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An investigation into the development of toppling at the edge of fractured rock plateaux using a numerical modelling approach

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ABSTRACT

The mechanisms controlling the onset of minor slope instability at the edges of rocky plateaux exhibiting lateral spreading phenomena are yet to be fully understood. Hypotheses have recently been introduced to explain the influence of groundwater within these plateaux on geomorphological processes leading to slope instability. We present a back analysis of a recent landslide which occurred on 27th February 2014 in the town of San Leo, Italy. The role of the softening of basal clay shales and erosion due to seepage is investigated using finite element geomechanical models. Both processes were observed in the field and are related to groundwater discharging along the contact between the rocky slab and the clay-rich substratum. Fracture propagation paths involving pre-existing discontinuities and intact rock bridges failure were simulated using a simplified discrete fracture network (DFN) model coupled with a Voronoi polygonal mesh approach. Model results allow the failure to be classified as a secondary toppling phenomenon. Moreover, a critical amount of undermining was indicated by the models agreeing with field observations made prior to the failure. Based on the modelling results, an interpretation of the overall mechanism inducing failures at the edges of fractured rock slabs is given. In particular, the inter-relationships between groundwater flow and geomorphic processes acting within the rock masses are presented.

1. Introduction

Deep-seated gravitational slope deformations (DGSDs) may involve large parts of a rock slope and are often classified as sackungen and lateral spreads, depending on the observed slope deformation mechanisms (Dramis, 1985; Soldati, 2013). In both cases, the overall movements are generally slow and the principal hazards encountered are often due to secondary instability phenomena developing within the DGSD slope (Agliardi et al., 2001; Bonnard et al., 2004). Where lateral rock spreading phenomena involve brittle rock units overlying a more ductile substratum, associated secondary instabilities such as rockfall, toppling and rock slides may occur. These instabilities generally affect the edges of the plateau, while earth slides and earth flows can impact the underlying terrains (Pasuto and Soldati, 2013). Such a variety of mechanisms, specifically related to the long-term evolution of DGSDs, can lead to a high level of risk for elements located at both the top and base of the rock slabs. Several examples have been described in Europe and particularly in the northern Apennines area of Italy, where historical villages were often built on the top of plateaux. Both tourist and historical sites suffer from similar phenomena in the Maltese archipelago (Gigli et al., 2012; Mantovani et al., 2013). The differential movement of the travertine blocks on which the Spis castle in Slovakia was built is suggested to be the main cause of processes endangering it (Benko, 1997; Vlcko, 2004). Slope instability phenomena endangering the towns of Orvieto, Civita di Bagnoregio and Pitigliano in Central Italy have been recognized and investigated (Cencetti et al., 2005; Delmonaco et al., 2009; Fanti et al., 2012). The marked contrast between the mechanical properties of the overlying and underlying geological units was indicated as one of the main causes for lateral spread. This has been confirmed by Casagli (1994) and D'Ambra et al. (2004) using 2D continuum numerical models that investigated the resulting stress distributions within the slabs. Other influencing factors have been recognized, including for example stress relief in the stiffer overlying units due to the erosion of the underlying softer units (Bozzano et al., 2008) and overburden load due to the rock slabs causing deformation of the underlying weaker units (Pasuto and Soldati, 2013).

On the 27th of February 2014 a large landslide endangered the historical centre of San Leo, a medieval town built on the top of a calcarenitic slab (Fig. 1). A volume of about 330,000 m^3 of rock detached from the north-eastern side of the plateau, resulting in the evacuation of several private houses, a primary school and a police station (Borgatti et al., 2015). Before the failure, severe undermining of the rock slab was noticed in the area of the failure, as a result of the progressive

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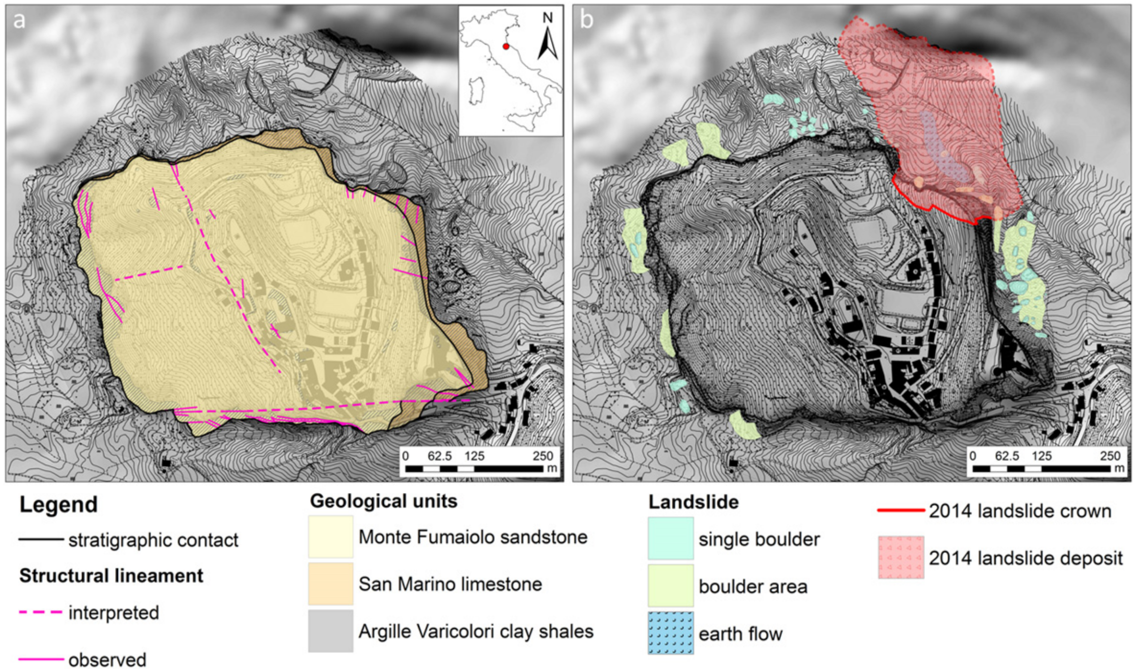

