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On the reactivation of a large landslide induced by rainfall in highly fissured clays

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ABSTRACT

The paper discusses the field investigations, geotechnical characterization and time evolution of horizontal displacements in a wide landslide. The latter, triggered by an earthquake occurring in September 2002, is located in Sicily and involves a thick body of stiff and highly fissured clays belonging to a Varicoloured Clay formation. In order to characterise the reactivation of landslide mechanisms induced by rainfall, a three-year monitoring programme (2008–2011) was implemented to measure rain, pore water pressures, and deep and superficial displacements. The monitoring data made it possible to recognize three distinct landslides, which evolve at variable rates in different directions, within the overall landslide area. The landslides were reactivated by the increase in pore water pressures in the period autumn 2009–spring 2010. The data clearly show the mechanical role of pore water pressures in the stability of the slope and point out the dependence of the time evolution of the horizontal displacement on the pore water pressure variation induced by rainfall. Back-analysis carried out on the single landslides confirmed that they are reactivated ones since the residual shear strength is mobilised on the pre-existing sliding surfaces. The pore water pressure variation and the landslide body displacement rates can be effectively related to 5-month cumulative rainfall by simple models, characterised by three parameters. These models, calibrated on the period October 2009–September 2010, made it possible to predict the horizontal displacement rates in the ensuing time period. The displacements forecasted by the model in the period September 2010–May 2011 agree very well with the measured ones.

1. Introduction

Highly fissured clays belong to the group of structurally complex formations of prevalent clayey composition, widespread in Sicily, along the Italian Apennine Mountains, in many other countries of the Mediterranean area (Ogniben, 1960; Esu, 1977; AGI, 1985; Picarelli et al., 2000a,b; Santaloia et al., 2001; Fearon and Coop, 2002; Vannucchi et al., 2003; Nardelli et al., 2016) and in many other parts of the world (Skempton, 1964; Fookes, 1965; Skempton and Petley, 1967; Skempton et al., 1969; Chandler and Skempton, 1974; Sauer, 1984; Stark and Eid, 1997; Hight et al., 2007; Eid et al., 2016). Highly fissured clays are also locally known in literature as scaly clays or tectonised clays. In spite of the different geological origins and mineralogical composition, these soils share very peculiar common geotechnical characteristics (Airò Farulla and Valore, 1993; Picarelli et al., 2005; Vitone et al., 2009) and complexity of geological and tectonic processes (stress history) which have determined their actual emplacement (Leroueil and Vaughan, 1990; Leroueil, 2001; Picarelli et al., 2003, 2006; Di Maio et al., 2010).

A notable characteristic of slopes where fissured clays outcrop is their high susceptibility to landslides. These soils are often affected by very wide and deep landslides, quiescent or moving at low or very low rates. However, they can reactivate or "suddenly" accelerate due to earthquakes or increase in pore water pressures induced by rainfalls (adverse meteorological conditions), accumulating displacements of many metres in a few hours or days. In spite of the diffusion and great damage to inhabited places and infrastructures caused by these wide landslides, the literature is poor in case histories of extensive and long-term monitoring measurements, which are useful to depict reliable scenarios resulting from the predisposing and triggering factors and to characterise landslide mechanisms (Cotecchia et al., 2015).

In general, predisposing causes (Terzaghi, 1950) of fissured clay slopes landsliding can be grouped in three broad categories such as: (i) geomorphologic evolution, for instance fast erosive processes inducing depressed pore water pressure in the slopes involved, (ii) long-term actions of tectonic processes still active in the regions involved (Airò Farulla et al., 2015), and (iii) peculiar physical and mechanical characteristics of the clays. In this regard, intense fissuring, weathering

