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Back analysis of a rock landslide to infer rheological parameters

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ABSTRACT

On 30 January 2009, a rock slide involving approximately 0.23 Mm^3 of highly jointed gneiss from the local Ercinic substratum was recorded in southern Italy. The landslide occurred after exceptional autumnal rainfalls and involved a quarry whose activity has been documented over the past 10 years by aerial images.
An engineering-geology model of the slope involved in the landslide was developed based on the geomechanical classification of the outcropping rock masses, the ISRM (2007) indexes Ib (the block size index) and Jv (the volumetric joint count), and the observed geological setting of the slope. An equivalent continuum approach was adopted to attribute strength and stiffness parameter values to the different classes of jointed rock masses.
A simplified evolutionary model of the slope was developed, starting from 300 ka (i.e., from the erosional phase following the deposition of the 300-m-a.s.l. marine terrace deposits overlaying the gneiss substratum) to 30 January 2009. The model took into account the main depositional phases as indicated by the Pleistocene marine terrace deposits and the documented stages of quarry activity.
Time-dependent stress–strain numerical modelling was performed by the FDM software FLAC 6.0. A visco-plastic Burger model was used to back-analyse the landslide event and to define the values of the rheological parameters for the jointed gneiss.
The results, which were strongly constrained by the geomorphological evidences and by the displacement field observed before and after the landslide, demonstrated a combination of i) time-dependent gravitational slope deformation and ii) anthropogenic release due to quarry activity, which induced a progressive failure process and an increase in the jointing within the gneissic rock mass located behind the cut-wall of the quarry. Failure was ultimately triggered by intense rainfalls that occurred in the 3 months before the landslide.
The stress–strain numerical modelling demonstrated the reliability of visco-plastic rheology for simulating the rock mass creep in this case history: viscosity values in the range of 10^{19}–10^{23} Pa·s were derived.

1. Introduction

Time-dependent rock mass deformations are particularly common in the Apennine chain due to the juxtaposition of stiff and ductile materials (Nemcok and Baliak, 1977; Canuti et al., 1990; Conti and Tosatti, 1993; Esposito et al., 2007; Bozzano et al., 2008) and the presence of aquifers within the carbonate ridges (Martino et al., 2004; Maffei et al., 2005; Discenza et al., 2011). In the southern Calabrian Apennines, rock mass deformations can be induced by the intense Pleistocene–Holocene evolution of the landforms responsible for erosional processes due to marine, fluvial and gravitational phenomena (Ricchetti and Ricchetti, 1991; Ferranti et al., 2007; 2008). In the same region, several diffused geomechanical conditions that act at the slope scale, such as the weathering of crystalline rocks (Prestininzi, 1984; Calcaterra et al., 1996; Pellegrino and Prestininzi, 2007; Pellegrino et al., 2008) and the structural and jointing conditions of rock masses (Bozzano et al., 2011), make the rock masses prone to landslides. These conditions result from the very complex, polyphasic structural evolution of the area (Scandone, 1979; Ghisetti, 1984; Vai, 1992; Finetti et al., 1996; Guarnieri et al., 2004; Guarnieri, 2006; Ferranti et al., 2007; Carbone et al., 2008).

The specific role of rock mass jointing in the time-dependent evolution of gravity-induced slope deformations cannot easily be determined because viscosity values are difficult to be attributed to discontinuous media (Eberhardt, 2006; Varga, 2006; Apuani et al., 2007). In the past several decades, several proposals have been made to characterise discontinuous media according to continuum equivalence criteria (Priest, 1993; Sridevi and Sitharam, 2000; Asef and Reddish, 2002; Zhang and Einstein, 2004). These criteria consider the jointed rock system to be a homogeneous medium, whose strength and stiffness parameters can, depending on the number and/or the geomechanical properties of the joints, be evaluated by reducing the intact rock values. Some of these approaches also take into account the confining stresses for varying of the stiffness and strength

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of the equivalent media with depth. Many numerical experiments have been performed (Sitharam and Madhavi Latha, 2002; Esposito et al., 2007; Bozzano et al., 2011, Esposito et al., 2011) to test the continuum-equivalent approaches for modelling landslide events under time-independent conditions (i.e., with elasto-plastic constitutive laws in addition to ubiquitous joint laws). Nevertheless, no specific solutions have been proposed for evaluating the viscosity of jointed rock masses or adopting specific rheological models.