Fig. 1. Pre-event maps of the San Leo rock plateau (modified after Badioli, 2012). a) Geological and structural map. b) Landslide deposits and the area involved in the 2014 landslide.

removal of the clay shale units. As this erosional process was thought to be associated with surface runoff and shallow landslides occurring in the surrounding small-scale catchments, countermeasures such as earthen dams and retaining walls founded on piles were designed to avoid further slope instabilities. Recently, Spreafico et al. (2015a, 2015b) described the aquifer-characteristics of the calcarenitic plateau. The complex network of fractures and joints generates a relatively high secondary permeability with respect to the clay shale substratum; several perennial springs, fed by the groundwater within the slab, are observed at the base of the cliffs. The erosion from emerging spring water is referred to as seepage erosion and/or groundwater sapping (Dunne, 1980). In bedrock headwalls, with a contrasting bi-modal stratigraphy, seepage weathering precedes erosion at the seepage face and, if favorable joint intersections are present, caves can develop (Lamb et al., 2006). This leads to the progressive undermining, collapse and retreat of the headwall, creating amphitheatre-headed valleys (Nash, 1996). Rock mass failures in the cliffs can thus also be related to the weathering and erosion occurring at the contact between the rocky slab and the basal clay-rich units (Spreafico et al., 2015a). During the investigations undertaken after the occurrence of a similar landslide, affecting the northern cliff of San Leo in 2006, a 3 m thick softened layer was recognized (Gibertoni, 2007). This has been confirmed by more recent surveys carried out in the proximity of the 2014 landslide, indicating a softened layer of approximately 6 m thick (Lucente, C.C., personal communication). In a similar geological context, Picarelli et al. (2006) and Di Maio et al. (2013) highlighted the presence of softened layers outcropping in the southern Apennines of Italy: these layers are characterized by high plasticity clay shales, with thickness reaching 10 m.

The softening of the clay-rich layer and/or the undermining of the slab at San Leo could have caused the onset of toppling, as previously described within the literature in similar environments. Goodman and Bray (1976) describe different types of toppling in detail. Among these, secondary toppling failures are characterized as failures triggered by undercutting due to the weathering or the removal of the underlying materials. Evans (1981) focused his work on secondary toppling slope processes investigating possible failure mechanisms and describing the weathering pattern in claystones underlying sandstone cliffs. Since both erosion and softening have been detected at San Leo, the recent slope detachment failure is suggested to be due to this form of secondary toppling. Tommasi (1996) investigated the methods that have been used to study similar slope instability mechanisms and suggested that toppling caused by the weathering of underlying materials can be correctly interpreted if numerical methods are used (finite elements, finite difference and distinct element methods). Spreafico et al. (2016) conducted a back analysis of the San Leo 2014 landslide using the distinct element method (DEM) code 3DEC (http://www.itascacg.com). Their results highlighted the importance of slope undermining as a predisposing and/or triggering factor, although the failure surface was not fully reproduced with the DEM code.

We present in this manuscript a back analysis of the San Leo 2014 landslide with the objectives of better understanding the secondary instability developing at the edges of the plateau and recognition of the mechanisms acting on the slope in the medium- to long-term (i.e., decades to centuries). The Finite Element Method (FEM) code Phase2 (now called RS2, http://www.rocscience.com) was used to simulate the event. This FEM code has been widely used to simulate similar slope failures. Styles et al. (2011) used Phase2 to back-analyze the Joss Bay Chalk cliff failure where the progressive development of a wave-cut notch at the base of a coastal cliff was modelled using simulated model excavation stages. Sturzenegger and Stead (2012) also used Phase2 to model the Palliser Rockslide, Canada, as a stepped failure surface, while Kaşmer et al. (2013) assessed the stability of natural slopes prone to toe erosion in Cappadocia, Turkey.

Based on field evidence, two main simulations of the San Leo slope were conducted, in order to consider two possible processes leading to failure: (1) the softening of a relatively thin clay shale layer (5 m thick) and (2) the undermining of the rocky slab. To investigate the critical conditions leading to the 2014 San Leo slope failure, different softening/undermining rates were simulated by (1) considering progressively lowered values of the mechanical properties or (2) assuming different extent in term of length of the undermined area. In both simulation methods, (1 and 2) the role of a main iron-stained pre-existing discontinuity, observed in the cliff after the failure, was investigated.

The latter simulation method (2) was chosen to investigate the influence of groundwater within the rock slab on slope instability. In particular, the role of the assumed groundwater level and the effect of the water pressure on the main discontinuity were taken into account.