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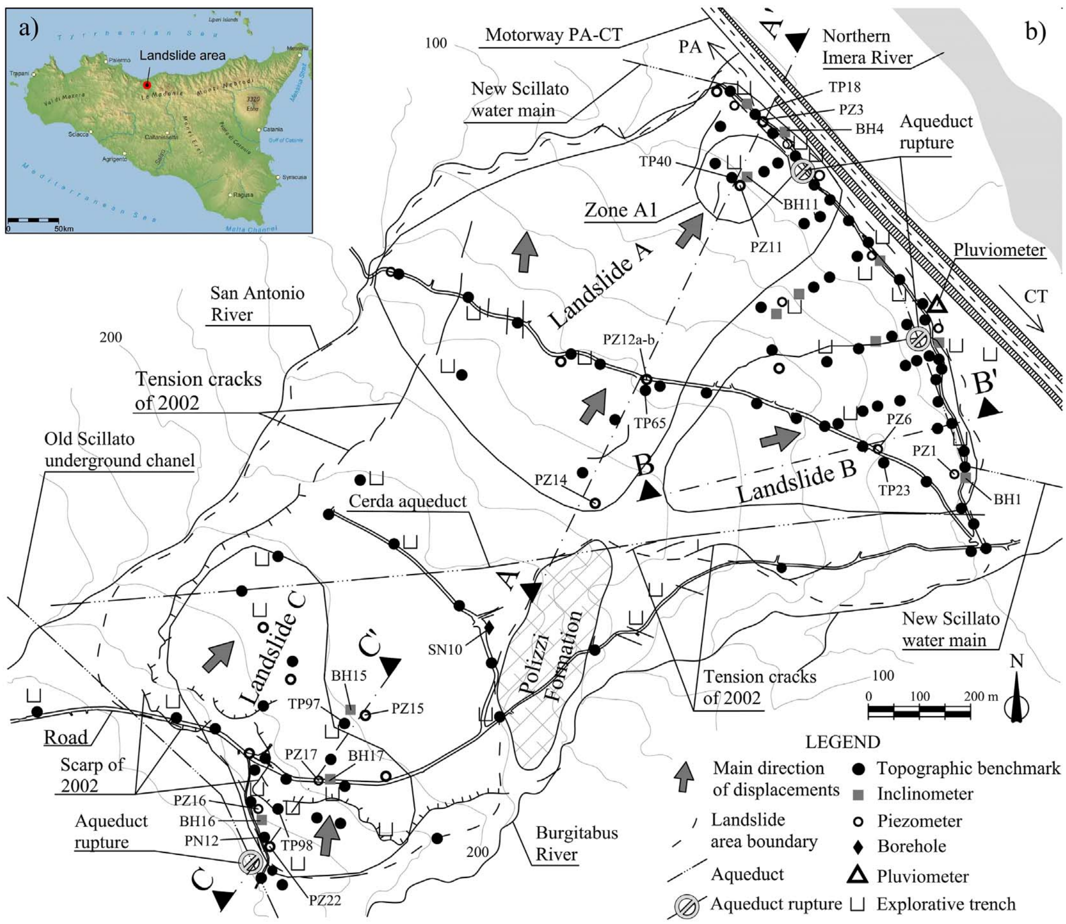

Fig. 1. Sketch map of the landslide area. a) Location; (b) limits of the landslide area triggered by the September 6th, 2002 earthquake (within which landslides *A*, *B* and *C* reactivated by rainfall in the period 2008–2011 are drawn. Inside the landslide *A* has been detected a second shallow landslide indicated in the figure as zone *A1*). The figure shows the main "infrastructures" affected by the landslide, the monitoring system implemented in autumn 2008 - late spring 2009 and the main geotechnical investigations performed.

processes and microstructure arrangement could be taken into account to interpret the volumetric and shear strength behaviour of the clays involved (Picarelli et al., 2003; Airò Farulla et al., 2010; Vitone and Cotecchia, 2011; Rosone et al., 2016; Mandaglio et al., 2016).

In September 2002 a large landslide (known in the literature as the Cerda landslide) in the district of Palermo (Sicily, Italy), Fig. 1a, involving a thick body of fissured clays belonging to a Varicoloured Clay formation, was reactivated by an earthquake. On the landslide body some important infrastructures (civil and irrigation aqueducts; farms of significant economic value; small or medium size irrigation water reservoirs; some secondary roads) suffered serious damage. The landslide area is still active and periodically reactivated by increase in pore water pressures induced by rainfall. In particular, there were recurring ruptures (on average two ruptures per year) between 2002 and 2007 of the New Scillato water main (one of the main drinking water conduits of Palermo), and less frequently of the Old Scillato channel, located respectively at the toe and at the head of the landslide area (Fig. 1b). This gave rise to the need to provide an in-depth analysis of the reactivation mechanism of this wide landslide.

In the paper, after a presentation of the main geotechnical properties of the soils involved, an analysis is presented of the time evolution of the horizontal displacements of the more active zones of the landslide area, namely landslides *A*, *B* and *C* (see Fig. 1b), measured during a monitoring programme lasting about three years. The monitoring system was implemented to record rainfall, pore water pressures, and deep and surficial displacements. With reference to these active landslide zones, the dependence of the horizontal displacement rates on the pore water pressures was investigated. An analysis of the monitoring data collected made it possible to establish a quantitative correlation between cumulative rainfall, pore water pressures, and the activity of the landslides in this complex soil formation.

2. Landslide geometry in September 2002

On September 6th 2002 at 3.21 a.m. an earthquake of magnitude M = 5.6 (Richter Scale) occurred in the Southern Tyrrhenian Sea, with the following epicentral coordinates: latitude 38.45 *N*, longitude 13.70 *E* (about 50 km north of the city of Palermo), while its focal depth was about 18–20 km (INGV, 2002).

The earthquake was felt in a large part of the northern coast of Sicily and its effects (even though it was a moderate intensity earthquake) were very intense in the old city of Palermo, where some buildings and monuments were badly damaged (Azzaro et al., 2004). The main ground effect of this seismic event was represented by the Cerda landslide, located about 50 km East of Palermo, on the left bank of the Northern Imera River (Fig. 1b). Some other secondary effects such as small falls were also observed on the island of Filicudi (Aeolian Islands), and some variation in discharge and temperature were registered in springs in the Termini Imerese area (Azzaro et al., 2004).

The reactivation of the Cerda landslide in 2002 was due to local amplification of the seismic signal in the low frequency range (2.5–4.5 Hz) in its head portion. In the lower portion of the slope, no significant amplification was registered with detailed geophysical investigations since, in this part of the slope, the clayey soils are more heterogeneous, remoulded and disturbed (Bozzano et al., 2008). These seismic amplifications are due to so-called "basin-like" effects (Bozzano