Numerical experiments have been performed (Apuani et al., 2005; Apuani et al., 2007) on deep-seated gravitational deformation in the central Italian Alps. These experiments used finite-difference methods to evaluate the stress–strain response of the simulated slopes under visco-elastic or visco-plastic constitutive laws (such as in the Maxwell or Burger models) compared to the response under an elasto-plastic constitutive law (i.e., the Mohr–Coulomb model). The results demonstrated a better response with visco-plastic constitutive laws, but they also revealed a severe inability to determine the inferred viscosity values, which were very different from the laboratory-derived values.

This paper describes the results of a back-analysis performed using a stress–strain finite-difference analysis of the Santa Trada (Calabria, southern Italy) landslide of 30 January 2009 (Fig. 1). The features of this landslide are particularly useful for constraining a time-dependent process at both long (i.e., 10^4-years) and short (i.e., 10-years) time scales.

The Pleistocene–Holocene evolution of the Santa Trada Creek Valley can be divided into major stages of fluvial erosion, which can be dated by using the marine terrace succession. Beginning in 2002, a stress release was induced through quarry activity, which has been documented in aerial images. Finally, the failure event of 30 January 2009 was widely documented by terrestrial and satellite interferometric data and direct field surveys.

Landslides induced by anthropogenic stress release have been widely documented for both rock and soil materials. In these cases, the geological evolution of the slope is generally considered to be an essential feature of accurate models for back-analysis (Matheson and Thomson, 1973; Chandler and Skempton, 1974; Burland et al., 1977; Benko and Stead, 1998; Cooper et al., 1998; Bozzano et al., 2006). In particular, the superimpositioning of anthropogenic activities on geological evolution and/or natural predisposing conditions allows a complete interpretation of both the mechanisms and the timing of the observed failure events. In this regard, numerical models have been widely applied to reproduce stress and strain fields, i.e., to evaluate stress ratios and the orientations of principal stresses within the slope before the anthropogenic release (McTingue and Mei, 1981; Miller and Dunne, 1996; Potts et al., 1997; Haneberg, 1999; Eberhardt et al., 2004; Stead et al., 2006).

As a consequence, a good fit of the geomorphological and kinematical data with the outputs of the numerical modelling provides a strong constraint for calibrating the rheology (i.e., the time-dependent constitutive law and related parameter values) of the rock masses involved in the landslide.

2. Geological setting

The Santa Trada landslide area is characterised by the outcropping of highly jointed gneiss (Figs. 2, 3a) that can be ascribed to the Ercinic substratum of the Calabrian arc and part of the Aspromonte metamorphic unit (Lentini et al., 2000; Carbone et al., 2008). These metamorphic rocks are characterised by a predominant isotropic, granular texture, including biotitic micas, plagioclasic minerals and rounded xenoliths. A major Alpine foliation is also detectable, and wide zones of cataclasitic to mylonitic rocks generally correspond to the main fault lines.

Up to 340 m a.s.l., the area is also characterised by wide outcroppings of deposits, which correspond to many hierarchical terrace marine orders, over marine abrasion platforms. These deposits are composed of reddish-brown gravels and sands with a dip angle of less than 10°. They are transgressive on the Ercinic metamorphic substratum, as demonstrated by an about one meter-thick pebbly level that can be observed at their base (Fig. 3b). Where visible, this level has an attitude of approximately 320/40 (dip direction/dip). The deposits at the top of the Santa Trada landslide slope (340 m a.s.l. terrace) that lay over the abrasion platform dated approximately 300 ka (Miyauchi et al., 1994; Dumas et al., 2005).

Fig. 1. a, b) Location on satellite images of the study site in the Messina Strait area of southern Italy; c) panoramic view of the Santa Trada Creek near the landslide slope.