Simplified structural map of the study area. The squares (a) and (b) show the La Clapière and Isola landslides, respectively. Outcrop points in red show the zones where measurements have been performed. The segments AA′ and BB′ are the traces of cross sections shown in Figs. 3 and 5, respectively.

with different boundary conditions, model size, and resolution. In all cases the model evolution leads to inelastic deformation that at later stages can localize into sub-vertical shear bands, which follows by landsliding in the upper part of the damaged (inelastically deformed) volume.

2. Geological setting

2.1. General framework

The study area is located in the Tinée valley, southern French Alps, at the north-western edge of the Argentera-Mercantour massif (Fig. 1). The latter corresponds to a wide outcrop of Hercynian 300–320 Ma metamorphic rocks (mainly micaschists and gneiss) with steeply dipping schistosity planes trending N 150°E (Bogdanoff, 1986; Delteil et al., 2003). Several sets of dextral N140°E mylonitic shear zones crosscut the entire massif. They were formed at mid-crustal depth conditions between 32 and 20 Ma (Corsini et al., 2004; Sanchez et al., 2011a). Exhumation of this mid-crustal basement occurred in a mainly transpressive context during the last 20 Ma (Bigot-Cormier et al., 2005; Sanchez et al., 2011b). During exhumation, brittle deformation reactivated the former Hercynian or Alpine shear zones, and contributed to the basement fracturing. Symmetrical, decimeter-size conjugate shear fractures forming tectonic wedges and associated extension fractures have been identified (Gunzburger and Laumonier, 2002). For most wedges, fractures are oriented N115°E, 80°SW on average but also N70°E, 80°NW or N30°E, 80°NW. Related kinematics are right-lateral on N115°E planes and extensional + sinistral on the N30°E planes (Sanchez et al., 2010a). Deeply incised valleys in the region create optimal conditions for landsliding. About 30 landslides with mobilized volumes ranging from 5×10^6 to 60×10^6 m^3 have been documented in the valley (El Bedoui et al., 2011; Jomard, 2006; Sanchez et al., 2010b). Among them, La Clapière landslide is located less than 1 km downstream Saint-Etienne-de-Tinée village (Fig. 1). This landslide extends over a width of 800 m at hillside foot to a 120 m high scarp at an elevation of 1600 m. The failure surface depth ranges from 100 m to 200 m (Guglielmi et al., 2005). The landslide moves downward at a rate varying from 50 to 500 cm/yr (the average rate is of about 1 cm/day) (Casson et al., 2005; Jomard, 2006).

The Isola landslide is located at about 10 km from the La Clapière Landslide and at 1 km from the village of Isola (Fig. 1). This latter landslide corresponds mainly to superficial rock falls. It extends over a width of 1500 m at hillside foot to a 500 m high scarp at an elevation of 1200 m.

2.2. Characterisation of cleavage anisotropies and fracture sets

The La Clapière and Isola landslides areas were chosen for several reasons: i) they are among the largest active landslides of the Tinée

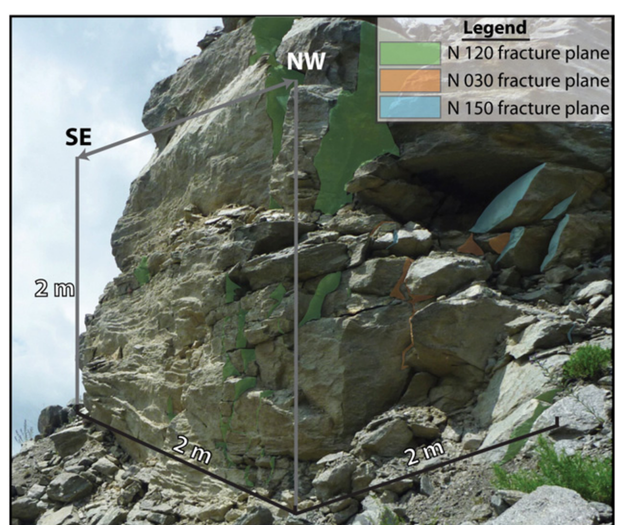

Fig. 2. Photo showing a representative outcrop for the structural measurements. The green, orange and blue colours highlight the fracture planes with an orientation of N120°E, N030°E and N150°E, respectively.

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